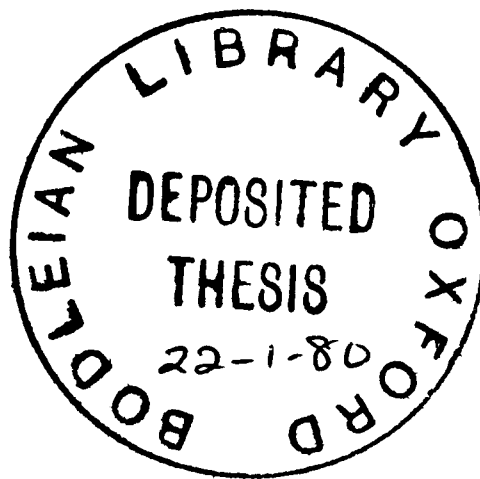




MEASUREMENTS OF THE VELOCITY-FIELD
CHARACTERISTIC OF INDIUM PHOSPHIDE

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A thesis submitted for the degree of
Doctor of Philosophy

Trinity Term 1979

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ABSTRACT

The thesis describes measurements of the velocity-field characteristic of indium phosphide, below threshold by a direct method and above threshold by domain measurements. Comparisons, with good agreement, are made with microwave measurements, below threshold on material from the same slices, and above threshold on material with very similar properties.

A historical description of the Gunn effect and domain theory precedes a description of the structure of indium phosphide and a survey of published velocity-field calculations and measurements, showing the difference between 2- and 3-level conduction band models.

A value for the Γ valley deformation potential has previously been deduced from the temperature variation of low-field mobility by adding reciprocal mobilities due to different scattering processes. This method is examined and experimental results of other workers are shown consistent with a lower deformation potential than supposed.

Sub-threshold results agree closely with other, published, measurements, using various techniques. Extended to 77 K, the sub-threshold method gave results agreeing reasonably with predictions for this temperature, and very well with extrapolations from other calculated and measured data.

Published high-field domain measurements made with a point-contact probe differ greatly from others. Experiments to produce a point-contact probe and associated differentiator with a known performance, and analysis of a simple circuit model indicate that the specimen resistivity controls the probe response, necessitating different probe resistances for different material resistivities. The probe was still found fundamentally difficult to use and is suspected of causing specimen damage due to localised heating under the point.

Domain shapes measured agreed with published measurements from capacitive probes, but domain velocity was higher, giving a higher valley velocity ($0.76 - 0.99 \times 10^7$ cm/s). Comparison of the deduced velocity-field curve with published calculations strongly supports a 2-level transfer mechanism.

CONTENTS

	<u>Page</u>
CHAPTER I HISTORICAL BACKGROUND AND DOMAIN THEORY	
1.1	Negative differential resistance 1
1.2	Bulk effect devices 1
1.3	The Ridley-Watkins-Hilsum mechanism 2
1.4	Gunn's observations 3
1.5	The mechanism of the Gunn effect 4
1.6	Instabilities 4
1.7	High field domains 5
1.8	Theory of high field domains. The equal-areas rule 6
1.9	Effects of diffusion 8
1.10	The domain characteristic. Triggered domains 9
1.11	Criteria for domain formation 10
CHAPTER II INDIUM PHOSPHIDE	
2.1	The structure of indium phosphide 13
2.2	Electron propagation 13
2.3	Band structure 14
2.4	Intervalley electron transfer 15
2.5	Calculations of the velocity-field characteristic of indium phosphide 16
2.6	Measurements of the velocity-field characteristic 19
2.7	Dipole domains in indium phosphide 23
CHAPTER III LOW FIELD TRANSPORT	
3.1	Low field scattering mechanisms 28
3.2	Combined mobility 30
3.3	The ' $\frac{1}{\mu}$ ' rule 31
3.4	Measured temperature variation of mobility 32
3.5	Calculated temperature variation of mobility 33
3.6	Comparison of theory and experiment 33
3.7	The scattering factor 35
CHAPTER IV DESIGN AND PRODUCTION OF SPECIMENS	
4.1	Requirements for low-field velocity-field measurements 37
4.2	Analogue of specimens 37
4.3	Specimen length 38
4.4	Preparation of photo-etched specimens 39
4.5	Bar-type specimens 43

CHAPTER V SUB-THRESHOLD VELOCITY-FIELD MEASUREMENTS

5.1	Measurement of resistivity and Hall mobility	44
5.2	Apparatus for current-voltage measurements	45
	5.2.1 Measuring system	45
	5.2.2 Specimen holder	46
	5.2.3 Apparatus for measurements at 77 K	46
	5.2.4 Calibration	46
5.3	Point-contact probe	47
	5.3.1 Specification for probe	47
	5.3.2 Probe construction	47
	5.3.3 Probe resistors	48
	5.3.4 Probe response	48
	5.3.5 Probe points	49
	5.3.6 Probe mounting and position measurement	49
5.4	Experimental details	49
	5.4.1 Preliminary experiments on bar-type specimens	49
	5.4.2 Current-voltage measurements	50
	5.4.3 Probe measurements	51
5.5	Deduction of central field in specimens	51
	5.5.1 Analogue of specimens	51
	5.5.2 Analytical method of Majerfeld	53
	5.5.3 Point-contact probe measurements	53
	5.5.4 Wide-bridge specimens	54
5.6	Sub-threshold velocity field characteristic	55
5.7	Comparison with other results	56
	5.7.1 Comparison with microwave measurements on similar material	56
	5.7.2 Comparison with theoretical calculations	57
	5.7.3 Comparison with other measured characteristics	58
5.8	Sub-threshold velocity-field characteristic at 77 K	59
5.9	Comparison with published low-temperature data	59
5.10	Substrate conduction	62
5.11	Accuracy	62
	5.11.1 Field measurement	62
	5.11.2 Velocity measurement	63

CHAPTER VI SURVEY OF PUBLISHED HIGH-FIELD DOMAIN RESULTS

6.1	High field domains in indium phosphide	68
6.2	Comparison of domain measurements	69
6.3	Domain shapes	70

CHAPTER VII DEVELOPMENT OF POINT-CONTACT PROBE FOR HIGH-FIELD DOMAIN MEASUREMENTS

7.1	Basic requirements for probe	73
7.2	Capacitive probe	73
7.3	Point-contact probe	74
7.4	Preliminary experiments	75
7.5	Development of point-contact probe design	75
7.6	Point-contact probe - final design	77
7.7	Differentiating circuit	78
7.8	Construction of differentiator	81
7.9	Testing of differentiator	82
7.10	Probe bias	82
7.11	Probe system - rise time measurements	83
7.12	Probe system - tests on gallium arsenide	83
7.13	Tests on higher resistivity material	84

CHAPTER VIII MODEL OF PROBE-SPECIMEN SYSTEM

8.1	Introduction	86
8.2	Equivalent circuit	86
8.3	Component values in the probe model	87
8.4	Transfer function of probe-specimen model	88
8.5	Probe response calculations	90
8.6	Probe response equalisation by shunt capacitance	91
8.7	Change in spreading resistance during domain passage	92
8.8	Conclusions	93

CHAPTER IX HIGH FIELD DOMAIN MEASUREMENTS

9.1	Apparatus for domain measurements	94
9.2	Measurement of domain velocity	94
9.3	Measurement of domain field profile	95
	9.3.1 Difficulties with point-contact probe	95
	9.3.2 Localised specimen heating	96
	9.3.3 Precautions	96
9.4	Stray coupling to probe	97
9.5	Filter response	98
9.6	Derivation of domain field, voltage and depletion ratio	100
9.7	Domain results	101
9.8	Derivation of velocity-field characteristic	102
9.9	Effects of diffusion	103
9.10	Comparison with other results	104

CHAPTER X CONCLUSIONS

10.1	Electron transfer mechanism in indium phosphide	106
	10.1.1 Sub-threshold measurements	106
	10.1.2 Overall velocity-field characteristic	107
10.2	Comparison with microwave measurements on similar material	108
10.3	Point-contact probe design and measurements	109
10.4	The possibility of high-field measurements at low temperatures	111

CHAPTER I

HISTORICAL BACKGROUND AND DOMAIN THEORY

1.1 Negative differential resistance

At microwave frequencies the usefulness of transistors is reduced by high frequency effects, namely the transit time of carriers across the base region and the junction capacitances. With the dimensions of such devices approaching the limits of technology, a different approach to microwave devices was needed. The tunnel diode of Esaki^[1] was a two-terminal device working on the principle of negative differential resistance and which, incorporated in a resonant circuit and biased into its negative differential resistance region, could be used as an oscillator. It was, however, still a junction device with its inherent capacitance.

1.2 Bulk effect devices

The advantage of a two-terminal device at high frequencies was realised as early as 1954 by Shockley^[2] who proposed such a device consisting of a bar of semiconductor with a negative differential mobility, and pointed out that the structural simplicity of a bulk-effect device (one without junctions) would be an attribute at microwave frequencies.

In a solid the electron is regarded as having an 'effective mass', given by

$$m^* = \hbar^2 \frac{\partial^2 E}{\partial k^2} .$$

An E-k relation for an electron in the conduction band might have the shape shown in Fig. 1.1, with a region at high energies where the curvature and hence the effective mass is negative, and if the high

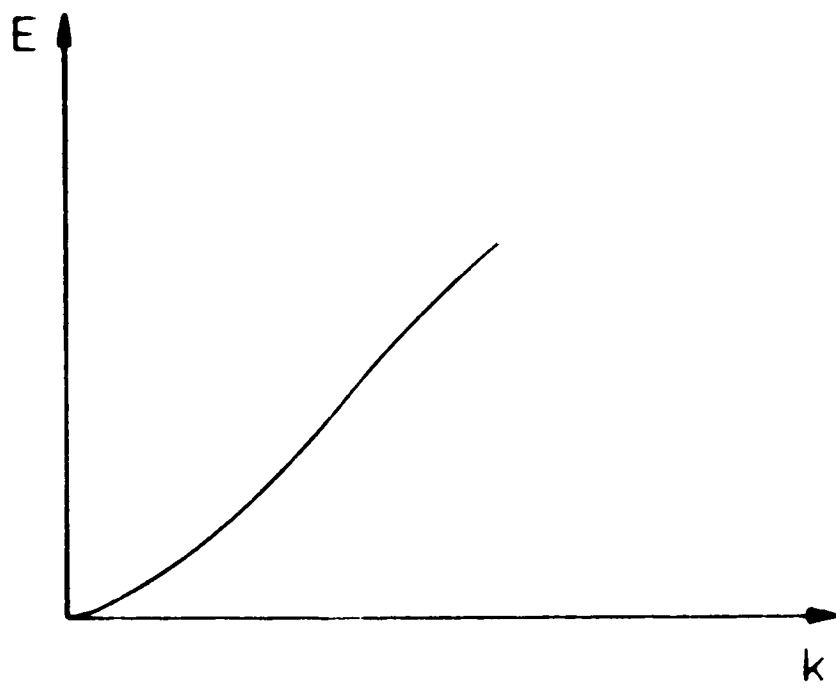


Fig.1.1. E - k relation for conduction band

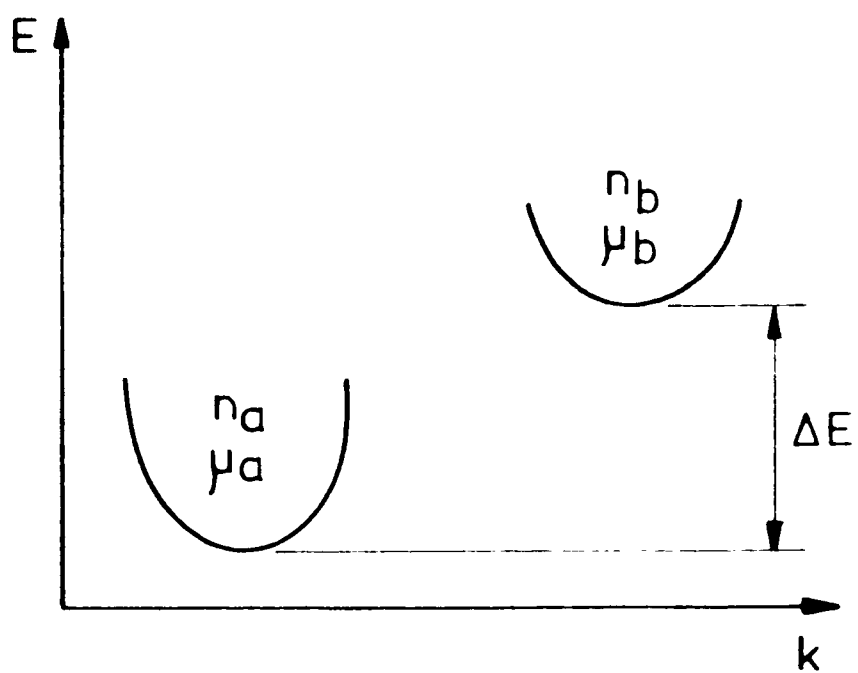


Fig.1.2. Two - valley conduction band.

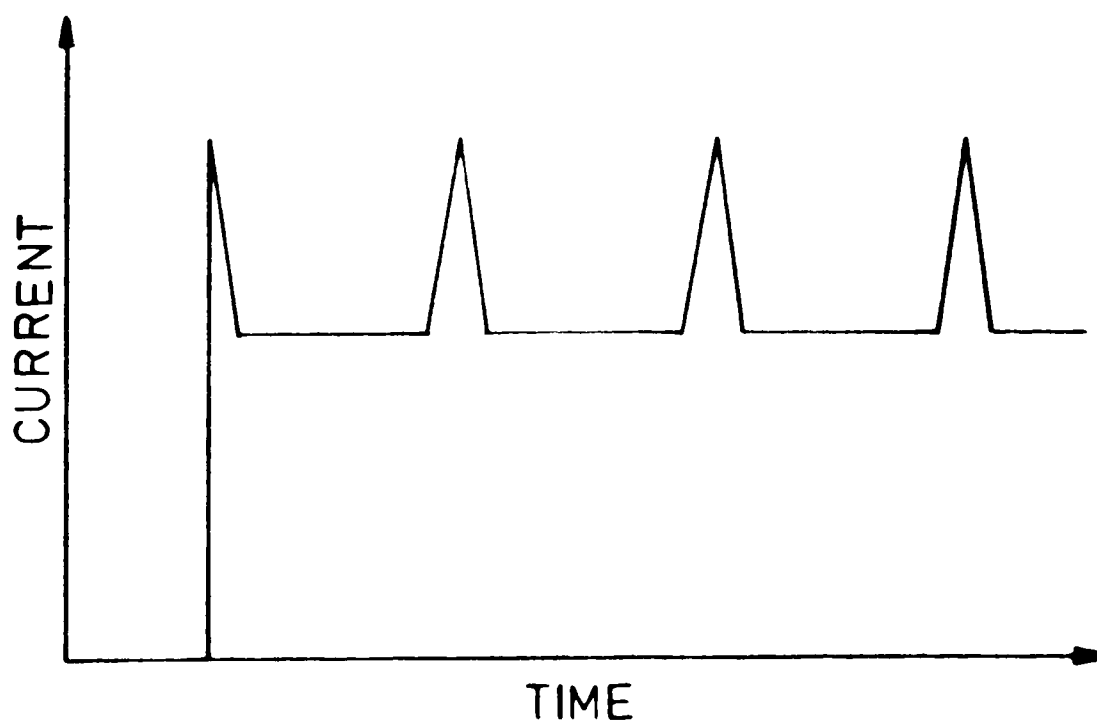


Fig 1.3 Current in device with high - field domain

energy states could be sufficiently populated, a negative differential mobility would be expected. Searches (Ryder and Shockley^[3]) failed to find such an effect in n-type germanium, as did attempts to find a negative differential hole mobility in p-type germanium (Kroemer^[4]).

1.3 The Ridley-Watkins-Hilsum mechanism

In 1961, Ridley and Watkins^[5] proposed a new mechanism for negative differential mobility in a bulk-effect device, based on the fact that the conduction and valence bands in a semiconductor comprised a number of sub-bands, of which only the lowest was normally populated. The effective mass of the electrons would be higher (and hence the mobility would be lower) in the higher energy sub-bands, making the conductivity of the material vary according to the relative population of the sub-bands. A similar theory was suggested, independently, by Hilsum^[6] in 1962.

Both consider a two-valley conduction band (Fig. 1.2), the valleys being separated by an energy ΔE ; the electron density in the valleys is estimated by assuming a Maxwell-Boltzmann distribution with a common electron temperature. An applied electric field increases the effective temperature of the electrons with the more energetic electrons being transferred to the upper valley. The overall conductivity is given by

$$\sigma = e(n_a \mu_a + n_b \mu_b)$$

where n_a , μ_a , n_b , μ_b are the electron densities and mobilities in the lower and upper valleys respectively. At low fields the electrons are in the lower valley, but as the field increases more are transferred to the upper valley, giving a decrease in the overall mobility.

Basing his assumptions on the work of Stratton^[7], which calculated the field dependence of electron temperature for a single valley subject to polar optical scattering, Hilsum predicted the threshold field for negative differential mobility in gallium arsenide to be 3 KV/cm, which subsequent experiments have shown to be quite accurate.

1.4 Gunn's observations

In 1963 Gunn observed current instabilities in samples of gallium arsenide and indium phosphide at high electric fields, and consequently investigated their current-voltage properties. At low fields, the expected result, a linear variation of current with field was found, but above a certain critical field the current started to vary, and had a mean value less than the current at the critical field. This was interpreted as a negative resistance effect causing some form of oscillation.

On investigating the variation of current with time, Gunn found evidence of coherent oscillation, and on testing further gallium arsenide specimens in an adjustable cavity, obtained significant amounts of microwave power. A typical result was 155 mW at 2.73 GHz with an efficiency of 0.8% which was promising, as the system had not been optimised for maximum power.

Gunn suggested several mechanisms as possible explanations of the negative resistance effect, none of which he considered satisfactory:

- a) pinch effect
- b) trapping of hot electrons
- c) energy-dependent scattering of hot electrons
- d) amplification of acoustic waves
- e) population of upper conduction band minima.

The last is the Ridley-Watkins-Hilsum mechanism. Taking the energy

gap between the two lowest conduction band minima to be 0.36 eV in indium phosphide (the latter is now known ^[31] to be 0.6 eV), Gunn calculated that the necessary electron temperature for significant electron transfer to occur was around 4000 K, compared with the calculated electron temperature at his experimental threshold field which was 300 - 400 K, and at which it was likely that only a negligibly small fraction of the electrons would be transferred. Without further evidence, therefore, this mechanism seemed improbable.

1.5 The mechanism of the Gunn effect

It was shown by Kroemer ^[9] that Gunn had overlooked the fact that in gallium arsenide the density of states in the six (100) valleys is approximately 400 times that in the central valley; immediately the evidence in favour of the Ridley-Watkins-Hilsum mechanism became stronger. Final confirmation was obtained in 1965 from Hutson et al. ^[10] who subjected a gallium arsenide specimen which showed the Gunn effect to hydrostatic pressure. It was known ^[30] that the energy separation between the (100) and (000) minima decreased with pressure, and as the pressure on the specimen was increased, the threshold field decreased, which was exactly the result expected from the narrowing of the energy gap.

Allen et al. ^[11] provided further evidence from experiments on gallium arsenide phosphide alloys, $\text{GaAs}_x\text{P}_{1-x}$, where the energy separation between the two minima decreases from 0.36 eV to zero as x varies from 1 to 0.5, with a corresponding decrease in threshold field. The results agreed closely with theory.

1.6 Instabilities

Ridley and Watkins ^[5] predict that a crystal, under negative resistance conditions, should be electrically unstable. At any point in the crystal a random perturbation in carrier density will produce

a space charge, and hence a field perturbation.

Considering current flow in one dimension, and solving the current continuity equation and Poisson's equation for small perturbations of field, carrier density and velocity, a solution for the electric field was obtained:

$$E = f(x - vt) \exp\left(-\frac{t}{\tau}\right), \quad \tau = \frac{\epsilon}{\mu n_0 \ell}$$

which represents a field perturbation travelling with a velocity v and governed temporally by the exponential term. If μ is negative the perturbation grows with a time constant τ ; in a practical situation it will grow until its amplitude is limited by the extent of the negative differential mobility region on the velocity-field characteristic. According to Ridley^[12], the instability would be a flat-topped high-field domain, but this prediction has since been shown to be incorrect^[13].

1.7 High field domains

Investigating the form of the instabilities, Gunn^[15,16] found that the current oscillated periodically with the waveform shown in idealised form in Fig. 1.3. The period between the current spikes varied according to the length of the specimen. The potential distribution along the specimens was measured with a capacitively-coupled probe, revealing triangular regions of high field building up near the cathode and propagating towards the anode; the periodic time of the current oscillation corresponded to the transit time of the high-field domain.

Measurements made on gallium arsenide specimens having a high-field domain in transit by Gunn^[15] and Heeks^[17] have shown that such a specimen exhibits a negative differential resistance - as the applied voltage is increased, the current decreases. This was shown to be due to the characteristic of the high field domain itself.

Numerical studies of space-charge instabilities were made by Kroemer^[14], using a simple expression for the velocity-field characteristic based on central and satellite valley mobilities of $5000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ and $1000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ respectively. Poisson's equation and the equation for total current density (conduction, displacement and diffusion currents, the diffusion constant being obtained from Einstein's formula) were solved for a specimen with uniform doping subjected to constant voltage bias. The result was a travelling accumulation layer, a layer of high electron density nucleating at the cathode and propagating along the specimen to the anode (Fig. 1.5). The specimen contains high field (near the anode) and low field (near the cathode) domains, the fields being such that at any instant the drift velocities are the same. As the layer travels these values of field, as well as the current, change continuously.

This result was at variance with the uniformly propagating high field domains which had been observed. However, when the simulation was modified to include random microscopic doping fluctuations, it predicted high field domains. Calculations by McCumber and Chynoweth, made on a similar basis, gave similar predictions^[18].

An interesting history of some of this early work appears in a paper by Hilsum^[25].

1.8 Theory of high field domains. The equal-areas rule.

To investigate the nature of the instabilities which form when the velocity-field characteristic has a region of negative differential mobility, strictly, Boltzmann's equations should be solved for the multi-valley conduction band structure, where the distribution function is allowed to depend on position and time. A simplified theory has been suggested by Butcher^[13], starting from the velocity-field relation, $v(E)$, Poisson's equation,

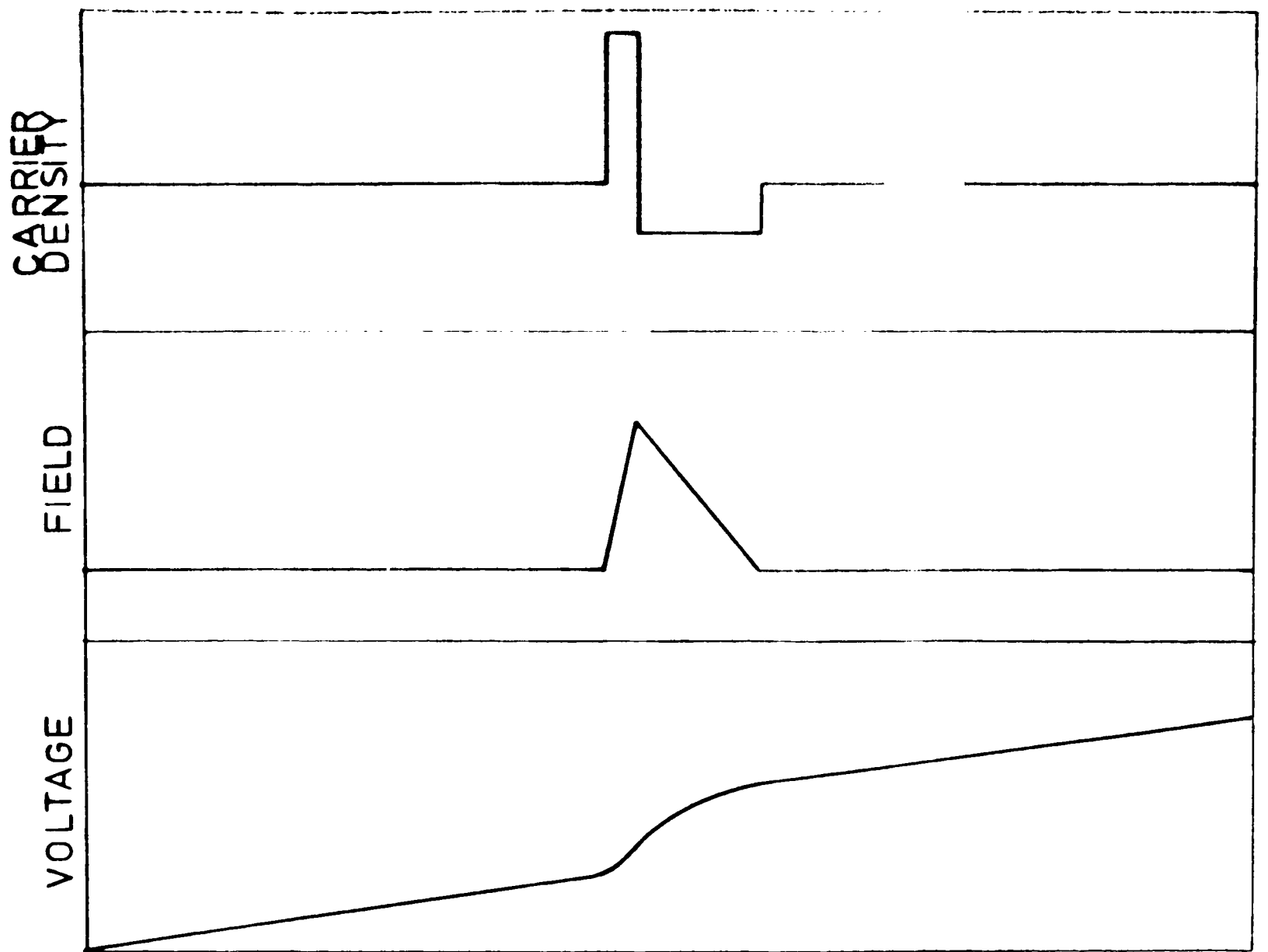


Fig.1.4. High field domain.

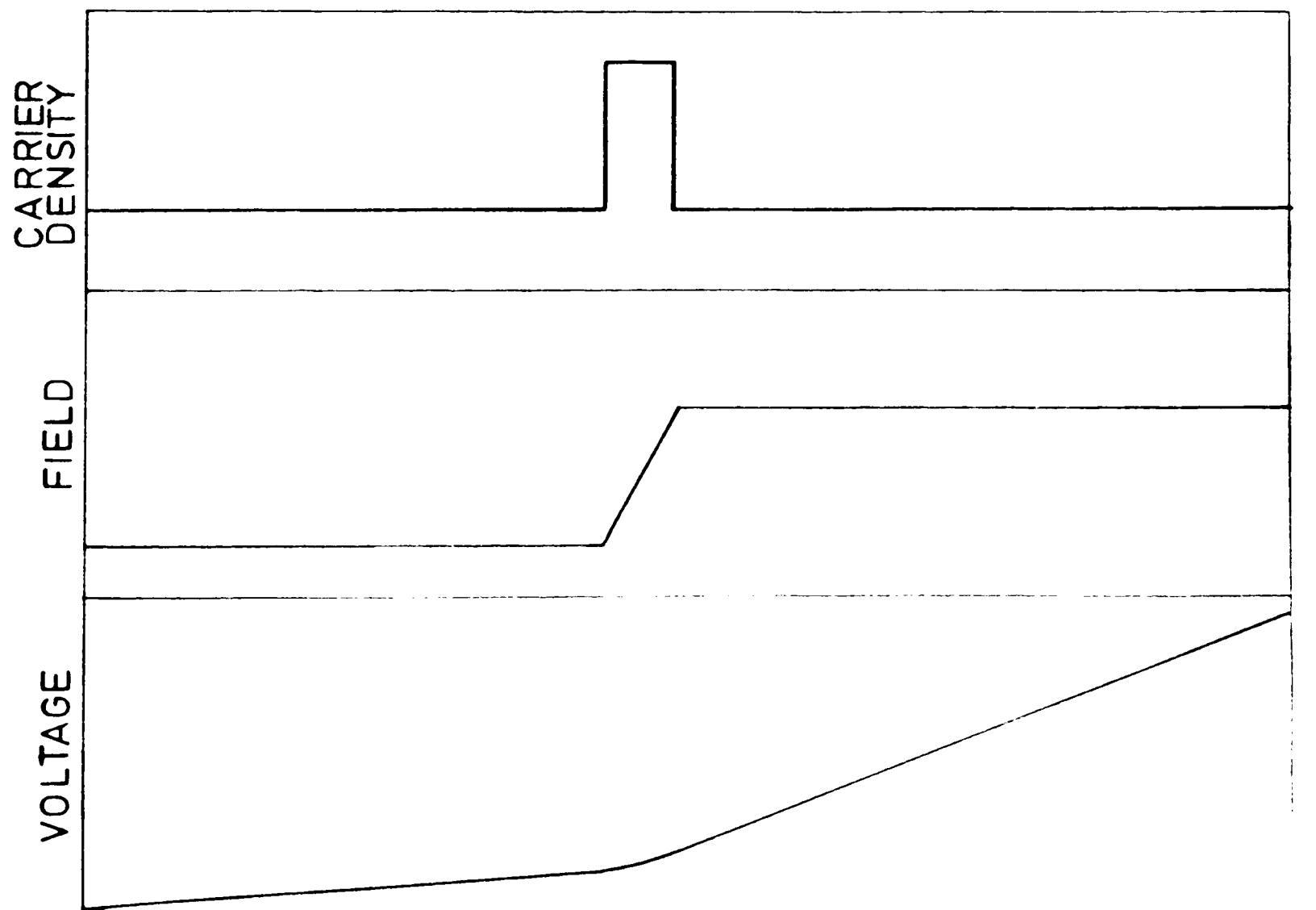


Fig.1.5. Accumulation layer.

$$\frac{dE}{dx} = \frac{e}{\epsilon} (n - n_0), \quad 1.8.1$$

and the equation for total current density,

$$J = n e v(E) - e \frac{d}{dx} (Dn) + \epsilon \frac{dE}{dt} = e n_0 v_1 \quad 1.8.2$$

The diffusion coefficient, which is really field-dependent, is at first approximated by a constant D .

It is assumed that the domain has a velocity v_D and is surrounded by material in which $n = n_0$ and field = E_1 ; hence E and n become functions of $z = x - v_D t$, with forms shown in Fig. 1.7. It follows that

$$\frac{d}{dx} = \frac{d}{dz}, \quad \frac{d}{dt} = -v_D \frac{d}{dz} \quad 1.8.3$$

From 1.8.1, 1.8.2 and 1.8.3,

$$D \frac{e}{\epsilon} \frac{dn}{dE} = \frac{n[v(E) - v_D] - n_0(v_1 - v_D)}{(n - n_0)}$$

which has the solution

$$\frac{n}{n_0} - \ln \left(\frac{n}{n_0} \right) - 1 = \frac{\epsilon}{n_0 e D} \int_{E_1}^E \left[(v(E) - v_D) + \frac{n - n_0}{n} (v_1 - v_D) \right] dE \quad 1.8.4$$

Applying the condition that $n = n_0$ at the peak of the domain, that is at the junction of the accumulation and depletion branches, to the integral on the right, it is seen that this integral must have the same value whether it is taken over the accumulation or depletion. However, in the second term $\left(\frac{n - n_0}{n} \right)$ would have different values on the two branches unless $v_D = v_1$. The domain travels with a velocity equal to the drift velocity outside it.

If the integral in 1.8.4 is taken over one branch of the domain from $n = n_0$, $E = E_1$ outside it to $n = n_0$, $E = E_2$ at the junction of the accumulation and the depletion, then

$$\int_{E_1}^{E_2} \{v(E) - v_1\} dE = 0 \quad 1.8.5$$

which is Butcher's equal-areas rule - the value of E_2 is determined by the condition that the two shaded areas in Fig. 1.6 are equal. This condition is independent of the diffusion coefficient if this is taken as constant.

Allen et al.^[19] have given a modified version of the equal-areas rule to apply when the diffusion coefficient is field-dependent:

$$\int_{E_1}^{E_2} \frac{v(E) - v_1}{D(E)} dE = 0 \quad 1.8.6$$

Equation 1.8.4 gives a relation between n and E at every point; for every value of field there are two values of n , one greater than and one less than n_0 , corresponding respectively to the accumulation and depletion branches of the domain. If the diffusion constant is small enough, the low value of n is close to zero and the large one is very large, corresponding to an almost completely depleted region in the domain, which now approaches the idealised triangular shape shown in Fig. 1.7. In this limiting case the voltage across the domain is

$$v_D = \frac{\epsilon(E_2 - E_1)^2}{2en_0}$$

1.9 Effects of diffusion

Still taking the diffusion coefficient D as a constant, calculations of domain shapes were made by Butcher and Fawcett^[20] using an analytical approximation to the velocity-field characteristic, and by Carroll^[21], using a 'three-line' approximation. Both found that at low domain voltages (peak fields less than about 20 kV/cm) the domain became symmetrically shaped, with incomplete depletion, whereas at high domain voltages the domains had a rounded asymmetrical triangular shape, with almost full depletion. The lack of complete

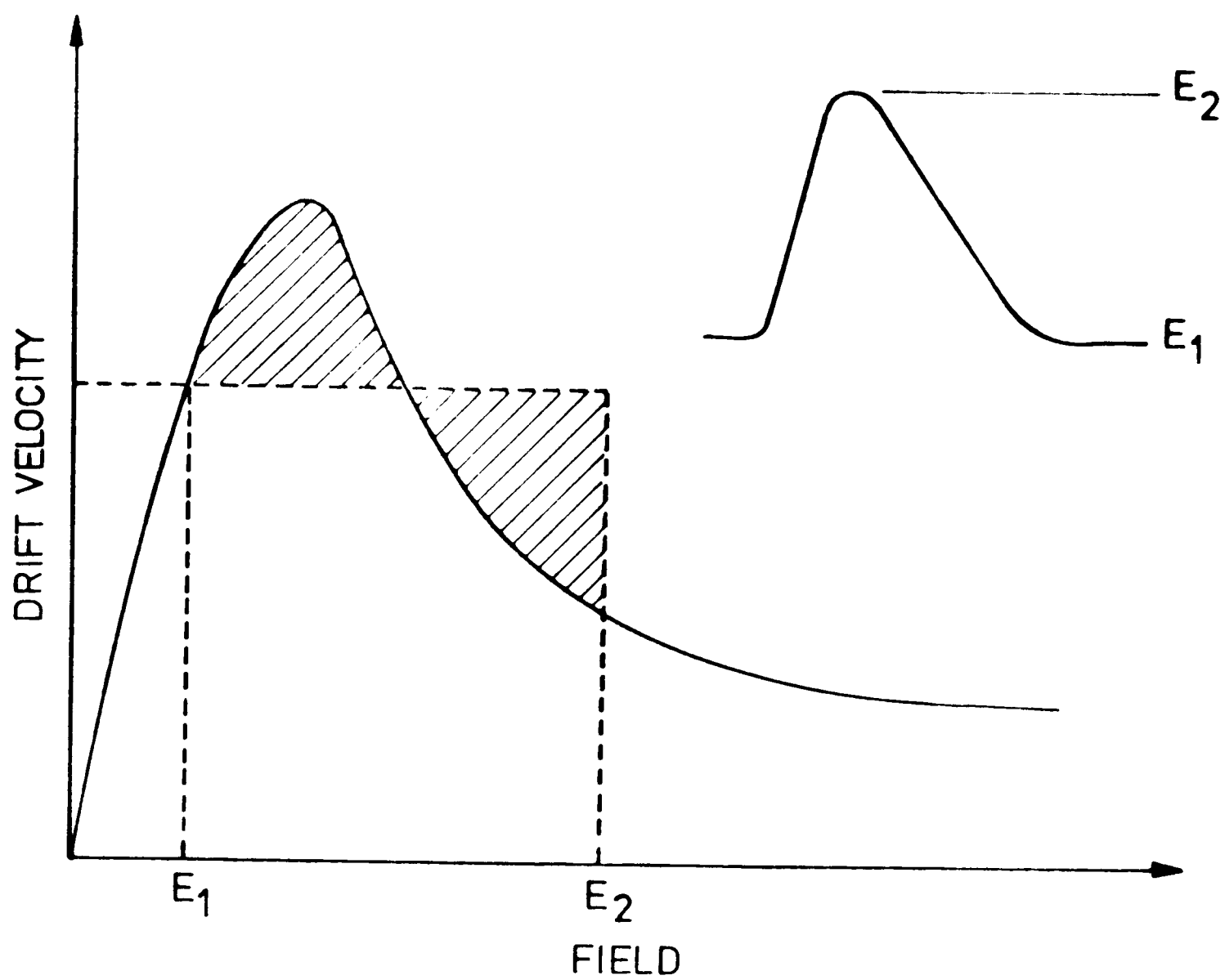


Fig.1.6. The equal - areas rule.

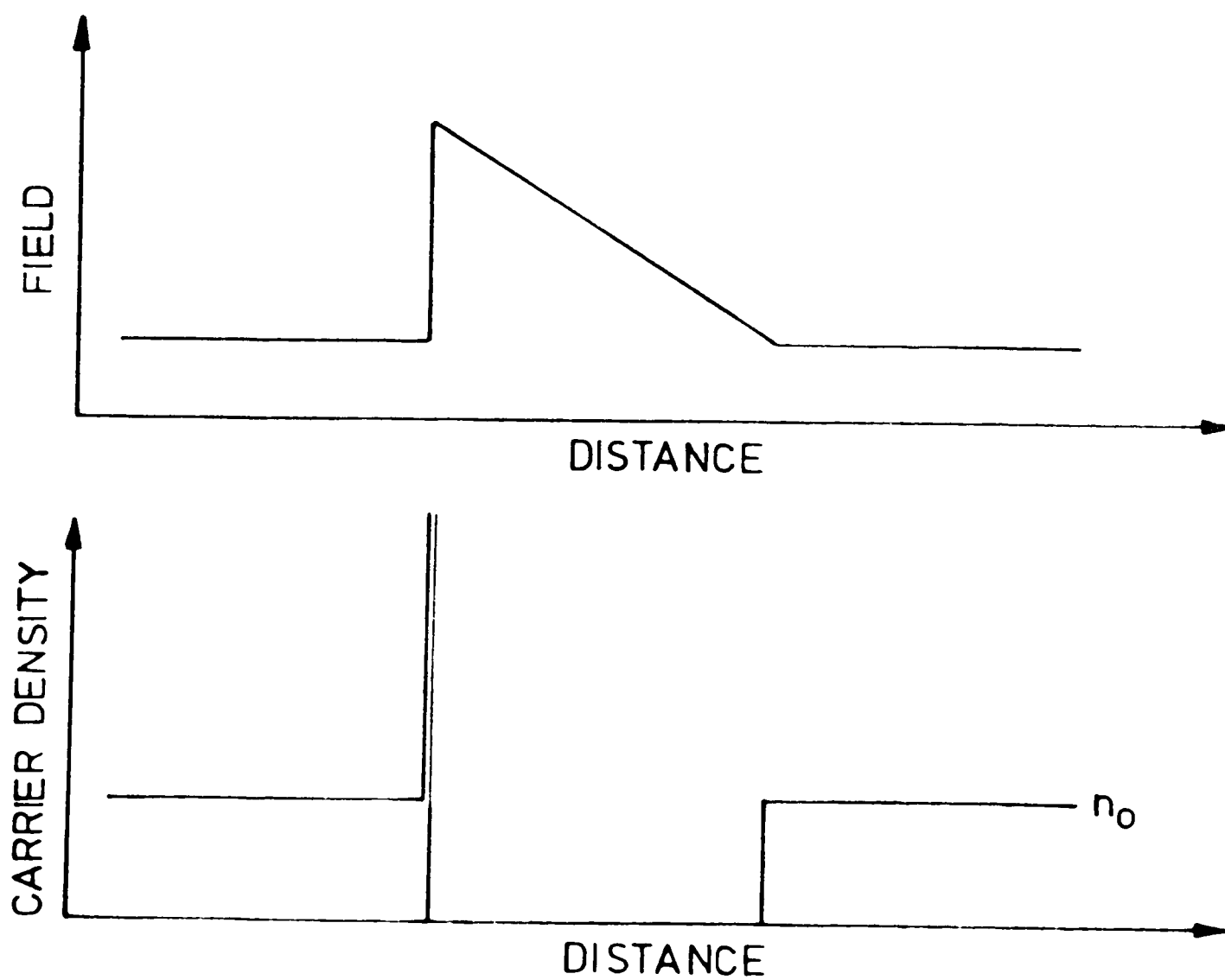


Fig.1.7 Ideal domain shape for zero diffusion

depletion at low domain fields was more marked in lower resistivity material ($< 1 \text{ ohm cm}$).

Numerical calculations using a field-dependent diffusion coefficient were carried out by Copeland^[22], using data from McCumber and Chynoweth^[18] and by Butcher et al.^[23], using data from Butcher and Fawcett^[20,24]. The results were qualitatively the same as those for the constant diffusion coefficient except that the lack of strong depletion in small domains and in low resistivity material was more marked. In 1 ohm cm material, for example, with a peak domain field of 10 kV/cm the depletion ratio is 50%, rising to 80% for a peak domain field of 20 kV/cm . The domain velocity was found to be greater than the outside drift velocity, except for very small domains, where it was slightly less; the difference was small for large domains. It increased with decreasing resistivity and its maximum was as much as 25% of the outside velocity in 1 ohm cm material.

The lack of strong domain depletion at low domain voltages could be important in velocity-field characteristic measurements based on domain behaviour. Bastida et al.^[26] made measurements on gallium arsenide using such a method and assuming ideal triangular domains. Most of their measurements were at domain fields where this assumption was justified, but for measurements at very low domain fields, or in indium phosphide, where the domain shapes are reported by Prew^[27] to be greatly modified by diffusion, allowance must be made for it.

1.10 The domain characteristic. Triggered domains.

The excess domain voltage, V_D , is defined as

$$V_D = \int (E - E_1) dx$$

across the domain and this varies with the current through the device in the manner shown in Fig. 1.8,^[24] where v_T and I_T represent the

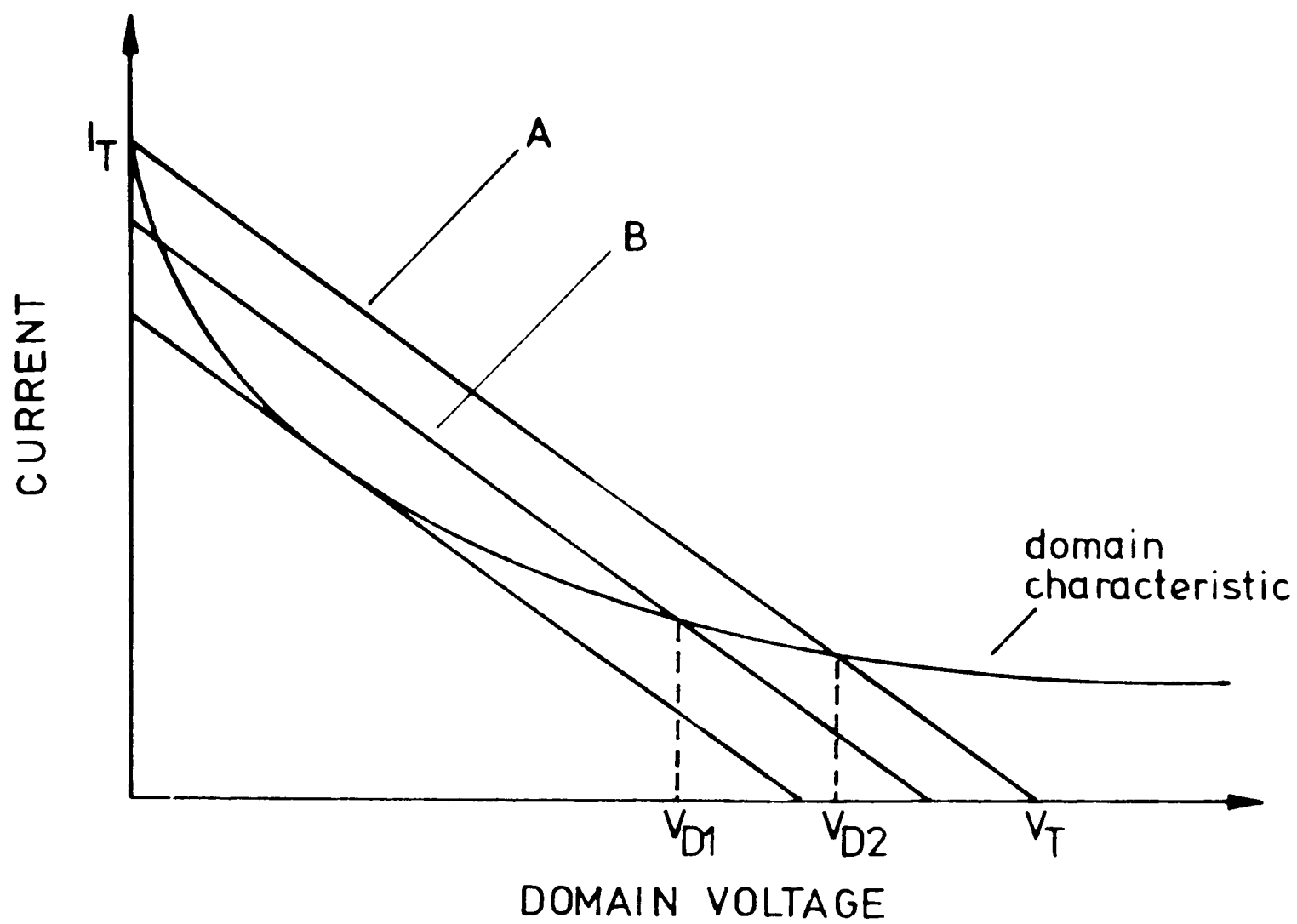


Fig 1.8 The domain characteristic.

voltage and current at threshold. It is possible to find the 'working point' of a domain in a given specimen by drawing a load-line on the curve. If the specimen's low-field resistance is R_0 and the applied voltage is V , then this line is given by

$$v_D = V - IR_0$$

and the operating point is given by its intersection with the domain characteristic.

It is known that the bias voltage must reach threshold for a domain to form and this corresponds to load line A in Fig. 1.8, for which the domain voltage is v_{D2} . Once the domain is formed, if the bias voltage is reduced, the load line still intersects the domain characteristic (load line B), with a domain voltage v_{D1} . If the voltage is reduced still further the domain continues to exist until the voltage is so low that the load line is just tangent to the domain characteristic. This voltage is the extinction voltage, or minimum sustaining voltage for a domain and can be much less than the threshold voltage, and below it no domain is possible.

This mode of operation was first pointed out by Heeks^[17] and is known as the 'triggered mode'. If a device is biased between the extinction and threshold voltages, and a short pulse of sufficient voltage to take it above threshold is applied, the device current will drop for a time corresponding to a domain transit and then return to its quiescent value. This is of obvious use in logic devices^[28].

1.11 Criteria for domain formation

It has been predicted theoretically, and shown experimentally that for instabilities to form in a Gunn-effect device, the product of carrier density and device length must exceed a certain critical value.

McCumber and Chynoweth^[18] investigated in a computer

simulation field distributions under conditions of constant voltage bias in bars of material with a two-valley conduction band structure, applying boundary conditions of zero field at the contacts. It was found that in a specimen 200 microns long with $n_0 = 10^{13} \text{ cm}^{-3}$ at low applied voltages the field was uniform along the specimen, but as the voltage was increased the field became increasingly non-uniform, having a low value near the cathode and increasing towards the anode. The distribution was found to be stable with respect to small doping fluctuations. However, when the doping density was increased to 10^{14} cm^{-3} , above a critical voltage the field distribution became unstable to small perturbations: a small doping 'notch' near the cathode caused the formation of dipole domains. From considerations of the small signal impedance of the device, McCumber and Chynoweth calculated the condition for the formation of instabilities to be

$$n_0 \ell > 2.7 \times 10^{11} \text{ cm}^{-2} \quad 1.11.1$$

where ℓ is the device length. Kreomer^[9] had suggested a similar criterion on the basis of the total number of carriers in the device, arguing that if the doping density were low enough the necessary width of the domain would exceed the sample length and hence no domain would be possible. Similarly, Ridley^[12] had argued that the domain build-up time τ must be less than the transit time ℓ/v_D :

$$\tau = \frac{\epsilon}{\mu_n n_0 e} < \frac{\ell}{v_D}$$

or $n_0 \ell > \frac{\epsilon v_D}{\mu_n e} \doteq 10^{11} \text{ cm}^{-2}$ in gallium arsenide. 1.11.2

These estimates compared reasonably well with the measured values of Day^[30], $0.7 \times 10^{11} \text{ cm}^{-2}$ and Thim and Barber^[31], $5 \times 10^{11} \text{ cm}^{-2}$.

Kino and Robson^[32] performed a further analysis, considering thin epitaxial layers with a current flow parallel to the plane of the layer. The travelling domain was treated as a wave, and it was

suggested that its propagation would be modified if its wavelength were comparable with the thickness of the layer. Taking the criterion for domain formation in normal samples as $n_0 \ell > 5 \times 10^{11} \text{ cm}^{-2}$, the criterion for domain formation in thin layers became

$$n_0 d > 1.6 \times 10^{11} \text{ cm}^{-2} \qquad 1.11.3$$

d being the layer thickness.

CHAPTER II

INDIUM PHOSPHIDE

2.1 The structure of indium phosphide

In common with the other semiconducting III - V compounds, the lattice of indium phosphide has the zinc blende crystal structure, which can be regarded as consisting of two face centred cubic lattices of indium and phosphorus respectively, displaced with respect to one another (Fig. 2.1). Each face-centred cubic lattice is described by the basic translational vectors

$$\frac{a}{2} (1 \ 1 \ 0), \frac{a}{2} (0 \ 1 \ 1), \frac{a}{2} (1 \ 0 \ 1)$$

and the lattices are displaced by the vector

$$\frac{a}{4} (1 \ 1 \ 1),$$

where a is the lattice constant, equal to $5.87 \text{ \AA}^{[35]}$.

2.2 Electron propagation

The propagation of an electron in a region with a potential distribution $V(r)$ is described by the Schrödinger equation

$$\left[-\frac{\hbar^2}{2m} + V(r) \right] \psi_k(r) = E_k \psi_k(r)$$

where the ψ_k are wavefunctions corresponding to energy eigenvalues E_k . In a crystal, $V(r)$ is periodic with the period of the direct lattice, and the solutions of the Schrödinger equation are of the form

$$\psi_k = \exp i(\underline{k} \cdot \underline{r}) U_k(r)$$

where $U_k(r)$ is also periodic in the direct lattice. The wave function $\psi_k(r)$ has the symmetry of the lattice, which, according to group

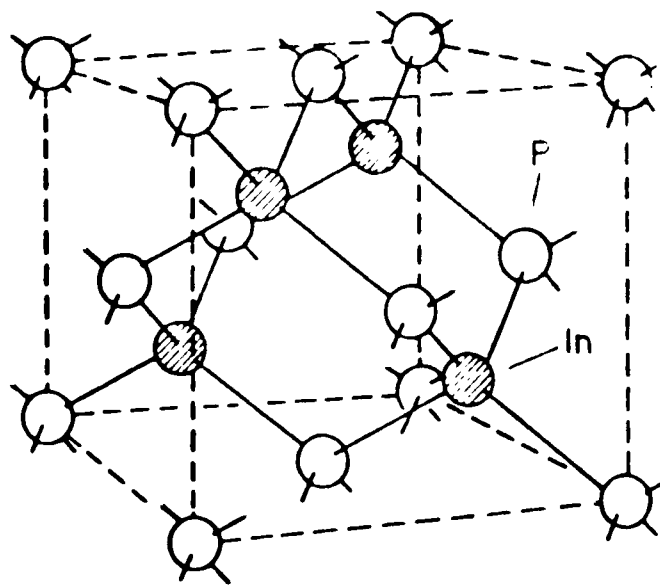


Fig. 2.1. Crystal lattice of indium phosphide

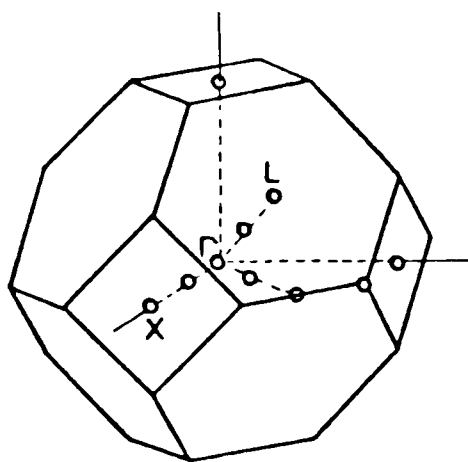


Fig. 2.2. Brillouin zone of indium phosphide.

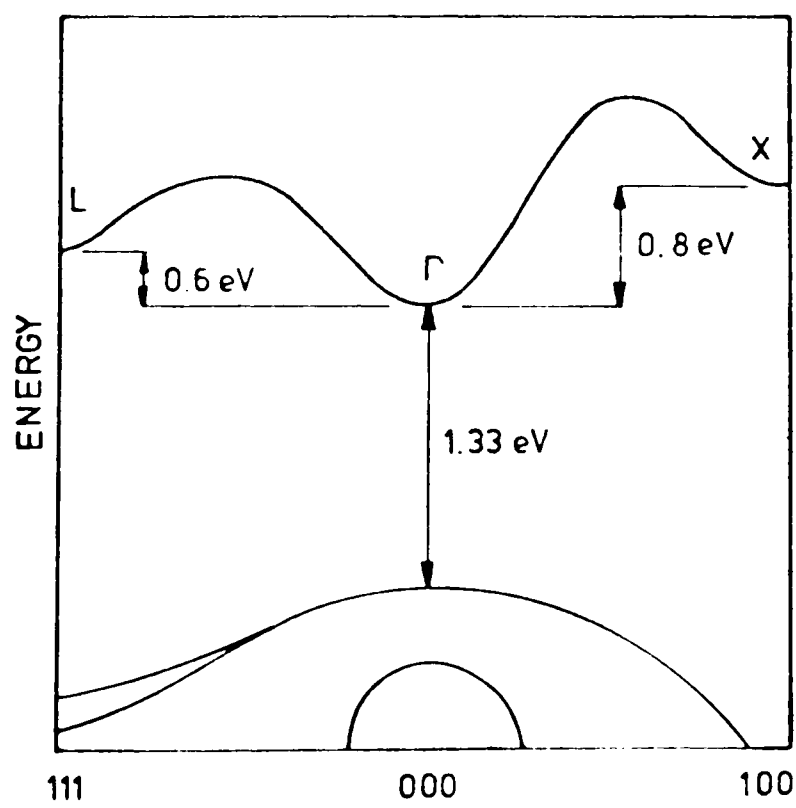


Fig 2.3 Band structure of indium phosphide

theory can be given different representations corresponding to the allowed energy bands; these are usually labelled according to the notation of Boukaert et al. [33].

The energy is periodic in the reciprocal lattice and has its symmetry. Therefore to define it uniquely only the $\underline{k}$'s in the unit cell of the reciprocal lattice, the first Brillouin zone, need be considered.

2.3 Band structure

The Brillouin zone of the zinc blende lattice is a truncated octohedron, and is shown in Fig. 2.2 where the standard notations are used for the symmetry points and lines. The important symmetry points are Γ at the centre of the zone, L in the $\langle 111 \rangle$ direction and X in the $\langle 100 \rangle$ direction. By the symmetry properties of the reciprocal lattice such points which can be transformed into one another by symmetry operations have the same energy spectra, and, hence there are three equivalent X points and four equivalent L points in the Brillouin zone. X

Fig. 2.3 shows the conduction and valence bands. Indium phosphide has a direct band gap of 1.35 eV [29], with both the valence band maximum and the lowest conduction band minimum at the Γ point. The conduction band has two further sets of minima at higher energies, at the L points which are 0.6 eV above the Γ minimum and at the X points which are 0.8 eV above the Γ minimum, the configuration which gave rise to the 'three-level' description of the band.

The electron effective mass is,

in the Γ minimum $0.078 m_0$ [34]

in the L minimum $0.25 m_0$ [35]

and in the X minimum $0.40 m_0$ [35],

and thus the electron mobility (which is inversely proportional to the effective mass) is considerably lower in the satellite valleys

than it is in the central one. As more electrons, gaining energy, are transferred to the upper minima the differential mobility decreases and becomes negative by a mechanism essentially the same as that already described for gallium arsenide, with the important difference that in indium phosphide three minima are involved in the process.*

2.4 Intervalley electron transfer

Electrons in the Γ minimum are scattered at room temperature predominantly by polar optical phonons, but as their energy is increased they are scattered into the higher minima at the edges of the Brillouin zone by phonons with larger values of $\underline{k}$. Birman et al. [36] showed that the phonons responsible for this scattering would be LA (L and X) and LO (L only). The coupling between the valleys may be characterised by intervalley coupling constants or deformation potentials $D_{\Gamma L}$, $D_{\Gamma X}$; according to Corwell and Vassell [37]

$$\frac{1}{\tau_{\Gamma L}} \propto D_{\Gamma L}^2, \quad \frac{1}{\tau_{\Gamma X}} \propto D_{\Gamma X}^2$$

where $\tau_{\Gamma L}$ and $\tau_{\Gamma X}$ are the relaxation times for the transfer processes.

The probability of transfer is thus proportional to the square of the deformation potential, and clearly the form of any calculated velocity-field characteristic will depend strongly on its value. The method used by most workers calculating such characteristics for indium phosphide has been to treat the deformation potential for $\Gamma - L$ scattering as a parameter whose value can be adjusted to give the best fit to experimental results.

* It has more recently been suggested as a result of stress experiments [70] that in fact three conduction band minima are involved in the electron transfer process in gallium arsenide.

2.5 Calculations of the velocity-field characteristic of indium-phosphide.

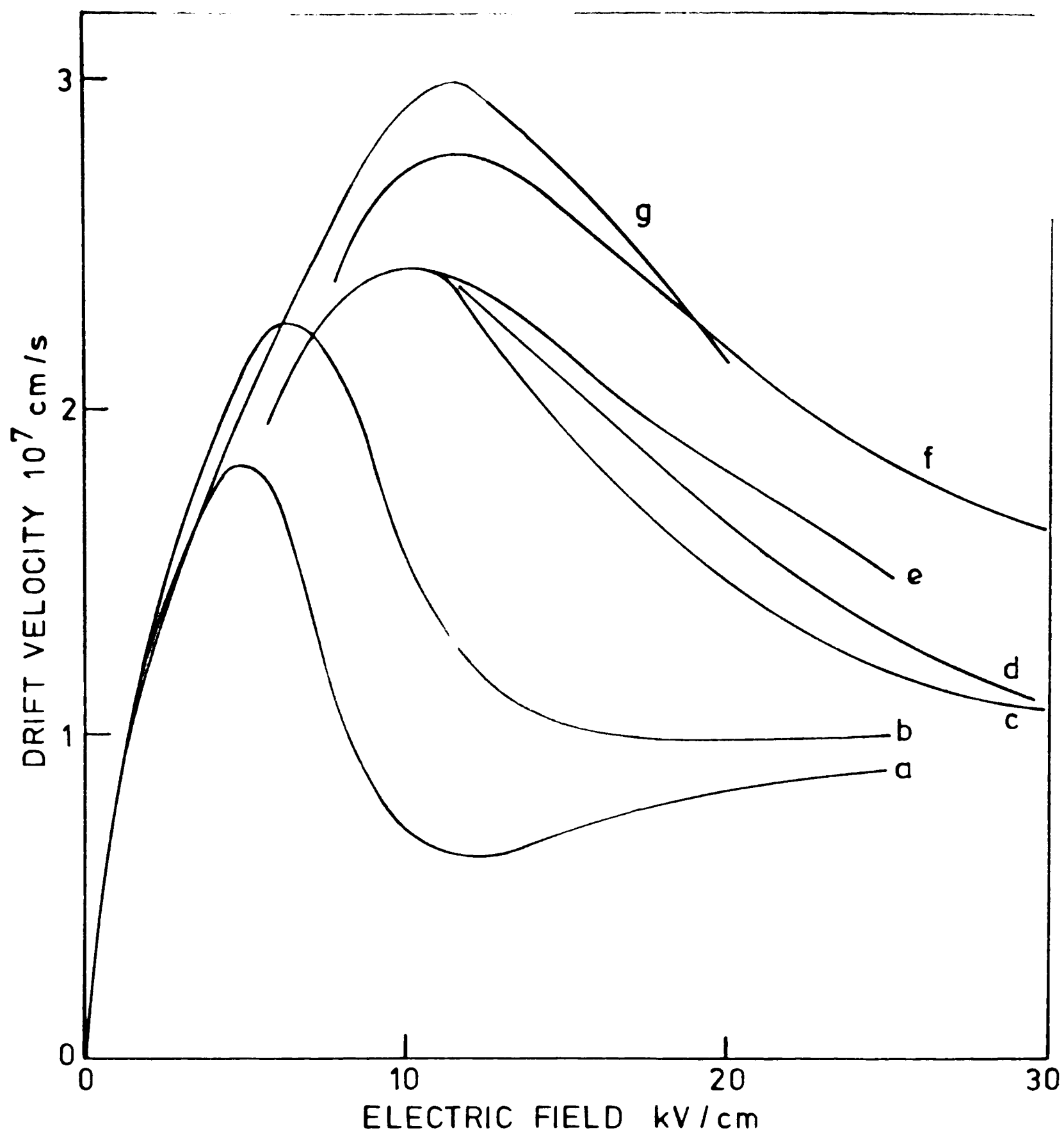
a) The three-level calculations

Interest in indium phosphide as a transferred-electron material renewed in 1970, with the velocity-field calculation of Hilsum and Rees^[35]. Hilsum and Rees pointed out that if the coupling between the Γ and L minima was weak ($D_{\Gamma L}$ in the range of 1×10^8 to 3×10^8 eV/cm) then all three minima, Γ , L and X would participate in the electron transfer process. Their calculated velocity field characteristic showed a threshold field in the range 5 - 7 kV/cm, and a large negative differential mobility, with a well-defined velocity minimum, at higher fields than which the differential mobility was positive (Fig. 2.4). The greater negative differential mobility, and the bigger ratio between peak and valley velocities than in gallium arsenide would mean that it should be possible to construct microwave oscillators more efficient than those using gallium arsenide.

Weak coupling between Γ and L minima implies a long relaxation time for that transfer process, and a result of slow transfer would be that the electrons would be unable to follow rapid field fluctuations. This, and an increased diffusion coefficient, would tend to prevent the growth of high field domains; indium phosphide should not exhibit the Gunn effect. If, however, a high field domain is injected, the positive differential mobility above the valley field should mean that a maximum domain peak field exists; if the bias on a sample is increased beyond this point, the domain's shape would change from triangular to flat-topped.

b) Two-level calculations

With measurements on the energy distribution of photoemitted electrons from indium phosphide, James et al.^[31] identified conduction band minima at 1.95 and 2.15 eV above the top of the valence



- a Hilsum and Rees: 3 level $D_{\Gamma L} = 1 \times 10^8$
- b " " $D_{\Gamma L} = 3 \times 10^8$
- c Fawcett and Herbert: screened pseudopotential
- d " unscreened "
- e Maloney and Frey: 2 level
- f Hammar and Vintner: 2 level
- g James et al 2 level

Fig. 2 4. Calculated velocity - field characteristics

band to which they attributed respectively L-type and X-type symmetry. A calculation of a velocity field characteristic was made assuming 2-level electron transfer between the Γ and L minima, and the salient points of this characteristic were (Fig. 24):

$$E_T = 11.5 \text{ kV/cm}, v_{DT} = 3 \times 10^7 \text{ cm/s}$$

It is notable that this is the only band structure determination which showed the existence of the L-type minima.

Hilsum and Rees had, prior to their 3-level calculation, performed a calculation based on a 2-level model^[38], using material parameters very similar to those used by James, which predicted $E_T = 8 \text{ kV/cm}$; they suggested^[39] that James overestimated E_T by using a Maxwellian energy distribution and also underestimated the effect of band non-parabolicity. In fact both calculations used a value of m^* which was smaller (0.06 m_0) than the (later) measured value (0.078 m_0).

A further analysis by James^[40] showed that band nonparabolicity had indeed been underestimated. James then calculated, from photo-emission data, a possible range of values for the coupling constant between the Γ and L minima:

$$4.1 \times 10^8 < D_{\Gamma L} < 1.5 \times 10^9 \text{ eV/cm}.$$

This would suggest that coupling between these two minima is sufficiently strong to predominate in electron transfer, with the role of the X-minima being unimportant - a 2-level system.

Hammar and Vinter^[41] performed a series of calculations, solving the Boltzmann equation for both three-and two-level systems. Their 3-level calculations assumed strong Γ -X coupling ($D_{\Gamma X} = 1 \times 10^9 \text{ eV/cm}$) and gave $D_{\Gamma L}$ a series of values from 3×10^8 (the value used by Hilsum and Rees) to $2 \times 10^9 \text{ eV/cm}$, which represents strong coupling. Comparing their results with the measured characteristics

of 'T Lam and Acket^[42], Nielsen^[43,44] and Glover^[45] which all agree in their general form, the best agreement was obtained with $D_{\Gamma L} = 1 \times 10^9$ eV/cm, that is, with strong $\Gamma - L$ coupling, and, as might be expected, the threshold field varied strongly with $D_{\Gamma L}$. A two-level calculation was then performed, assuming only Γ and X levels, and a very good agreement with experiment was found with $D_{\Gamma X} = 1 \times 10^9$ eV/cm, the different values of $D_{\Gamma X}$ making a very small change in the shape of the curve.

Further evidence was provided by Fawcett and Herbert^[46,47] who carried out pseudopotential calculations of the intervalley coupling constants, giving the possible range of values of $D_{\Gamma L}$ as

$$9 \times 10^8 < D_{\Gamma L} < 2.5 \times 10^9$$

They point out that coupling between the Γ and L minima would be larger than expected as, because of the breakdown of the group selection rules for transitions to the L minima, all phonons will contribute to $\Gamma - L$ scattering. A velocity field characteristic with

$$E_T = 10 \text{ kV/cm}, v_{DT} = 2.5 \times 10^7 \text{ cm/s}$$

was then calculated, and later the calculation was extended by Fawcett and Hill^[48] to predict its temperature variation.

As part of an analysis of transient effects, using a Monte Carlo method, Maloney and Frey^[49] have calculated velocity-field characteristics at 300 K and 77 K, using a two level system with $D_{\Gamma L} = 2.5 \times 10^9$ eV/cm, and for material with donor densities of 0 and 10^{17} cm^{-3} . As the material used in most experimental measurements has had a carrier density in the range 10^{14} to a few times 10^{15} cm^{-3} , closest agreement would be expected with the curve for $N_D = 0$, which predicts

$$E_T = 10 \text{ kV/cm}, v_{DT} = 2.5 \times 10^7 \text{ cm/s. at } 300 \text{ K}$$

Up to threshold these results agree very closely with those of Fawcett and Herbert at 300 K, but show a slightly higher velocity about threshold. This work includes the only published calculation of a velocity-field characteristic for a temperature of 77 K.

The important points of the results of these calculations are summarised in Table 2.1.

2.6 Measurements of the velocity-field characteristic

Four main methods have been used to study the variation of electron drift velocity with applied electric field in indium phosphide:

1. Space-charge waves
2. Microwave conductivity measurement
3. Measurements on dipole domains
4. Measurement of current-voltage characteristic

a) Microwave methods

The first measured characteristic to be reported was by Boers [50] who determined different parts of it using different methods. The space-charge amplification method of Fay and Kino [51] was used between 14 and 32 kV/cm: a specimen is subjected to a pulsed bias and fed with a microwave signal and, provided certain conditions are met (which require material with a resistivity of 10^3 ohm cm) the electron drift velocity is equal to the phase velocity of the space charge waves, which is measured by a probing technique. The characteristic from 32 to 200 kV/cm was obtained from measurements on dipole domains, using the equal areas rule (Chapter I) assuming constant depletion ratios of 50% and using material with $n = 1 \times 10^{15} \text{ cm}^{-3}$. The sub-threshold characteristic was obtained from similar specimens, but by direct measurement of current and voltage, and

scaling to give velocity and field. These results gave good agreement with the 2-level calculation of James et al.^[31]

A measurement using a microwave heating technique was performed on epitaxial material by Glover^[45]. The d.c. conductivity of samples placed in waveguide and irradiated with a high power pulsed microwave field is measured, and from this is deduced the velocity field characteristic. The fast time-variation of the microwave field inhibits high field domain formation. Results were obtained at 9.5 GHz and 35 GHz and showed excellent agreement with each other below threshold and close agreement above, the 35 GHz results being claimed as more likely to be accurate. Compared with 3- and 2-level calculations, agreement is much closer to those based on the 2-level model.

Similar microwave measurements on epitaxial material were performed by T Lam and Acket^[42] at 33 GHz, and agreed closely with Glover's results. Part of the sub-threshold curve was checked using pulsed d.c. current-voltage measurements, and agreed well with the microwave results.

Microwave measurements on bulk material were made by Nielsen^[43,44] at 9.375 GHz and again agreed well with James' calculation. Comparable results for E_T and μ_n , but a lower peak velocity were obtained by Tebbenham and Walsh^[52,53] with measurements at 35 GHz on epitaxial material. Some of this material used by Tebbenham and Walsh was from the same slices as that used in the present work.

Hays^[54], using a similar microwave technique, and employing a computer simulation to estimate errors due to field non-uniformity in his devices obtained lower values for E_T and v_T , which are considerably nearer to the results of the 3-level calculation than are the other microwave results.

b) Direct and dipole domain methods

Subthreshold measurements of current-voltage characteristics

on samples of bulk material sculptured to have a long region of uniform field remote from the contacts were made by Kaul et al.^[55]. The field uniformity along the specimens was checked using a point-contact probe, and the threshold field for the start of oscillation was found to be in the range of 6.8 ± 0.6 kV/cm, again values seeming to agree with the 3-level theory. An identical experiment was carried out by Prew^[27] whose results for the threshold field was similar.

Prew also reported a velocity-field characteristic derived from measurements on dipole domains using a point-contact probe to determine the domain field distribution, rather than simple assuming a constant depletion ratio, as did Boers^[50]. The equal-areas rule was used to convert the data into a velocity-field relation which, when combined with the low-field results agreed closely with the 3-level calculation.

It is noticeable that the domain shapes measured by Prew were symmetrical in comparison with those measured by Boers with a capacitive probe, which showed a narrower accumulation layer; Boers suggested that the use of a point-contact probe in the non-uniform field situation of a high-field domain might distort the measured domain profile^[56]. An analysis by Prew^[57] of the predicted distortion caused by the probe, however, showed that distortion because of unequal response times in the accumulation and depletion regions would not give the observed symmetrical shape, which he attributed to the fact that the domains were 'small', and so would tend to be symmetrical. However, a discrepancy still exists as the domains shown by Boers and Prew are of comparable voltages, with Boers using lower resistivity material (380 V and 325 V in $1 \times 10^{15} \text{cm}^{-3}$ and $6 \times 10^{-14} \text{cm}^{-3}$ respectively) which, according to the theory of Butcher and Fawcett^[20] should show more symmetrically shaped domains. A method similar to that of Kaul et al.^[55] was used by

Majerfeld et al. [58,59,60] on specimens of both bulk and epitaxial material made into 'H'-shaped devices, which had a long region of uniform field. The field in this region was measured using a point contact probe, and the values of threshold field and peak velocity obtained seem to support the 2-level transfer theory. Dipole domain measurements were made by Robson et al. [61] using a carefully designed and characterised capacitive probe, the measured domain shapes being narrower and more asymmetrical than those of Prew. A velocity field relation deduced from these showed a valley velocity of around 0.7×10^7 cm/s.

These results are summarised in Table 2.2.

c) Accuracy

The main sources of error in the microwave methods are field non-uniformity in the specimen and energy relaxation effects. To assure field uniformity requires that the microwave frequency be sufficiently high to prevent any instability developing. Energy relaxation becomes more significant at higher microwave frequencies where the measured values of both threshold field and peak velocity may be higher than their true values, owing to hysteresis effects in the electron energy's following the varying electric field (Glover [62]).

In the determination of threshold field using the onset of instability as the criterion a uniform field is absolutely essential, and is rather more difficult to ensure as small doping fluctuations in the material and the effects of contacts will be very significant, particularly as threshold is approached: the uniformity of field is directly dependent on the doping uniformity. High field regions near the contacts may cause current saturation and hence excessive non-linearity in the sub-threshold velocity. The presence of high field regions in a specimen will clearly cause an underestimate of the threshold field, if this is taken simply as the ratio of specimen

voltage to length; hence a threshold field measured in this way may at best be regarded as a minimum value.

It would obviously be of interest to perform measurements on similar material using different techniques; this has been achieved to a certain degree in the present work, as some of the material used for current-voltage measurements has been from the same epitaxial slices as that used by Tebbenham and Walsh in their microwave experiments. It may thus be possible to make a direct, and thus more meaningful comparison between results obtained by the two techniques.

2.7 Dipole domains in indium phosphide

According to the proposed 3-level transfer mechanism, the rate of electron transfer from the Γ to the L valleys would be too slow to allow high field domains to build up. Hilsum et al.^[65] performed current measurements on samples of bulk indium phosphide mounted in a resistive coaxial circuit and observed, above a threshold field of from 4 - 8 kV/km, coherent smooth current oscillations at frequencies of 3 - 4 GHz, which was much larger than the predicted transit time frequency for the length of sample used. These oscillations were attributed to an accumulation layer mode. A computer simulation showed that domain modes were possible, but that larger doping depletions than in gallium arsenide were required for their initiation.

Boers et al.^[64] observed both a high frequency mode and a domain mode, where the determining factor appeared to be contact size - tin dot contacts at opposite ends of the specimen face were used. When the contact width was comparable with the specimen width dipole domains were nucleated at a high field region near the cathode, but when the contacts were smaller the field distribution was found to be non-uniform with a high field near the contacts and a low field elsewhere, the specimen oscillating at between 2 and 4 GHz, and only the high field region near the cathode being active. Boers

[65] also reported capacitive probe measurements on bulk specimens with evaporated contacts and resolved triangular shaped domains with widths of 60 - 70 μ . Similar results, particularly with specimens with large contacts, were obtained by Prew^[66], whose specimens showed also a gradual change in the current waveform in successive domain transits, suggesting that the domain mode may not be truly stable. Prew observed the high frequency mode as well, but instead of the active region being adjacent to the cathode it was, in a 500 μ specimen, some 150 μ from the cathode.

Using the method of Kuru et al.^[67] for measurement of the transient behaviour of high field domains, Prew obtained results which indicated that the total domain charge was proportional to the domain voltage, not to the square root of voltage as in gallium arsenide: the suggested explanation was a depletion ratio increasing with domain voltage, which was in agreement with probe measurements of domain shape.

Paxman et al.^[68] investigated epitaxial material on semi-insulating substrate with tin dot contacts and found that all their samples gave domain mode oscillations, some stable and some becoming noisy after a few domain transits. The unstable specimens were shown to be becoming ionised with each domain transit, a phenomenon which had also been described by Boers et al.^[64]. Observations of a stable domain mode were also reported by Nakamura et al.^[69].

It is apparent from these results that, contrary to the original expectations, indium phosphide will oscillate spontaneously in a domain mode on the application of a high electric field. It is not clear what factor determines whether the high frequency mode or the domain mode dominates, but the evidence suggests that the effect of the contacts is significant. It is also notable that, except in the case of Paxman et al., the material used had a Hall mobility in the range 3300 - 3500 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ at a room temperature, which is

appreciably lower than the theoretically predicted value of 5000
,
 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ indicating possibly impure material.

TABLE 2.1

Calculated velocity-field characteristics

Worker	$D_{\Gamma L}$ (eV/cm)	Type	E_T (kV/cm)	v_{DT} (cm/sec)	Comments
Hilsum & Rees[35]	1×10^8 3×10^8	3 level 3 level	5 7.5	1.8×10^7 2.2×10^7	-
James et al. [29]	-	2 level	11.5	3×10^7	-
James[40]	4.1×10^8 -1.5×10^9	-	-	-	-
Hammar & Vintner[41]	3×10^8 2×10^9 1×10^9 ($D_{\Gamma X}$)	3 level 3 level 2 level	9 11 11.5	2.4×10^7 2.7×10^7 2.9×10^7	-
Fawcett & Herbert[47]	9×10^8 2.5×10^9	2 level 2 level	10.5 10.5	2.5×10^7 2.5×10^7	-
Maloney & Frey	2.5×10^9	2 level	10.0 11.0	2.5×10^7 2.25×10^7	$N_D = 0$ $N_D = 10^{17}$

TABLE 2.2
Measured velocity-field characteristics

Worker	Method	Mat. type & mobility	E_T (kV/cm)	v_T (cm/sec)	μ_N ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)
Boers[50]	{ s.c. wave } domain	bulk (-)	12 - 13	2.7×10^7	-1000
Glover[45]	microwave	epitaxial (4000)	12	2.7×10^7	- 700
'TLam & Acket[42]	microwave	epitaxial (4620)	12	2.8×10^7	- 900
Nielsen[43,44]	microwave	bulk (3580)	12	2.5×10^7	-1000
Tebbenham & Walsh[52,53]	microwave	epitaxial	10.2	2.3×10^7	-1190
Hayes[54]	microwave	epi. & bulk (3400-5200)	7.2 - 9.8	2.0×10^7	-1800
Kaul et al.[55]	I - V	bulk (4100)	6.8 - 7.4	-	-
Prew[57]	{ I - V } domain	bulk (4400)	5.8 - 7.0	2.7×10^7	-3000
Majerfeld et al. [58,59,60]	I - V	epi. & bulk (4650-4950)	10.5 - 11.5	2.5×10^7	-

CHAPTER III

LOW-FIELD TRANSPORT

3.1 Low field scattering mechanisms

At low applied fields almost all the electrons are in the central (Γ) valley, and the mobility is limited by the scattering mechanisms appropriate to this valley. A method for combining the effects of the different mechanisms has been suggested by Wolfe et al. [71] who assume that each scattering process can be described by an energy-dependent relaxation time, that the scattering processes are independent and that the band is parabolic. An effective relaxation time is then determined from

$$\frac{1}{\tau(\mathbf{E})} = \sum_i \frac{1}{\tau_i(\mathbf{E})} \quad 3.1.1$$

and the overall relaxation time is calculated by averaging over all values of energy, using Maxwell-Boltzmann statistics:

$$\langle \tau \rangle = \frac{4}{3(\pi)^{1/2}} \int_0^\infty \tau(E) E^{3/2} \exp(-E) dE. \quad 3.1.2$$

This method has been applied to indium phosphide by Potter [60] who shows that in the temperature range from about 20 K to 1000 K ionised impurity scattering, deformation potential scattering and polar optical scattering dominate. Other mechanisms can be shown to be insignificant. As some calculations based on them are described in the next section the three important mechanisms will be discussed briefly.

a) Ionised impurities

Rutherford scattering theory has been applied to ionised impurities by Conwell and Weisskopf [72], and the analysis was

extended to include screening by Brooks^[73], giving for the relaxation time

$$\frac{1}{\tau} = 2.4149 \frac{(2N_A + n)}{\epsilon^2} (m^*/m)^{-\frac{1}{2}} T^{\frac{-3}{2}} \left[\ln(1 + b) - \frac{b}{1 + b} \right] E^{-\frac{3}{2}}$$

where $b = 4.3085 \times 10^{13} (\epsilon/n^*) (m^*/m) T^2 E$

and $n^* = n + (n + N_A)(N_D - N_A - n)/N_D \text{ cm}^{-3}$

at temperatures below the intrinsic range, $n = N_D - N_A$, giving $n^* = n$. Hence,

$$\tau = \frac{17.6 B^{-1}}{N_A + N_D} E^{3/2} T^{3/2} \quad 3.1.3$$

where B represents the function of b in brackets, which is slowly varying and, in averaging, is evaluated at $E=3 \text{ kT}$ and taken outside the integration.

b) Deformation potential scattering

This is due to the variation in band gap as a result of the strain from longitudinal vibrations of the crystal. A relaxation time has been given by Bardeen and Shockley^[74]:

$$\frac{1}{\tau} = 4.1667 \times 10^{19} \frac{\Xi^2}{c_\ell} \left(\frac{m^*}{m}\right)^{3/2} T^{3/2} E^{1/2} \quad 3.1.4$$

where Ξ is the deformation potential (the shift of band edge in eV per unit dilational strain) and c_ℓ is the longitudinal elastic constant, given by Rode^[75,76] as 14.5 eV and $12.10 \times 10^{11} \text{ dyn cm}^{-2}$ respectively. The mobility due to this mechanism alone is then

$$2.250 \times 10^{10} \Xi^{-2} T^{-3/2} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}. \quad 3.1.5$$

c) Polar optical scattering

Optical mode vibrations in a polar crystal displace ions with opposite charges in opposite directions from their equilibrium positions causing a dipole moment which influences moving electrons. An

expression for mobility under this type of scattering is given by Fortini et al. [77]:

$$\mu = \frac{16\hbar \epsilon_0 (2\pi kT)^{\frac{1}{2}}}{3e\omega_1 (m^*)^{3/2}} \frac{e^{\frac{\theta}{T}} - 1}{\left(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_s}\right)} F\left(\frac{\theta}{T}\right) \quad 3.1.6$$

where θ is the optical phonon temperature

ω_1 is the optical phonon frequency

$\epsilon_\infty, \epsilon_s$ are the high frequency and static dielectric constants

F is a function given by Fortini et al. This is an inelastic scattering process.

3.2 Combined mobility

The mobilities calculated separately, avering over the energy distribution according to (3.1.2) for three values of $(N_A + N_D)$ for the ionised impurity scattering and for two values of deformation potential are shown in Fig. 3.1, along with (3.1.6) which gives the polar-optical limited mobility. Also shown is the result of piezo-electric coupling, which, being always at least two orders of magnitude greater than any other mechanism, may be neglected.

The data splits into three temperature ranges. Below 100 K, for all but the lowest ionised impurity densities, the mobility is determined by a combination of ionised impurity and deformation potential scattering. Above about 150 K, polar optical and deformation potential scattering limit the mobility, whereas in the intermediate range Fig. 3.1 shows that all three mechanisms may be important. The ionised impurity and deformation potential mechanisms both have energy-dependent relaxation times which can be expressed analytically, making the combination, using (3.1.1) and (3.1.2), for the low temperature range, straightforward.

In both these mechanisms the amount of energy exchanged is small compared with the average electron energy, implying that the electron energy is practically unchanged during the scattering event

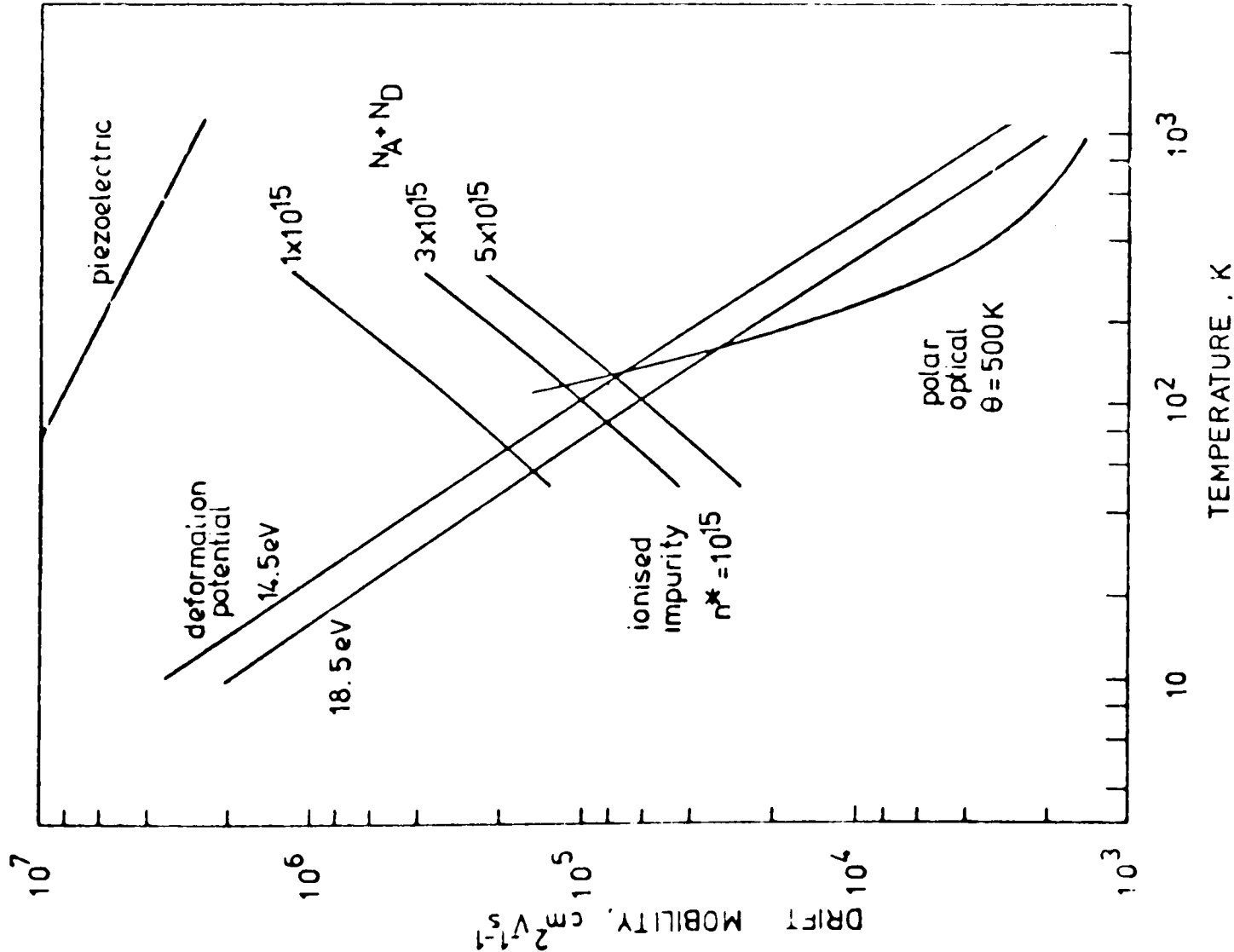


Fig 31. Mobilities due to separate scattering mechanisms in indium phosphide.

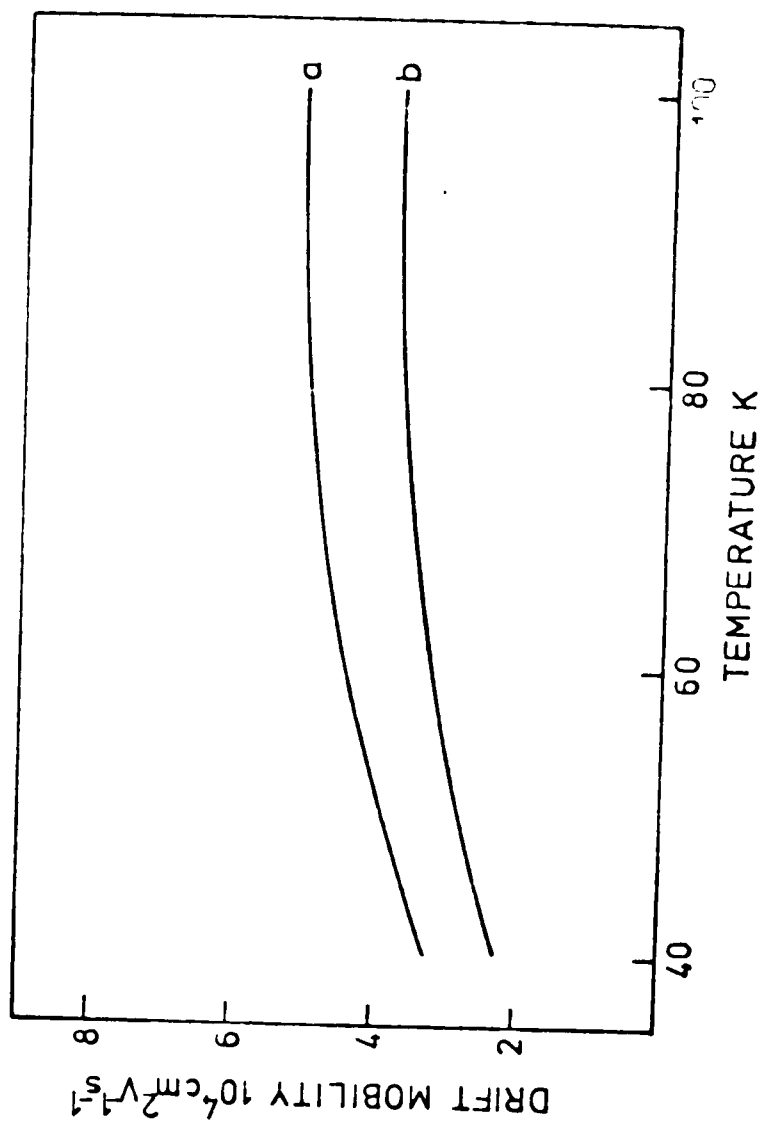


Fig 32. Comparison of approximate and accurate methods of combining ionised impurity and deformation potential scattering in indium phosphide

- a: approximate
- b: accurate

$$N_A + N_D = 3 \times 10^{15} \text{ cm}^{-3}, \quad \bar{\epsilon} = 14.5 \text{ eV}$$

and that the electron therefore remains in the same part of the distribution function. Polar optical scattering may be regarded as an interaction between an electron, whose average energy at room temperature is

$$\frac{3}{2} kT = \frac{3}{2} \times 1.38 \times 10^{-23} \times 300 = 6.2 \times 10^{-21} \text{ J.},$$

and an optical phonon, whose energy is given by

$$\hbar\omega_{\text{opt}} = \frac{1}{2\pi} \times 6.62 \times 10^{-34} \times 2\pi \times 10^{13} = 6.6 \times 10^{-21} \text{ J.},$$

taking the optical phonon frequency as 10^{13} Hz; these energies are of the same order of magnitude. When an electron interacts with a polar phonon, then, its energy change is comparable with its original energy, and it is therefore scattered to a different part of the distribution function. An energy-dependent relaxation time, to be averaged over the distribution function cannot be defined.

Ehrenreich^[78] has shown that this situation exists for the approximate temperature range given by

$$5 > \frac{\hbar\omega_1}{kT} > 1$$

which, in indium phosphide, corresponds to the range from 100 K to 500 K. Difficulty hence arises in including the polar optical mechanism in a combined mobility calculation.

3.3 The $\frac{1}{\mu}$ rule

An approximate method (Shockley [79]) of calculating an overall mobility is to combine the energy-averaged mobilities for the separate mechanisms using the relation

$$\frac{1}{\mu} = \sum_n \frac{1}{\mu_n} \tag{3.3.1}$$

where the μ_n represent the separate mobilities. It can give a large error, however, when the energy dependences of the relaxation times

are different.

An example is shown in Fig. 3.2 where ionised impurity scattering and deformation potential scattering are shown combined over the temperature range 40 K - 100 K, using (3.3.1) and the accurate method of (3.1.1) and (3.1.2). The energy dependences of the relaxation times are quite different, being proportional to $E^{3/2}$ and $E^{-1/2}$ respectively, and in this case the approximate method gives an error of about 30%, even though Fig. 3.1 shows that there is more than an order of magnitude difference between the separately calculated mobilities. It might be expected that the lower mobility would dominate, the higher one merely acting as a small perturbing influence on it, and making the error in the approximate calculation small. This is obviously not so; the case considered is an extreme one, with widely different variations with energy, but the result throws doubt on the accuracy of the approximate method in any circumstances where absolute values of mobility are needed.

This calculation is also useful in that, by comparing the calculated value with the measured value for particular material at 77 K a guide to its impurity density may be obtained. Table 3.1 shows calculated mobilities for material with $(N_D - N_A) = 10^{15} \text{ cm}^{-3}$ and various values of $(N_D + N_A)$.

3.4 Measured temperature variation of mobility

Galavanov and Siukaev^[80] and Potter^[60] have measured the temperature variation of mobility in indium phosphide, and by fitting theoretical curves to the experimental results have deduced values for the deformation potential. In both cases, to obtain the theoretical curve, the effects of polar optical and deformation potential scattering were calculated separately and combined using the ' $\frac{1}{\mu}$ ' rule, and the values of deformation potential which gave the best fit were respectively 21 eV and 18.5 eV. Galavanov and Siukaev

used a value of effective mass of $m^* = 0.073 m_0$, compared with Potter's value of $0.078 m_0$, which might explain the higher value of deformation potential obtained.

3.5 Calculated temperature variation of mobility

Rode^[76] has performed calculations, solving the Boltzmann equation and deducing the temperature dependence of mobility in intrinsic material as well as the variation of mobility with carrier concentration in intrinsic material, which suggests that for a carrier concentration of $10^{14} - 10^{15} \text{ cm}^{-3}$, at higher temperatures, the mobility will have tended to its extrinsic value. The values of deformation potential and effective mass used were

$$\Xi = 14.5 \text{ eV}, \quad m^* = 0.072 m_0.$$

Fig. 3.3 shows Rode's curve over the temperature range 200 - 500 K compared with a calculation combining deformation potential and polar optical scattering by the $\frac{1}{\mu}$ method, the separate mobilities being obtained from (3.1.5) and (3.1.6), using the same values of parameters. It is clear that the results are by no means comparable: the curves agree in shape but their absolute values differ by around 15%, the 'approximate' calculation giving the higher values. This again suggests the unreliability of the approximate method.

3.6 Comparison of theory and experiment

Fig. 3.3 includes also the experimental results of Galavanov and Siukaev and of Potter, and it is seen that agreement between these and the theoretical curve of Rode is by no means poor. The experimental results agree closely with each other, and indicate lower mobilities than the theory. This could be a result of the value for effective mass used in the calculation, $0.072 m_0$, which is

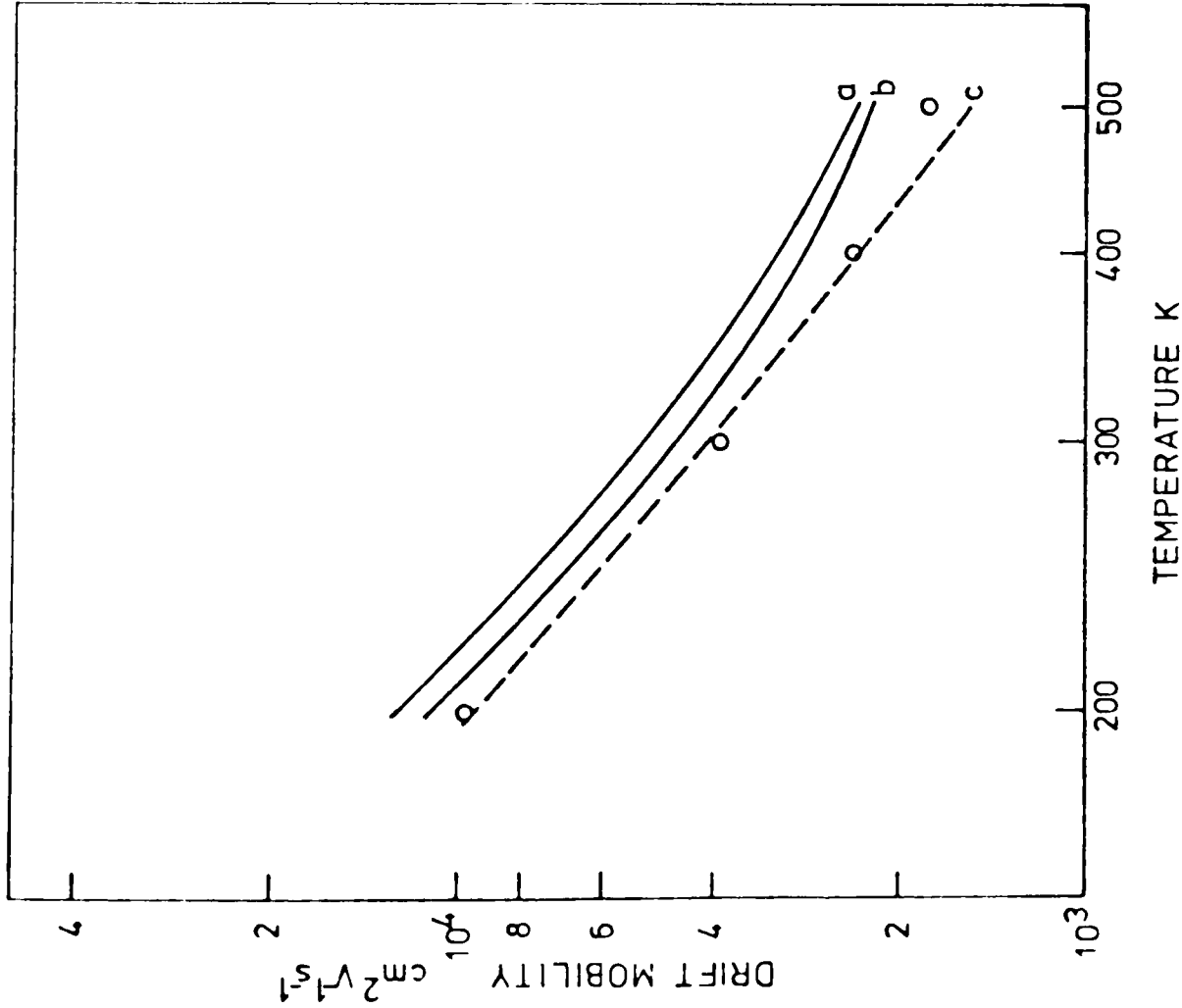


Fig 33 Variation of drift mobility with temperature.

- a Calculated (approximate method)
- b Calculated (Rode)
- (both with $m^* = 0.072 m_0$, $\bar{\epsilon} = 14.5 \text{ eV}$)
- c Experiment (Potter)
- o Experiment (Galavanov & Siukaev)

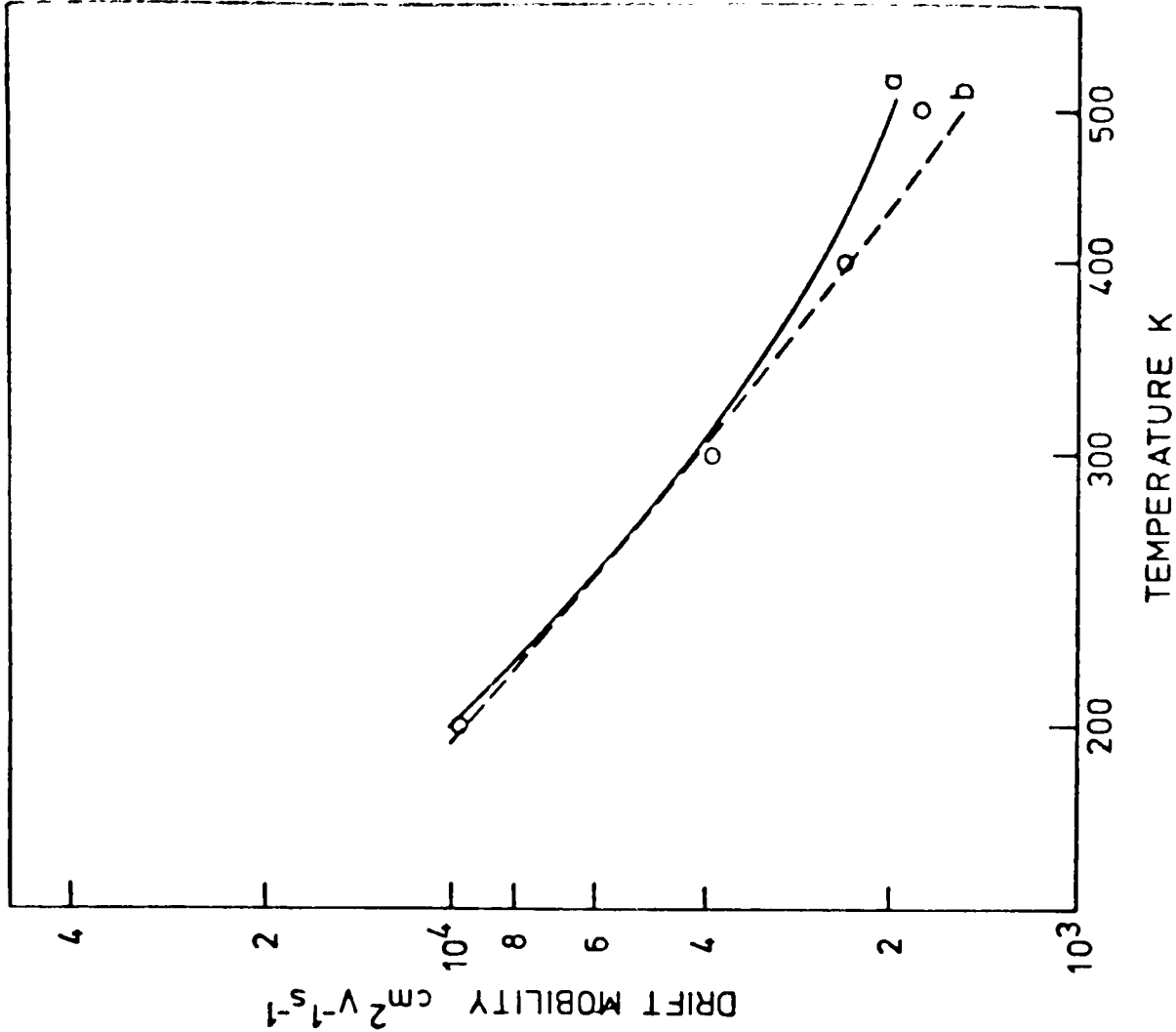


Fig.3.4. Variation of drift mobility with temperature.

- a Calculated (Rode) $\times (0.072 / 0.078)^{3/2}$
- b Experimental (Potter)
- o Experimental (Galavanov & Siukaev)

significantly lower than the more recently reported value of $0.078 m_0$.

It has been seen that the mobility due to polar optical scattering is proportional to $(m^*)^{-3/2}$ and that due to deformation potential scattering is proportional to $(m^*)^{-5/2}$. As the polar optical mechanism is the dominant one over this temperature range an approximate correction for the different effective mass might be used by multiplying the calculated mobility by $(\frac{0.072}{0.078})^{3/2}$. The result is shown along with the two sets of experimental data in Fig. 3.4 and agreement is seen to be very close, particularly at lower temperatures.

This effective mass correction is, if anything, an under-correction. Because of the deformation potential scattering the power to which the ratio of the effective masses should be raised should be between $3/2$ and $5/2$; perhaps a weighted mean of these values would give a more accurate correction. It is expected, however, that the resultant curve would be very little different from Fig. 3.4.

It is interesting to compare these curves with the results of Fortini et al.^[77] where calculated and measured mobilities in gallium arsenide due to polar optical scattering (which is, because of the low deformation potential, very dominant above 100 K) are compared over a similar temperature range. The curves have a similar shape to those for indium phosphide, with the measured one falling more steeply at high temperatures which is explained as possibly being due to a temperature variation of dielectric constant or more complex interactions with optical phonons. The implication is that, when theoretical and experimental curves are compared, agreement at the lower end of this temperature range may be more significant.

Treating the experimental results in this way has suggested that the value of the deformation potential taken by Rode can in

fact be shown to give good agreement with experiment by using a modified value of effective mass, and that the other estimates, 18.5 eV and 21 eV respectively, may have been perhaps too high because of the use of the $\frac{1}{\mu}$ rule.

3.7 The scattering factor

The usual method of measuring low-field mobility relies on the Hall effect. Because of the nature of this, where a voltage is measured in a direction at right-angles to the current flow, the measured mobility (the Hall mobility, μ_H) is not equal to the drift mobility, μ_D .

It can be shown that, when the scattering process is described by an energy-dependent relaxation time, τ_E ,

$$\frac{\mu_H}{\mu_D} = \frac{\tau_H}{\tau_D} = \frac{\langle \tau_E^2 \rangle}{\langle \tau_E \rangle^2} = r$$

where $r > 1$ and is called the scattering factor. This must be known if the drift mobility is to be deduced from Hall effect measurements.

Now, as the energy dependence of τ is different for the different scattering mechanisms, the value of r is also different. At any particular temperature, more than one scattering mechanism is important, and a combined scattering factor must be used. The situation for polar optical scattering is again difficult owing to the lack of an energy-dependent relaxation time over an important range of temperature.

Potter^[60] measured r over a temperature range from 77 K to 500 K and, on material with a room temperature μ_H between 4650 and 4950 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ obtained good agreement with experimental results of Hilsum^[81] at room temperature, and with calculations by Rees. These values (Fig. 3.6) are for a mobility range which includes most of the material used in the present work, and so were used in deducing drift mobilities.

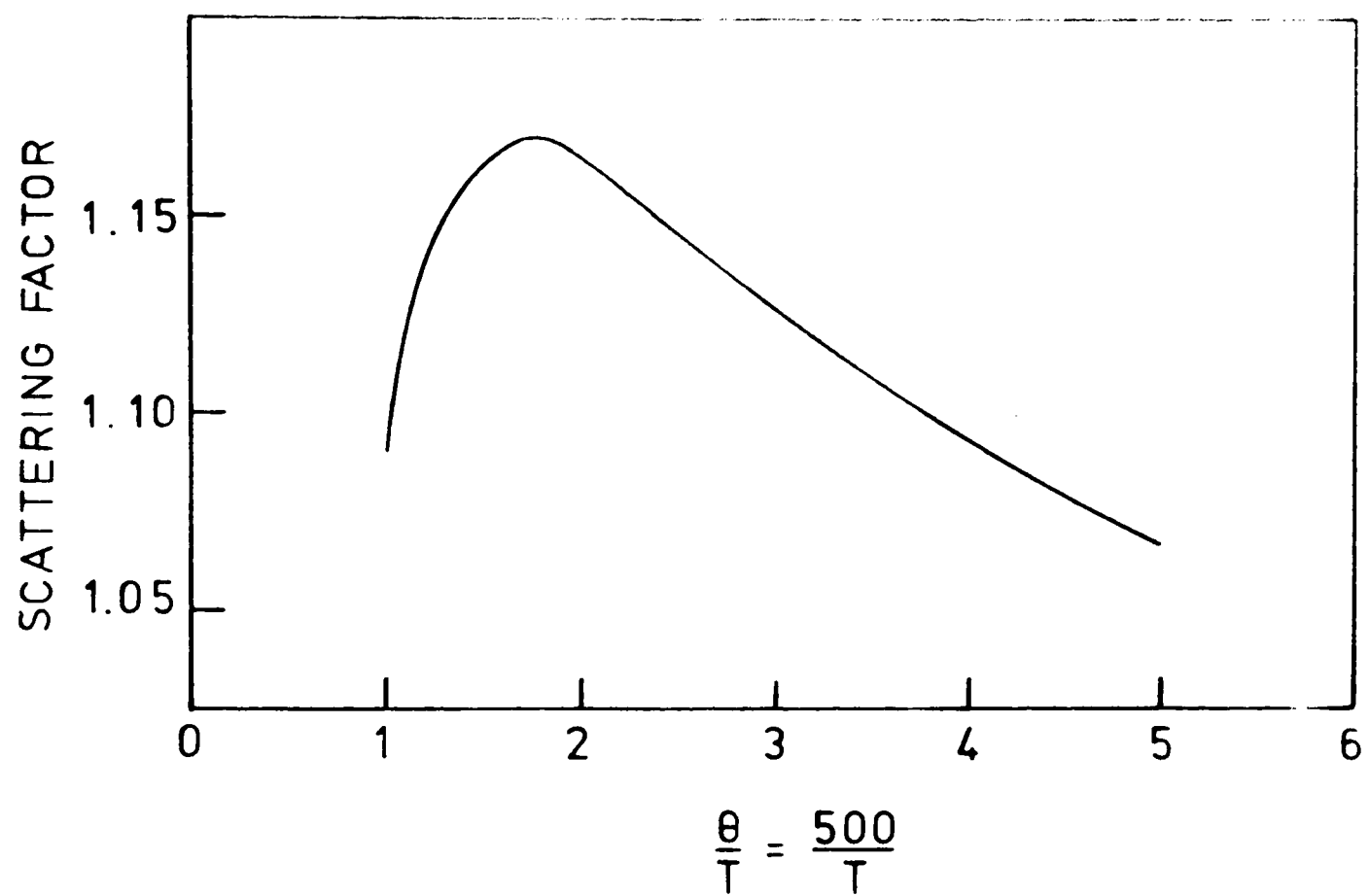


Fig. 3.5. Temperature variation of scattering factor (Potter).

TABLE 3.1

Calculated mobility of indium phosphide at 77 K due to deformation potential and ionised impurity scattering

$(N_D - N_A) = 10^{15} \text{cm}^{-3}, \quad = 14.5 \text{ eV}, \quad m^* = 0.078 m_0$

$(N_D + N_A)$ cm^{-3}	Mobility $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$
1×10^{15}	64,340
3×10^{15}	36,540
5×10^{15}	26,380

CHAPTER IV

DESIGN AND PRODUCTION OF SPECIMENS

4.1 Requirements for low-field velocity-field measurements

In order to make accurate measurements of field and velocity it is essential for the specimen to have a region where the field is uniform and whose geometry is accurately defined. The contacts are a source of field non-uniformity, and it is known^[8] that as the threshold field is approached in a Gunn device a high field region develops close to the cathode, from which a domain eventually nucleates. The contacts must therefore be well away from the measurement region.

A 'dumb-bell' shaped specimen (Fig. 4.1) satisfies these conditions; an idealised graph of the field distribution along such a specimen is shown in Fig. 4.2. The calculation of the central field is simplified if the material in the end regions can be assumed ohmic; velocity-field characteristics of other workers suggest keeping the field here less than one-third of the threshold field. This should also keep the field sufficiently low to prevent domains, nucleated in the high-field region at the cathode, being sustained. (In a 400 micron long gallium arsenide specimen Boers^[65] found the minimum sustaining field to be 0.6 of the threshold field.)

4.2 Analogue of specimens

Distributions of equipotentials in this specimen geometry were investigated using an analogue of 'Teledeltos' conducting paper and using the conventional bridge circuit of Fig. 4.4. A particular equipotential was traced by setting the resistance boxes to give a certain fraction of the applied voltage at X, and then probing to find the points which gave a null on the indicator. A low frequency

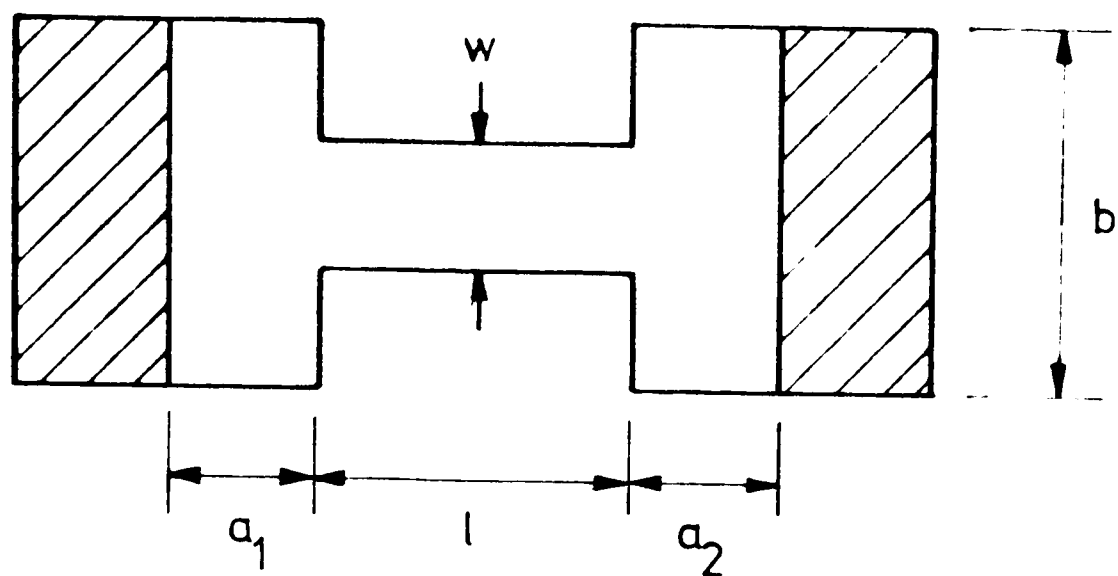


Fig. 4.1. H - type specimen

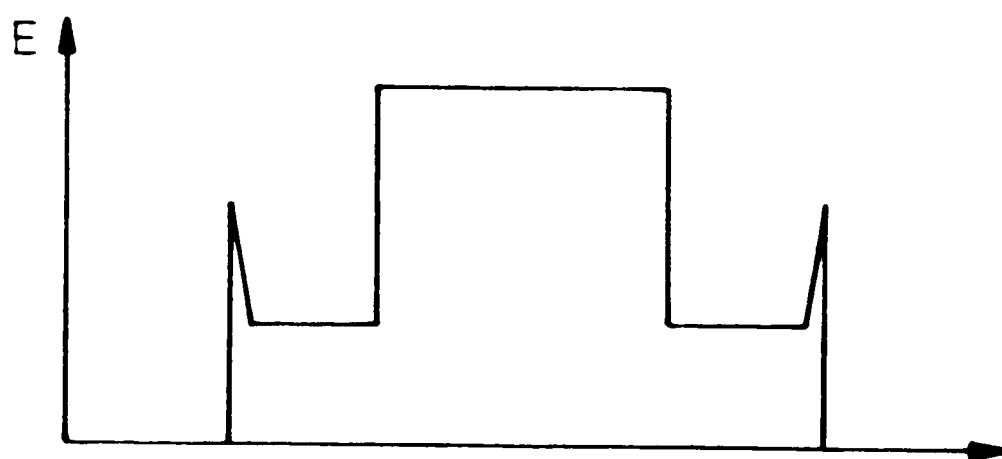


Fig. 4.2. Idealised field in H - type specimen

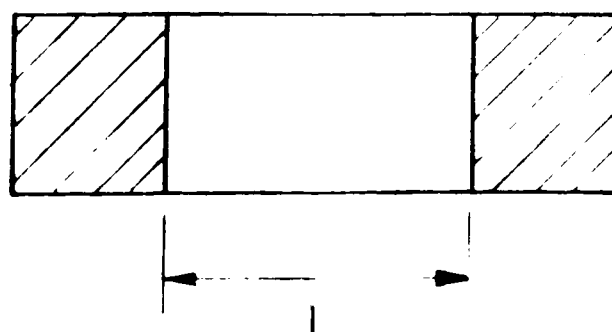


Fig. 4.3. Bar - type specimen

(200 Hz) square wave was used, with a sensitive oscilloscope as the null indicator.

Fig. 4.5 shows a result for a specimen where bridge length, bridge width and end width are in the ratio 5:2:15. (The symmetrical shape enabled analogues of only half-specimens to be used). Over more than three-quarters of the bridge length the equipotentials are virtually straight lines, indicating a uniform field. A specimen with half this bridge width gave a uniform field over practically the whole bridge length.

This geometry (5:1:15) was therefore used for most of the low-field measurements, although a small number were performed with wider bridges where the field was measured directly by probing.

4.3 Specimen length

The actual size of the specimen had now to be fixed so that the field in the central region could be varied from zero to threshold with a reasonable value of applied voltage. With the apparatus used it was convenient to keep this below 800 volts.

To make a rough estimate, the specimen was assumed ohmic and field distortion at the changes in width was neglected. Assuming the (5:1:15) geometry, and making $a_1 = a_2 = \ell$ (in practice a_1 and a_2 were always less than ℓ) gave a field of 14 kV/cm in a central region 500 microns long, which was more than adequate. Because of the curvature of the I - V curve towards threshold, the actual field would be higher.

The minimum $n_0 \ell$ product for the formation of instabilities was discussed in Section 1. No detailed calculations such as that of^[18] appear to have been made for indium phosphide, but an estimate, made on the criterion of Ridley^[12] based on domain formation time and taking the worst-case negative differential mobility of $2000 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ from the proposed velocity-field characteristics gives

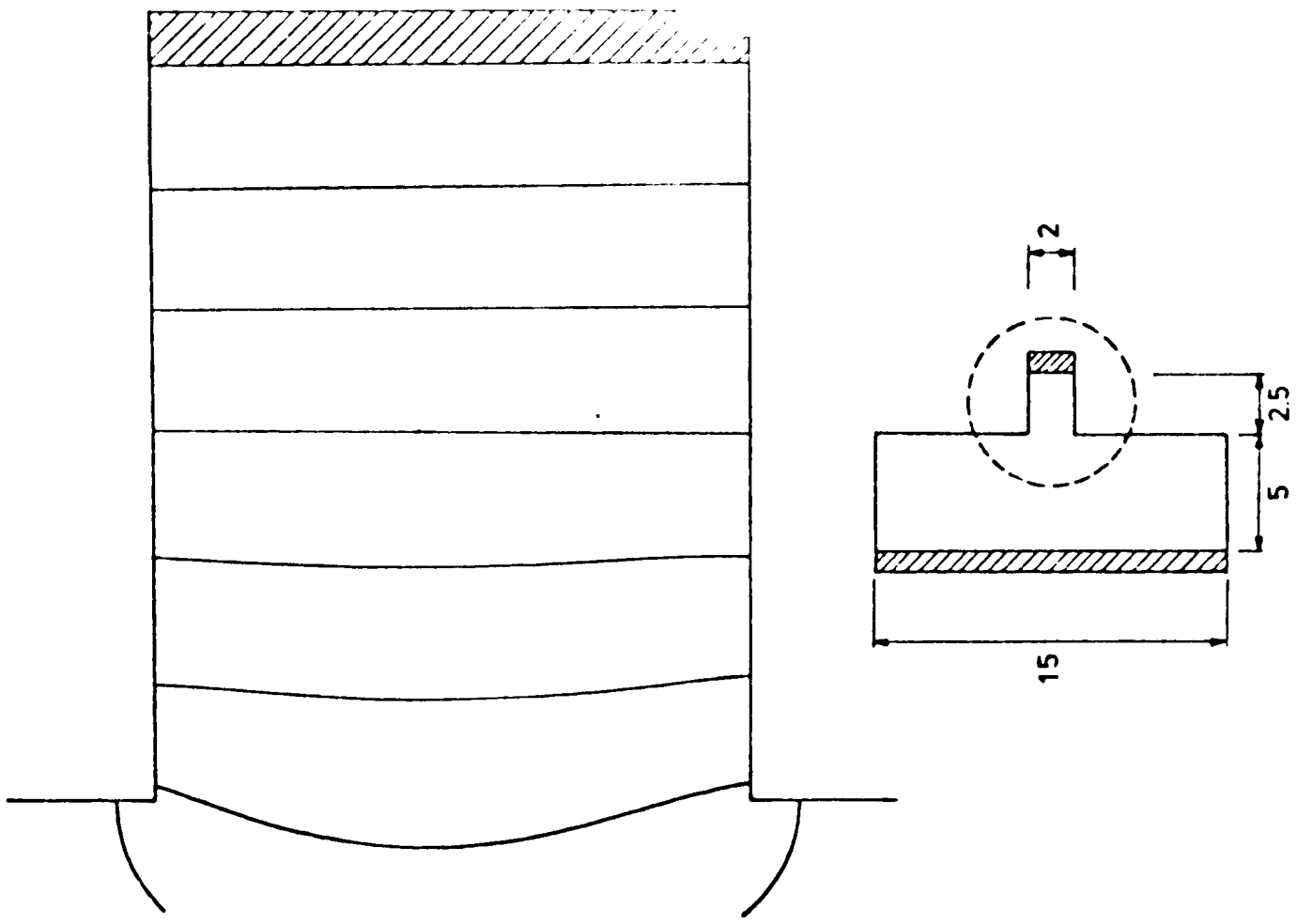


Fig.4.5. Equipotentials in analogue of H-type specimen

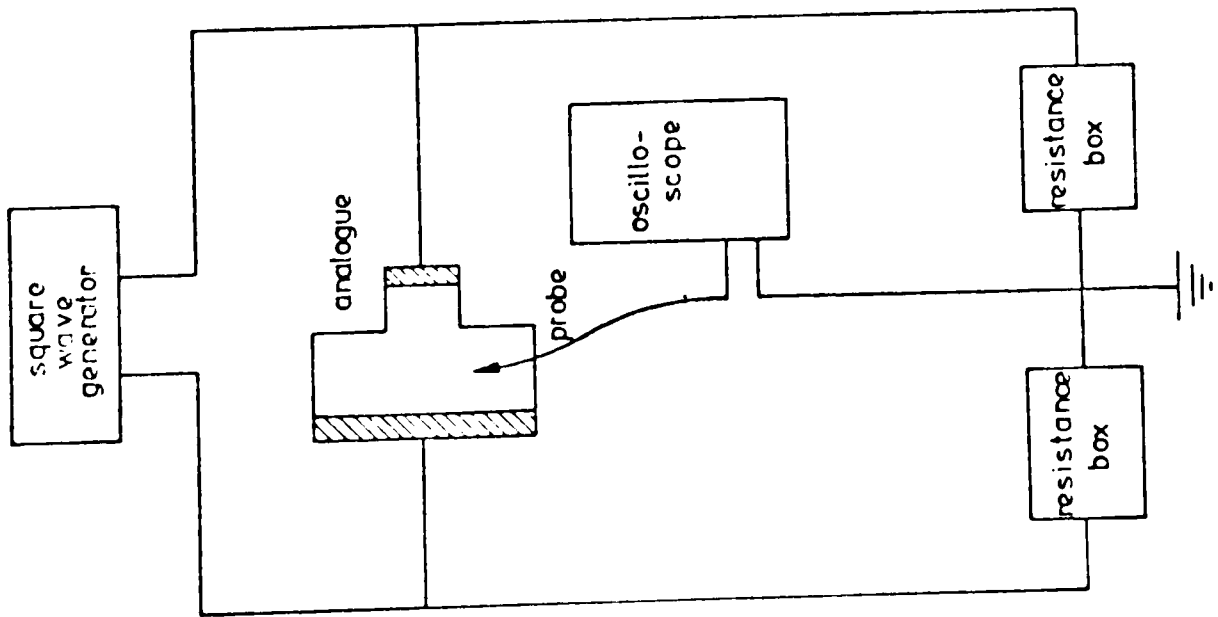


Fig 4 4. Field plotting apparatus

$$n_0 l > 3 \times 10^{10} \text{ cm}^{-2}$$

Taking $n_0 = 2 \times 10^{14} \text{ cm}^{-3}$ (a low value) and the specimen length of 500 microns gives

$$n_0 l = 1 \times 10^{13} \text{ cm}^{-2}.$$

Extending the criterion for epitaxial layer thickness (1.11.3) suggests that

$$n_0 d > 10^{10} \text{ cm}^{-2}.$$

The epitaxial layers used in the experiments all had thicknesses around 10 microns, giving

$$n_0 d = 2 \times 10^{11} \text{ cm}^{-2}.$$

Both conditions are therefore satisfied.

4.4 Preparation of photo-etched specimens

a) Masks

The final masks were made by optical reduction onto photographic plates from originals, sixteen times full size, cut out of 'Stabilene' masking film. For each specimen shape there were two masks, one for the etching process and one for the contact application.

b) Preparation of semiconductor

The epitaxial slices were cut up with a diamond scribe and then cleaned according to the following procedure:-

1) $\frac{1}{2}$ minute in trichloroethylene in an ultrasonic bath to remove grease.

2) $\frac{1}{2}$ minute in acetone in an ultrasonic bath.

3) $\frac{1}{2}$ minute in methanol in an ultrasonic bath.

The slices were dried in an oven at about 100°C and checked visually; if any surface contamination could be seen, the cleaning procedure

was repeated.

c) Photolithography

The photo-resist used was Shipley AZ 1350 H which is a negative resist, the areas which have been exposed to light being free of resist after development. The usual method of application is by spinning, which gave an even layer of resist over most of the specimen surface except around the edge, where a thick ridge was formed.

However, because of the small size of the available slices, the lithography had to be successful almost up to the edges, and a method of applying the photo-resist was needed which would avoid the ridges. A satisfactory result was obtained using a small, fine, artist's paint brush, sparingly loaded with photo-resist which was then transferred to the slice using a single brush stroke producing a uniform thin layer up to the slice edges. This layer was somewhat thicker than that produced by spinning, necessitating a longer exposure time, but by optimising exposure and development times (experimenting on glass slides) definition which was more than adequate for the geometries being produced was obtained, the patterns being indistinguishable under a microscope with 400 times magnification.

Exposure was for 70 seconds 25 cm from a 125 W mercury vapour lamp, followed by development for $3\frac{1}{2}$ seconds in PMD 'Superline' developer. The development time was quite critical - immediately it had elapsed the specimen was plunged into deionised water which acted as a stop bath.

The specimen was again inspected under the microscope and, if satisfactory, was baked at 100° C for 15 minutes to harden the resist.

d) Etching

The unwanted material had to be etched away to a depth below the epitaxial layer, leaving the specimen shapes as mesa-structures. The etch had the following composition:-

1 part bromine
17 parts concentrated hydrobromic acid
32 parts deionised water,

the bromine being added last. The bromine tended to evaporate if the etch was left standing, meaning that the etch had to be made freshly each time it was needed.

The etch rate was approximately 2 microns per minute and appeared to be fairly constant over a few minutes. The specimen was left in the etch for a time corresponding to removal of about twice the epitaxial layer.

The photo-resist, after etching, was removed by dissolving in acetone and the specimen was rinsed in methanol and again dried in the oven.

e) Contacts

'Contacting' masks had been made which left all the specimen except the contact areas covered with photo-resist. The etched specimen, coated and baked as before had the contacting mask aligned on it, while observing through a high magnification binocular microscope. The weight of the mask was found adequate to keep it in close contact with the specimen. The resist was exposed, baked and developed as before.

The specimen was then placed in a vacuum evaporator where, at a pressure of less than 10^{-5} torr, $100 \text{ \AA}$ of tin and $1000 \text{ \AA}$ of silver were successively evaporated, the layer thicknesses being measured by the change in oscillation frequency of a quartz crystal positioned near the specimen. The tin was cut from a high purity ingot and the silver was from high purity 16 s.w.g. wire, both being cleaned in trichloroethylene and acetone before use.

To remove the unwanted contact material the specimen was placed face upwards in a shallow bath of acetone to dissolve the photo-resist, and the evaporated metal was lifted by gently probing with a

pointed wooden stick, the specimen being held with another. The only metal remaining now was on the contact areas.

The contacts were annealed in a flow of hydrogen in the furnace shown in Fig. 4.7. The specimen having been loaded into the boat, the hydrogen was allowed to flow at about 1 litre per minute to purge the system. The temperature was then quickly raised to 500⁰ C, where it was kept for 1 minute, after which the specimen was allowed to cool, still with hydrogen flowing, which took about 1 hour.

It was originally thought that better contacts would result if the surface of the material were etched for a short time immediately before evaporating the contacts, to remove contamination. This was done using a 4% solution of bromine in methanol which, however, left a white deposit on the material surface which further etching did not remove. For this reason this etch was discarded in favour of the bromine/hydrobromic acid/water etch. It was eventually found that no improvement in contact quality resulted from the etching, and the process was not continued.

f) Preliminary testing and measurement

The specimens were examined, at low voltage, on a curve-tracer to assess the quality of the contacts: the characteristic should be a straight line with the same slope for both polarities, and the slope of the line should agree with the estimated resistance for the specimen shape. If both these conditions were satisfied, it was reasonable that both contacts were ohmic and of low resistance.

As the exact final dimensions of the specimens depended to a small extent on the lithography and etching processes, it was necessary to check these. This was done with a microscope with a measuring eyepiece calibrated against a standard slide.

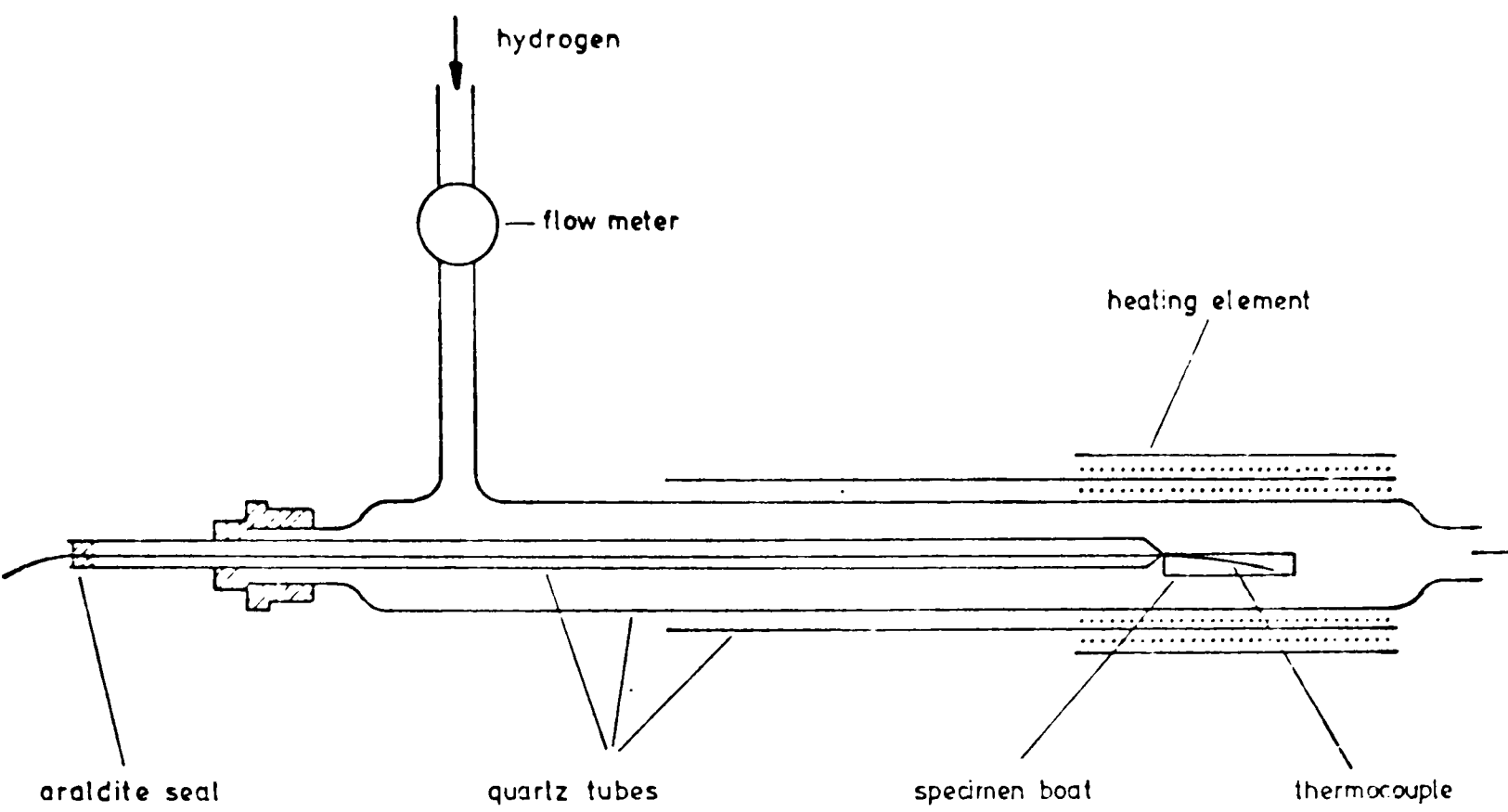


Fig.4.6 Annealing furnace

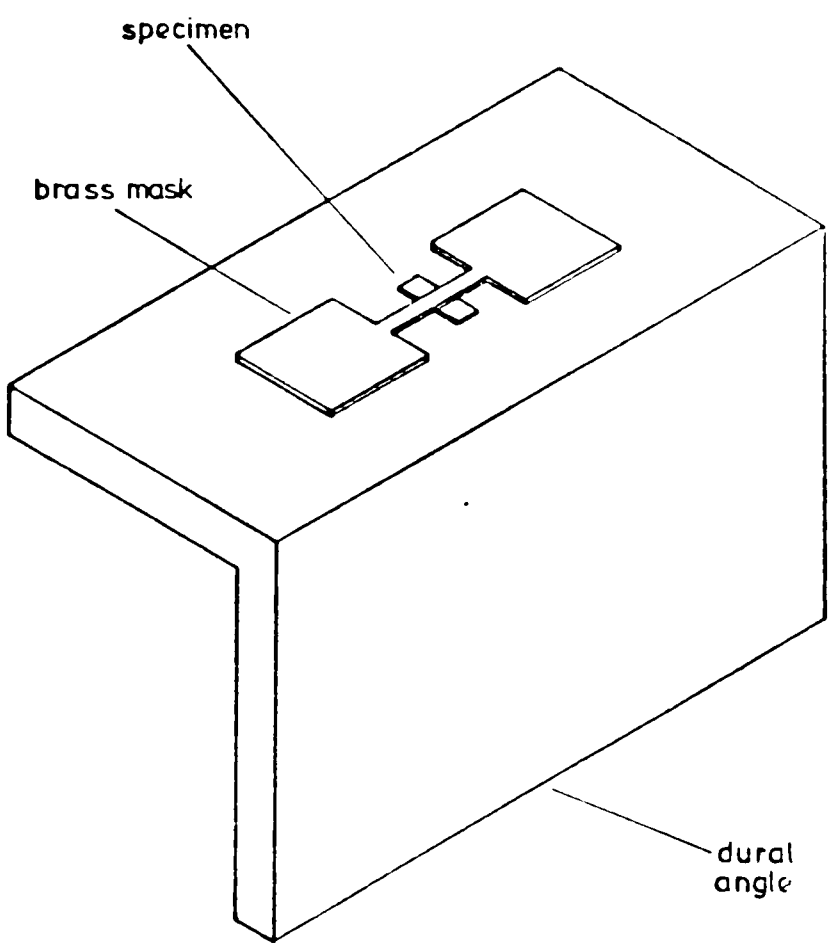


Fig 4 7. Masking jig for bar-type specimens

4.5 Bar-type specimens

These specimens comprised rectangular bars of material with contacts evaporated on the top face at opposite ends (Fig. 4.3), the region between the contacts forming the active part of the specimen. They were used for preliminary low-field experiments, and selected ones for the high-field domain measurements.

The material was cut and cleaned as already described, and then mounted in the jig shown in Fig. 4.7, in which the brass mask covers its central part, allowing the contacts to be evaporated on to the ends. The contacting and annealing processes were exactly the same as for the photo-etched specimens.

CHAPTER V

SUB-THRESHOLD VELOCITY-FIELD MEASUREMENTS

5.1 Measurement of resistivity and Hall mobility

The resistivity of a thin layer of material and the mobility of the current carriers in it may be measured by a method due to Van der Pauw^[82] where a sample of arbitrary shape has four small contacts attached at points around its circumference, the contacts being designated A, B, C, D in order.

The resistivity is shown by Van der Pauw to be given by:

$$\rho = \frac{\pi d}{\ln 2} \frac{(R_{AB,CD} + R_{BC,DA})}{2} f\left(\frac{R_{AB,CD}}{R_{BC,DA}}\right)$$

where d is the layer thickness and $R_{AB,CD}$ is the voltage between C and D due to unit current flowing between A and B and $R_{BC,DA}$ is the voltage between D and A due to unit current flowing between B and C.

$$f\left(\frac{R_{AB,CD}}{R_{BC,DA}}\right)$$

is a complicated function given graphically by Van der Pauw.

The Hall mobility μ_H is determined by measuring the change of $R_{BD,AC}$ when a magnetic flux density B is applied perpendicular to the sample, and is then given by

$$\mu_H = \frac{d}{B} \cdot \frac{\Delta R_{BD,AC}}{\rho}$$

This method was used to check the manufacturer's values of resistivity and mobility of the material used, taking great care to keep experimental errors as small as possible. A digital voltmeter was used to measure voltages, and the meter used for current measurement was calibrated against this using a precision resistor. The electromagnet used was calibrated against a rotating coil fluxmeter. The

total errors in this measurement were estimated at less than 2%, and, taking this into account, the values of resistivity and Hall mobility obtained were always within 5% of those quoted by the manufacturers. (Table 5.1).

5.2 Apparatus for current-voltage measurements

5.2.1 Measuring system

For current-voltage measurements the specimens were included in a 50-ohm coaxial circuit, the complete system being shown in Fig. 5.1. The short voltage pulses required were produced by a pulse generator using a mercury wetted relay to discharge a charged 50 ohm line, which was fed from a variable high-voltage power supply, enabling pulses of up to 1500 V to be produced.

The pulse from the generator was applied to one of the arms of a BNC 'T' adaptor, a line going from the opposite arm to the voltage-measuring channel of the sampling oscilloscope. The third arm was connected to the socket on the specimen holder. The main 50-ohm circuit therefore passed straight through the adaptor from generator to oscilloscope and the connection to the specimen formed a short side branch. As long as the specimen resistance (2-4 kilohms) was high compared with 50 ohms and the specimen branch was short enough the oscilloscope would measure the specimen voltage for practically the whole pulse length. The high specimen resistance also simplified the current measurement, where the usual method is to pass the current through a resistance low enough not to disturb the conditions in the circuit, and to measure the voltage across it. Because the specimen resistance was high compared with 50 ohms the current sensing resistance could be formed simply by the 50 ohm resistive input impedance of a matched line from the specimen to the oscilloscope input, avoiding the inclusion series with the specimen of an extra resistance which, to prevent mismatch, would have to be very small

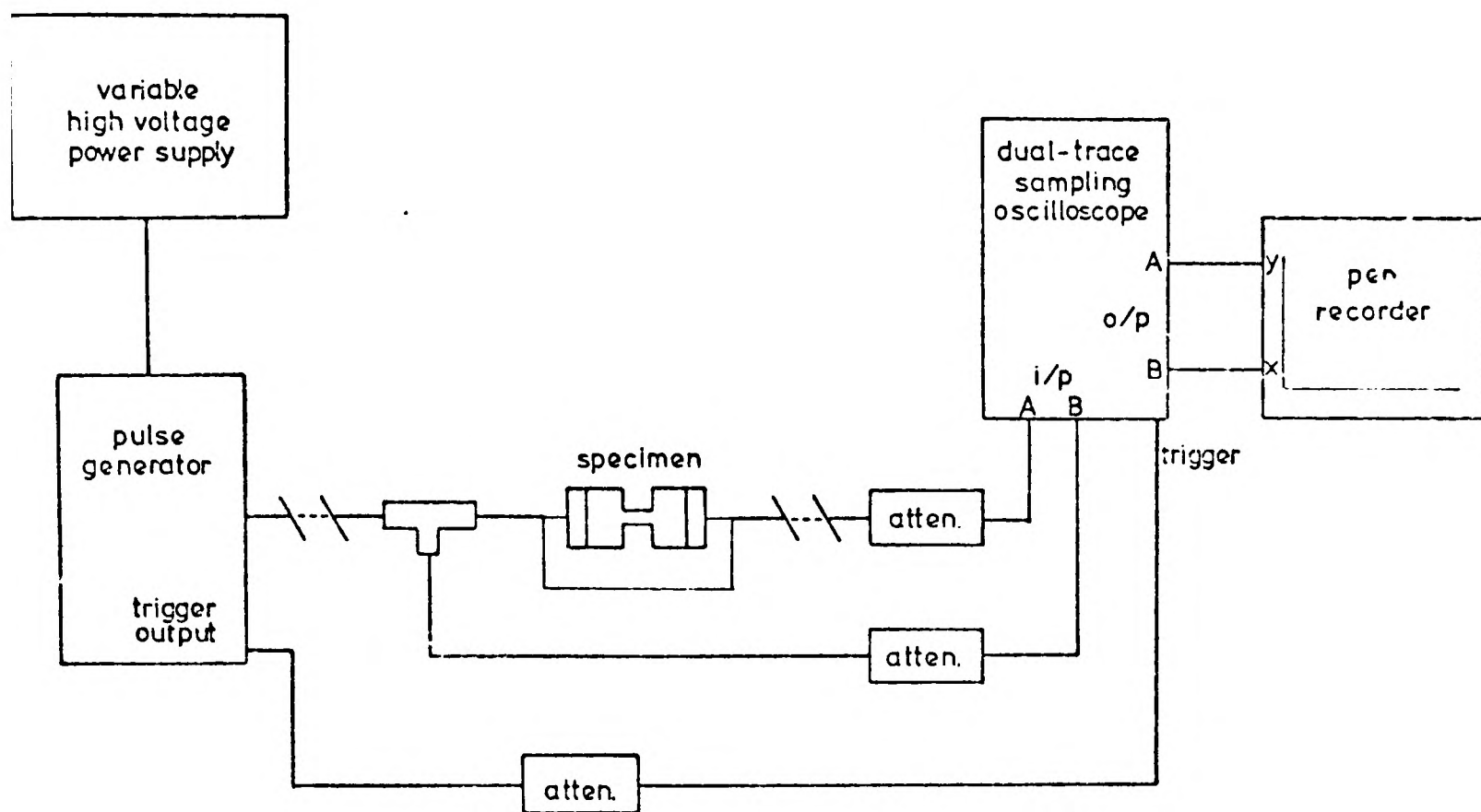
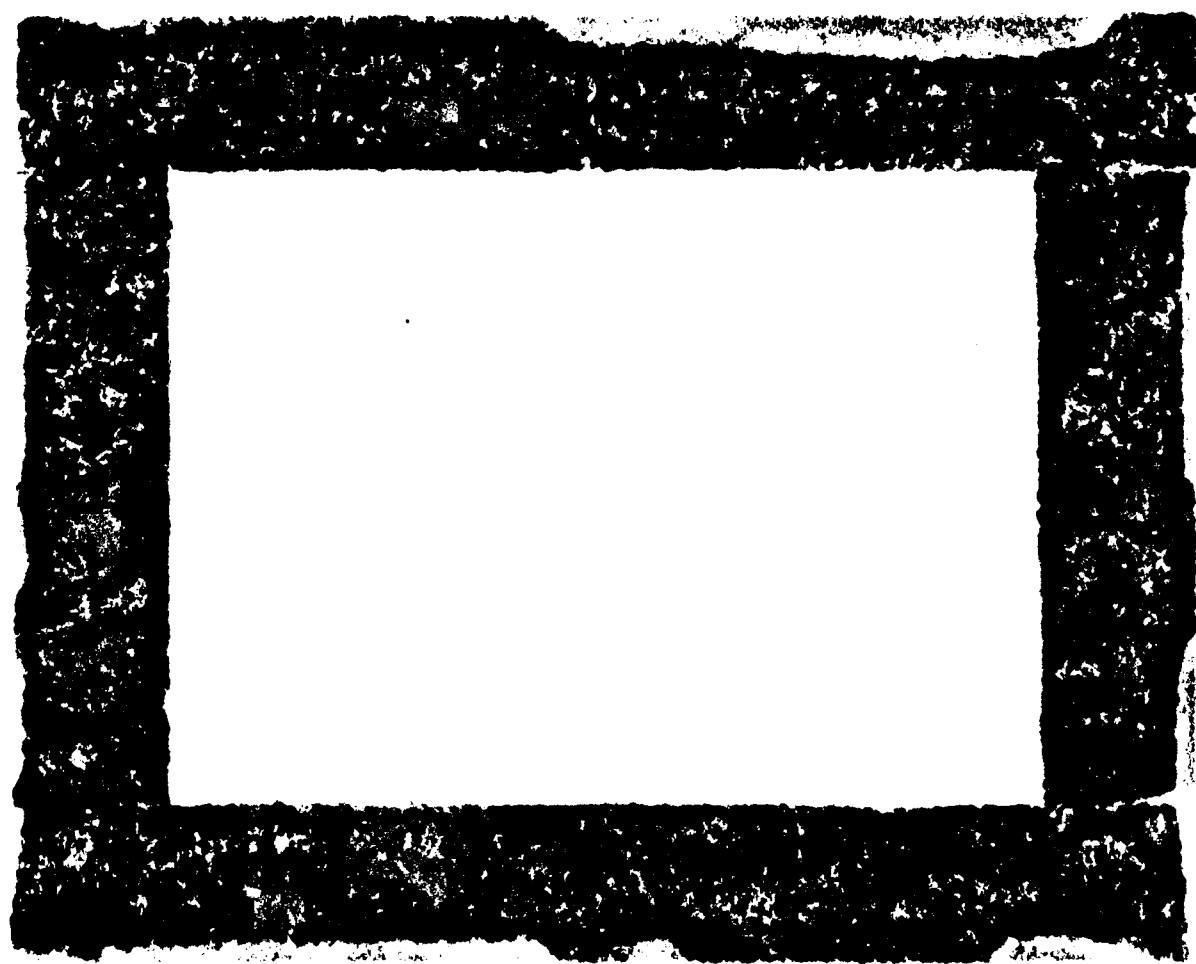


Fig. 5.1. Experimental apparatus for sub-threshold measurements



Fig. 5.2. Specimen holder for low field measurements.



physically. To produce a true current-voltage characteristic, current and voltage must be measured at the same instant. To ensure that their delays were equal, therefore, the lines from the specimen holder to the oscilloscope were accurately matched in length, taking into account that different attenuators were used in each. The sampled outputs from the two channels of the oscilloscope were fed to an x-y recorder on which a current-voltage curve could be plotted continuously, for a fixed sampling instant.

5.2.2 Specimen holder

This was a 3" diameter copper plate, $\frac{3}{16}$ " thick, with a pair of chassis-mounting BNC sockets and a pair of 'Conhex' sub-miniature coaxial sockets on it, one socket of each pair being used to apply voltage to the specimen and the other to monitor the current. The back of each socket, projecting through the top of the copper plate had attached to its centre conductor a small phosphor bronze spring contact, which rested on a piece of perspex mounted between the sockets. The specimen rested on this, held in place by the spring contacts.

5.2.3 Apparatus for measurements at 77 K

The apparatus used for these measurements is shown in Fig. 5.8. The basic arrangement was similar to that used for the room-temperature measurements, the 50-ohm circuit being made of sub-miniature cable and connectors mounted on a copper block which was attached to a stainless steel tube filled with liquid nitrogen. The specimen was in direct contact with the copper block, whose temperature was measured with a thermocouple, and the whole was contained in a vacuum chamber kept by a rotary pump at a pressure around 0.1 torr to prevent heat loss and formation of frost.

5.2.4 Calibration

Calibration was checked against a Tektronix 284 pulse generator,

which was specified accurate to $\pm 2\%$. Both channels of the oscilloscope and pen recorder were adjusted so that both the display and the pen-recorder output were correct, the x and y channels on the pen-recorder subsequently always being driven from the same oscilloscope channels. All the attenuators used were checked for accuracy.

The input impedance of the current measuring line, connected via two attenuators to the oscilloscope input was compared, using a time domain reflectometer, with a precision 50 ohm termination, and was found to be exactly 50 ohms.

5.3 Point-contact probe

5.3.1 Specification for probe

In order to measure the voltage distribution on the specimen to check the value and linearity of the electric field, the following characteristics were necessary:

1) The probe needed a fine point (a few microns diameter), but had to be soft enough to cause negligible surface damage to specimens. In epitaxial material surface damage can cause serious field non-uniformities.

2) The probe had to have a high resistance compared with that of the specimen so that the current drawn had a negligible effect on the field distribution.

3) The probe had to be positioned easily at any point on the specimen and movement in three mutually perpendicular directions was required, micrometer motion, combined with an electrical output proportional to probe position, being necessary in one direction.

5.3.2 Probe construction

The probe (Fig. 5.3) comprises a $1/4$ " diameter brass body with, at its lower end, a p.t.f.e. insert supporting the brass contact into which the point fits. Two miniature resistors in series connect the brass contact to a sub-miniature coaxial connector held in a screw-on

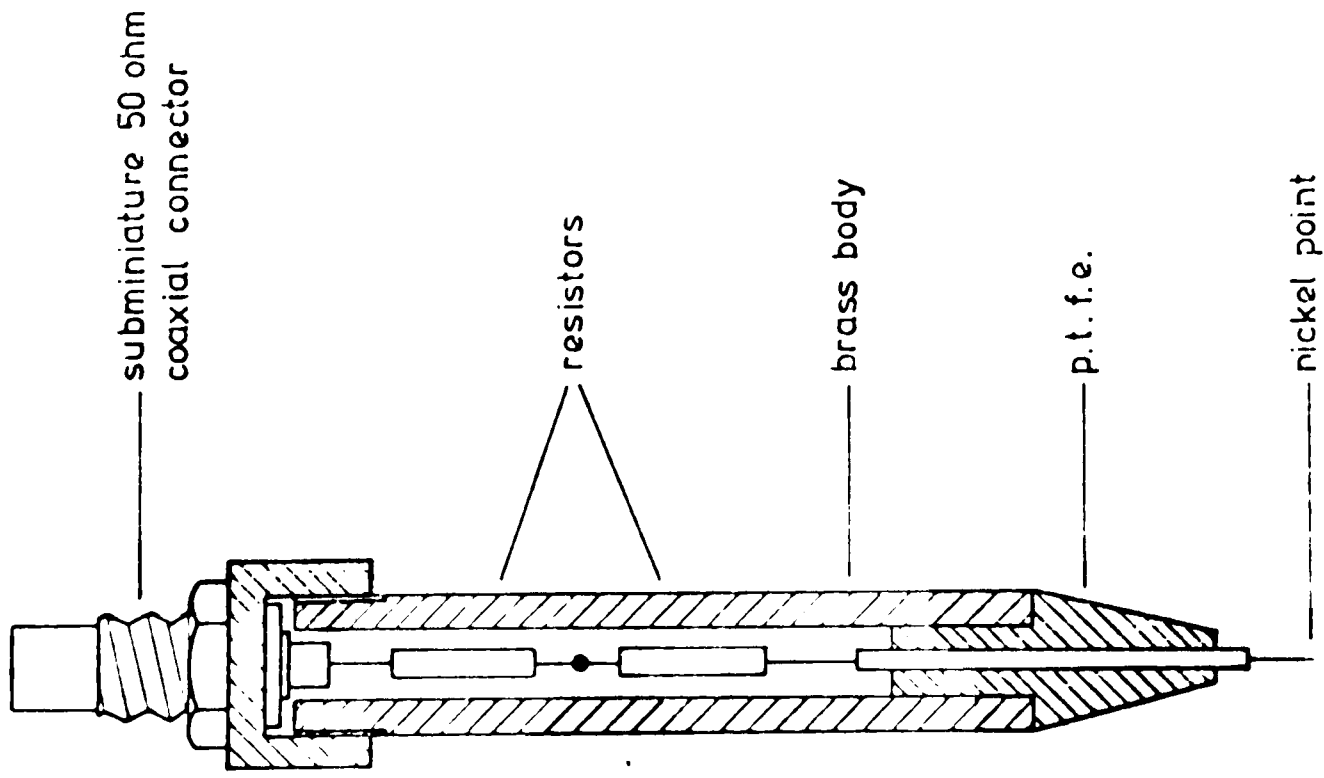


Fig 5 3 Point-contact probe for low-field measurements

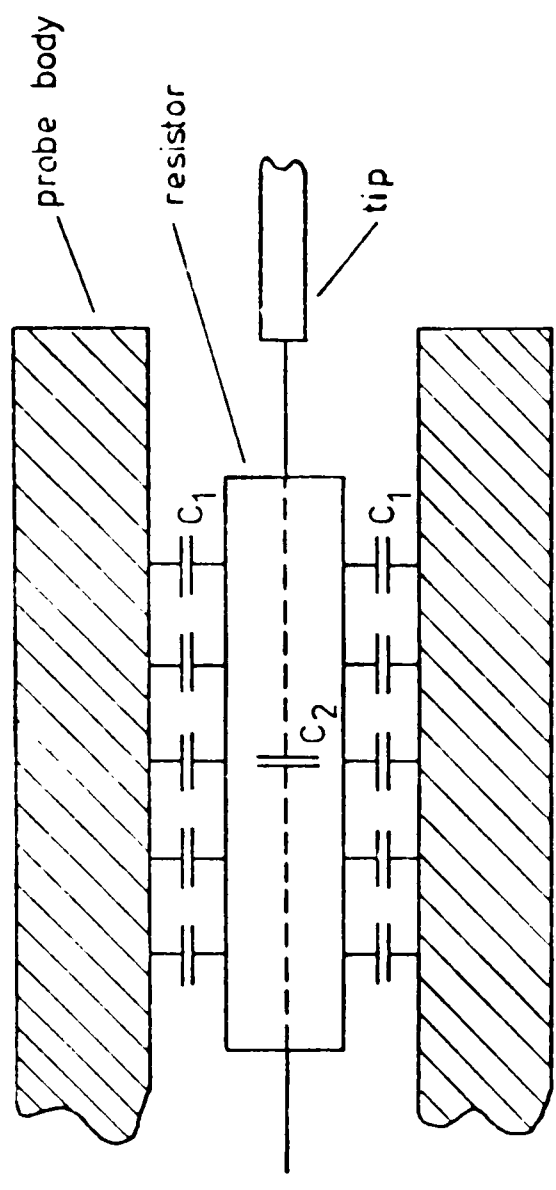


Fig 5.4. Capacitances in point-contact probe

cap at the other end of the body. The output of the probe fed into the 50 ohm input resistance of a terminated line. An earth connection from the probe to the pulse system was provided by a short piece of copper braid between the specimen table and a collar on the probe body.

5.3.3 Probe resistors

Two capacitances associated with the probe resistors will be significant in determining the probe's response (Fig. 5.4):

- 1) The distributed capacitance C_1 from the resistor to the probe body, which will slow the response and
- 2) The capacitance C_2 between the ends of the resistor which will cause coupling when a large rate of change of voltage exists between them, giving a step response with overshoot.

The desired value of resistance in the probe was about 25 kilohms, a compromise between excessive loading on the specimen and excessive attenuation. When a single resistor (of the $\frac{1}{8}$ W carbon type) of this value was used, the response to a rectangular pulse applied to a specimen showed a large amount of overshoot on the edges. Splitting the resistance into two equal resistors made the response unacceptably slow, presumably because of the dominance of the shunt capacitance. If one large and one small resistor are used, the end-to-end capacitance is still reduced by the larger separation, but the effect of the shunt capacitance in the small resistor will be less because of the low resistance per unit length there. Optimum results over the specimens used were obtained with resistors of 24 kilohms and 1 kilohm.

5.3.4 Probe response

As the probe was to be used only for examining non-time-varying fields in the specimens its response had to be fast enough only to respond to the 10 ns wide applied pulses. Its response to such a

pulse, measured at the centre of an H-type specimen is shown in Fig. 5.7.

5.3.5 Probe points

The points were electrolytically etched from 0.005" diameter wire using the apparatus of Fig. 5.5 with a 2% solution of sodium hydroxide. They were held in the brass contact of the probe with a drop of silver conducting paint.

With tungsten, which was first used for the points, although a good point was easily etched, too much surface damage was caused to specimens. Substitution of a nickel point reduced the damage but, being easily deformed, the point had to be replaced frequently.

5.3.6 Probe mounting and position measurement

The probe was mounted on a micromanipulator stage which had been modified to give micrometer controlled movement in the direction along the specimen. A 10-turn potentiometer attached to the micrometer and connected via the bridge circuit of Fig. 5.6 to the x-y recorder gave a measure of the probe position, the balancing potentiometer allowing the zero of the pen-recorder to correspond to any point on the specimen.

The probe was positioned above a specimen mount similar to that described for the current-voltage measurements, and its tip could be observed through a low magnification binocular microscope. Connection to the oscilloscope was made through a 14 dB attenuator; the lead to this was long enough (> 10 ns delay) to minimise the effect of reflections.

5.4 Experimental details

5.4.1 Preliminary experiments on bar-type specimens

Two lengths of specimen were used, nominally 500 micron and 1000 micron, with applied voltage pulses between 10 ns and 25 ns wide. A

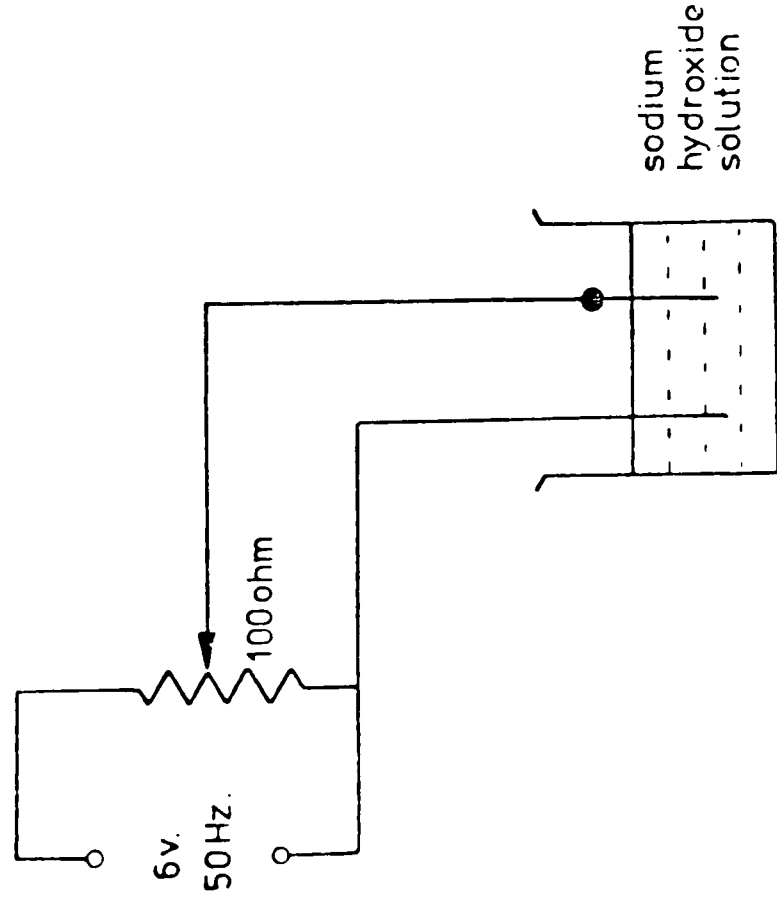


Fig 5 5 Electrolytic etching of probe points

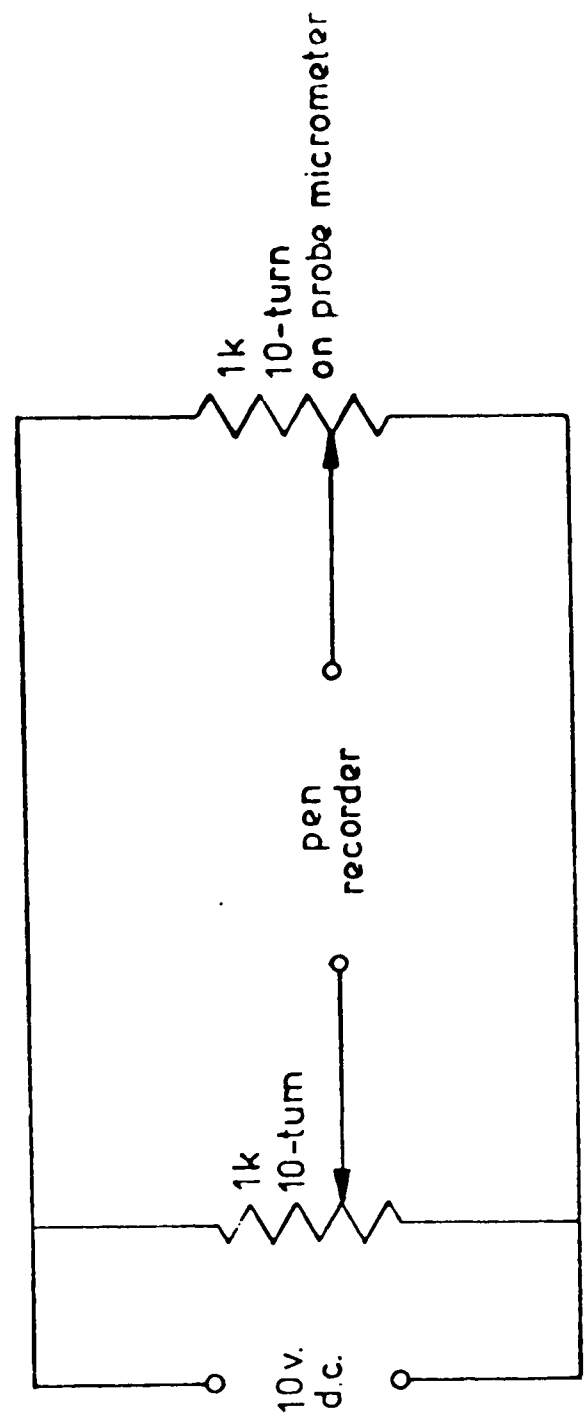


Fig. 5.6. Probe position measuring circuit

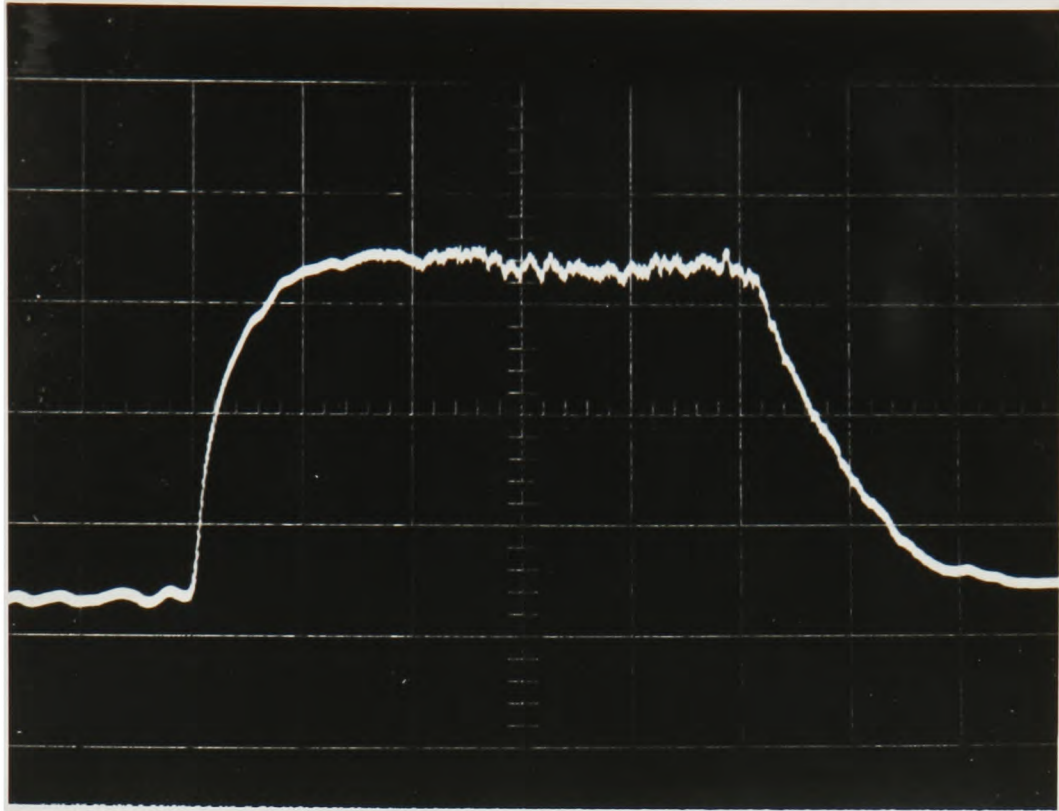


Fig. 5.7. Response of low field probe to rectangular pulse when positioned at the centre of an H-type specimen.
Horizontal scale: 5 ns/div
Vertical scale: uncalibrated.

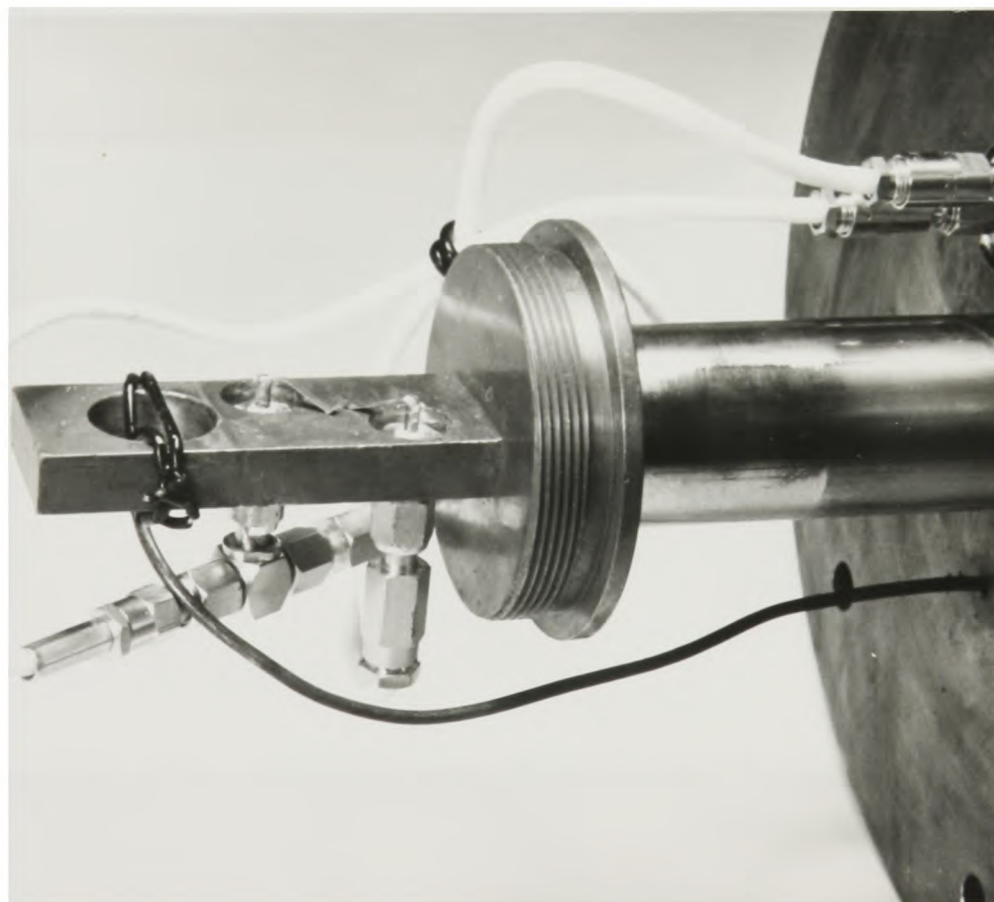
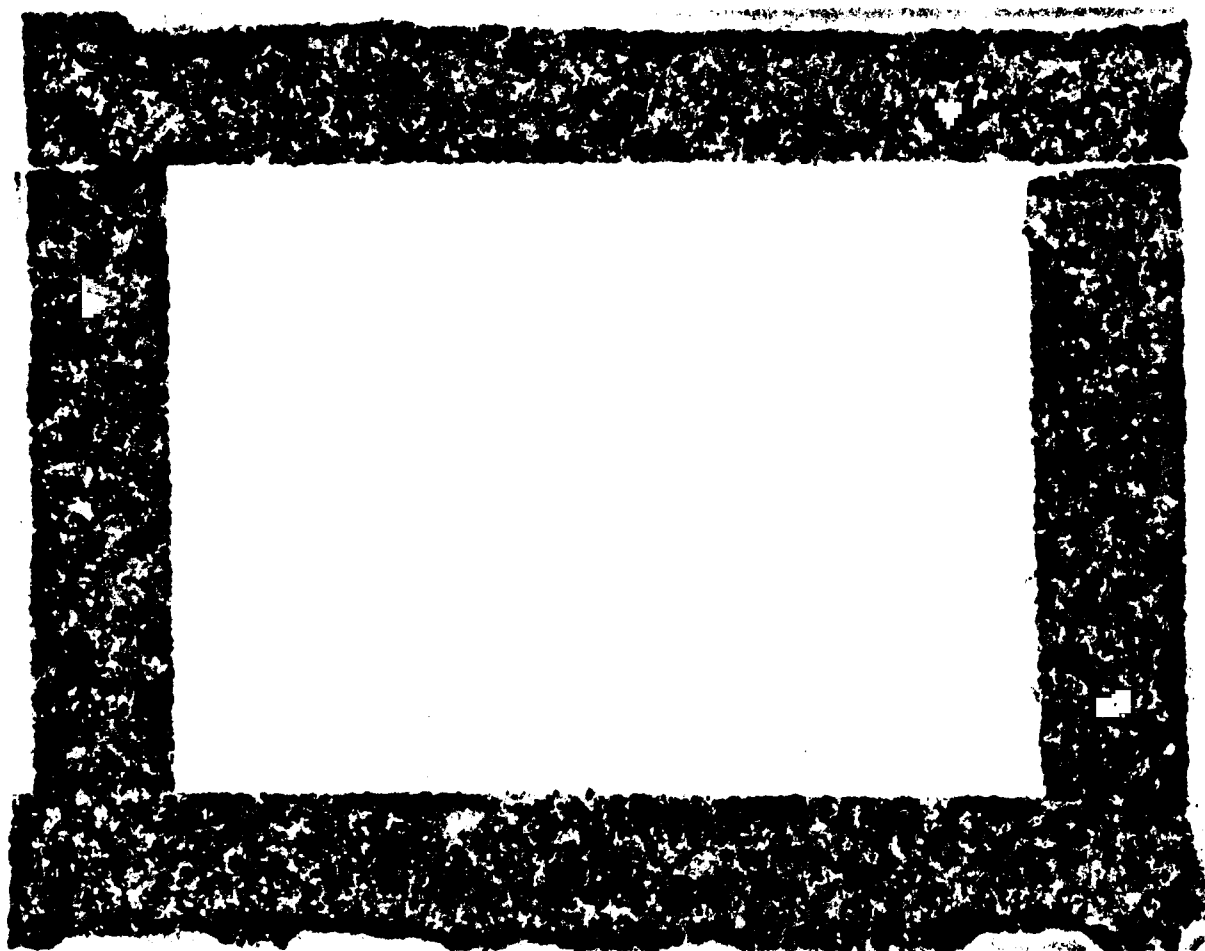
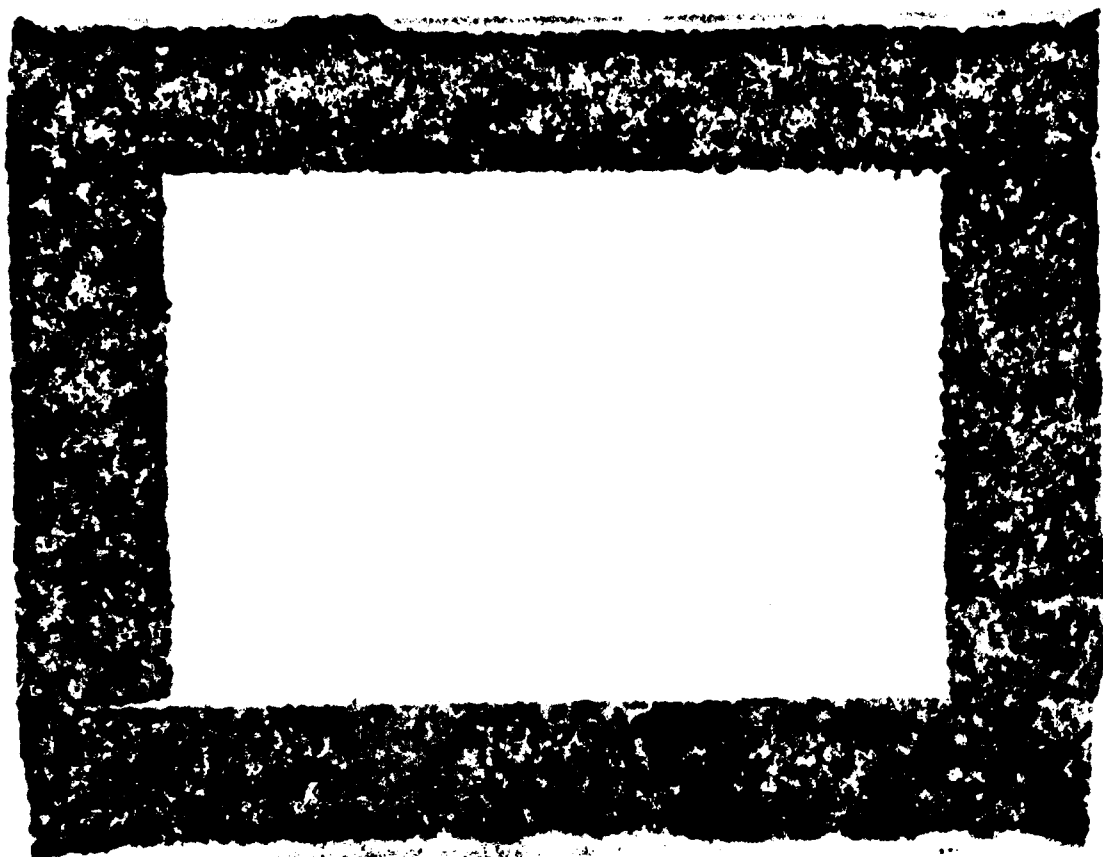


Fig. 5.8. Specimen holder of low temperature apparatus. The thermocouple can be seen at the bottom of the photograph.



typical current waveform for such a specimen is shown in Fig. 5.9, which indicates regular high field domain transits. The threshold fields for the onset of this oscillation, calculated as the ratio between applied voltage and the length of the central part of the specimen, were found to lie between 5.8 kV/cm and 8.4 kV/cm (Table 5.2). These figures must be taken only as minimum values, as it is probably that the domains are nucleating at regions of high field within the specimen, and the only conclusion to be drawn is that indium phosphide can sustain domain oscillation.

5.4.2 Current-voltage measurements

It was desired to plot continuously on the pen-recorder a current-voltage characteristic as the applied voltage was varied and to achieve this the sampling oscilloscope was set so that the sampling instant was fixed to about 4 ns after the beginning of the pulse, the pen-recorder recording current and voltage at this instant in every pulse. The instant was chosen to be in the first domain transit, and ensured that a clear indication of threshold field was shown by the drop in specimen current.

The supply voltage to the pulse generator was slowly increased until the current showed such a drop, indicating threshold field, after which the voltage was reduced quickly to avoid specimen damage. The zero point on the plot had to be checked often as, owing to the limited range of the oscilloscope's triggering circuit, the voltage could not be swept up continuously from zero. A typical current-voltage plot is shown in Fig. 5.10.

The very low duty cycle of the pulses kept specimen dissipation small. An approximate calculation was made, assuming 25 ns pulses with a p.r.f. of 100 Hz applied to a 0.2 ohm cm specimen and of a voltage to give just less than threshold field (all these parameters having 'worst-case' values). The heat loss was taken as being due to conduction through the perspex mount, although clearly there would

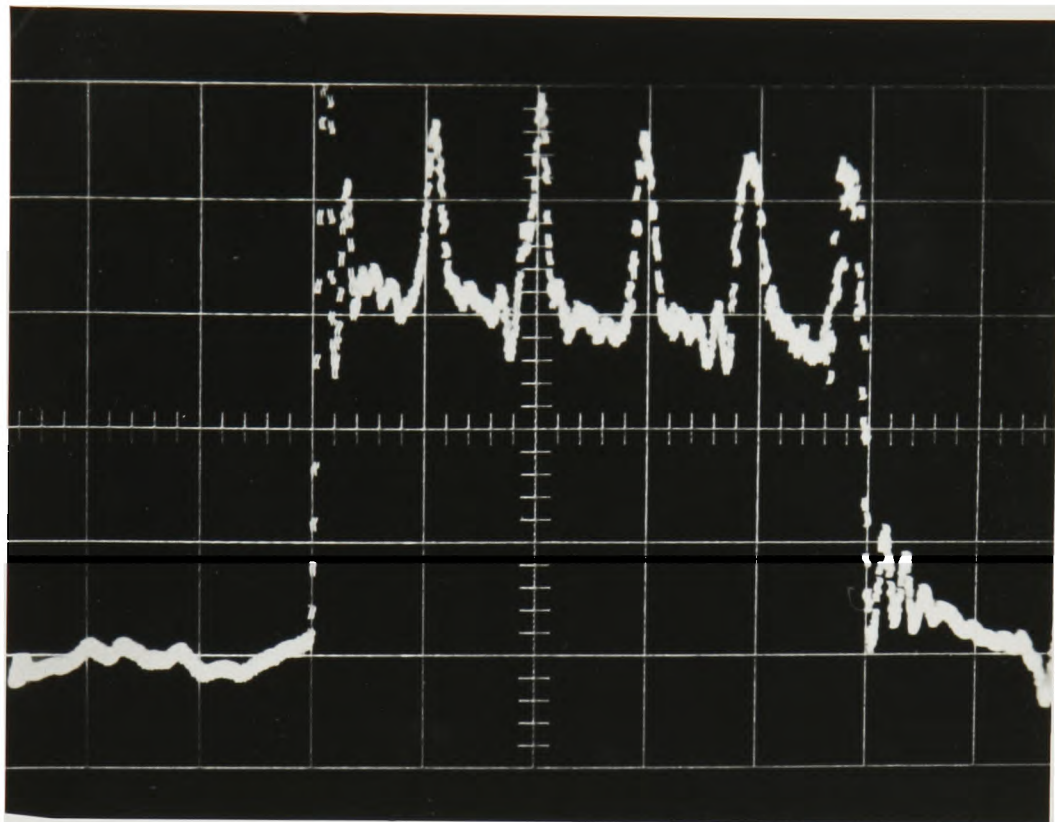
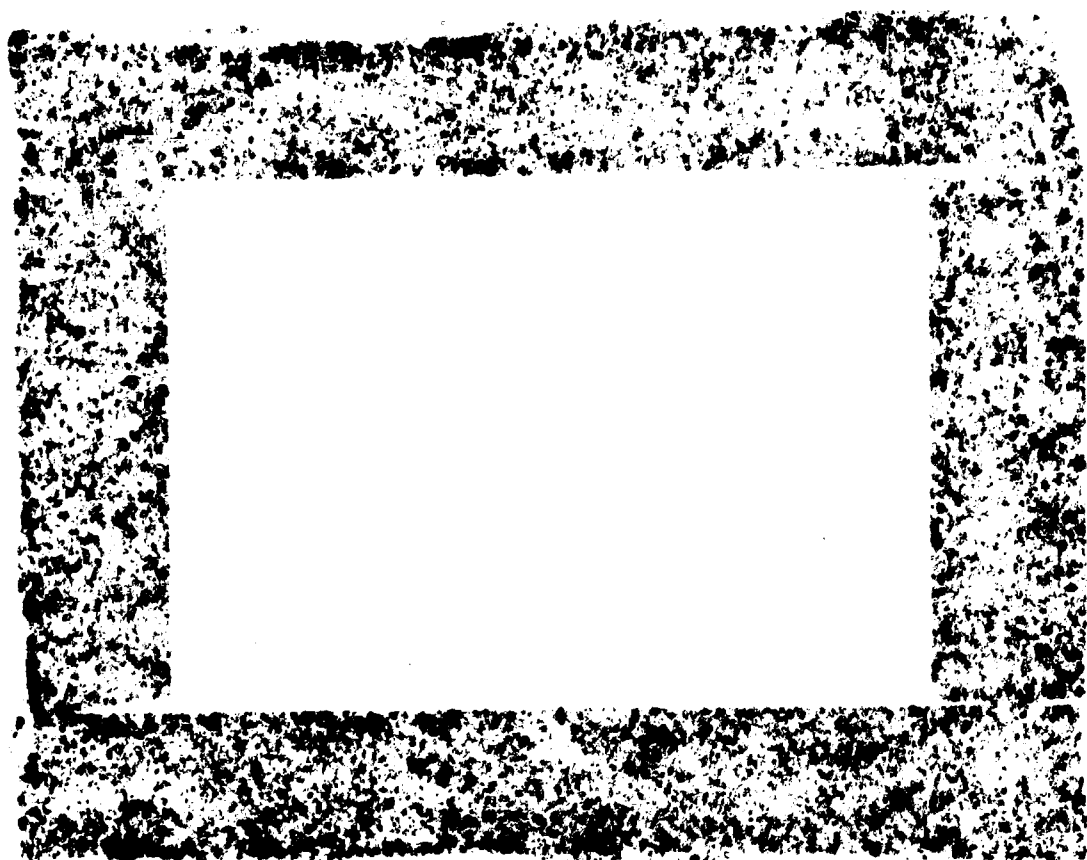


Fig. 5.9 Current waveform of bar-type specimen showing high field domains.
Horizontal scale: 5 ns/div
Vertical scale: uncalibrated.



also be loss from the specimen to the air, and the rise in specimen temperature was predicted to be of the order of 1°C , indicating that the specimens could be taken to be at room temperature (Appendix 1).

5.4.3 Probe measurements

The probe was positioned so that the micrometer moved it along the specimen's centre line. The x and y channels of the pen recorder were fed from the probe position measuring circuit and the sampled probe output respectively, the oscilloscope again being set to a fixed sampling time. The junction between the probe point and semiconductor forms a Schottky barrier which must be forward biased for a current to flow into the probe: for this reason the applied pulse had always to be negative-going.

The probe was moved in steps of about 10 microns from end to end of the specimens. At each point it was lowered just to touch the semiconductor and a point was plotted on the pen-recorder; this was facilitated by having a remote 'pen-drop' switch near the probe apparatus. The probe calibration could be checked by noting the deflection when it was on the high-voltage contact.

A typical plot from an H-type specimen is shown in Fig. 5.11.

5.5 Deduction of central field in specimens

5.5.1 Analogue of specimens

If certain assumptions can be justified then it should be possible to calculate the voltage drop across the ends of the specimen and hence deduce the field in the central part from measurements on a resistance-paper analogue of the specimen. These assumptions are:

- 1) that the material in the end parts of the specimens sustains a very low field so that it is ohmic with the low field resistivity
- 2) that the field in the central (bridge) part of the analogue is uniform so that the separately measured resistance of this may be subtracted from the total measured resistance, leaving the resistance

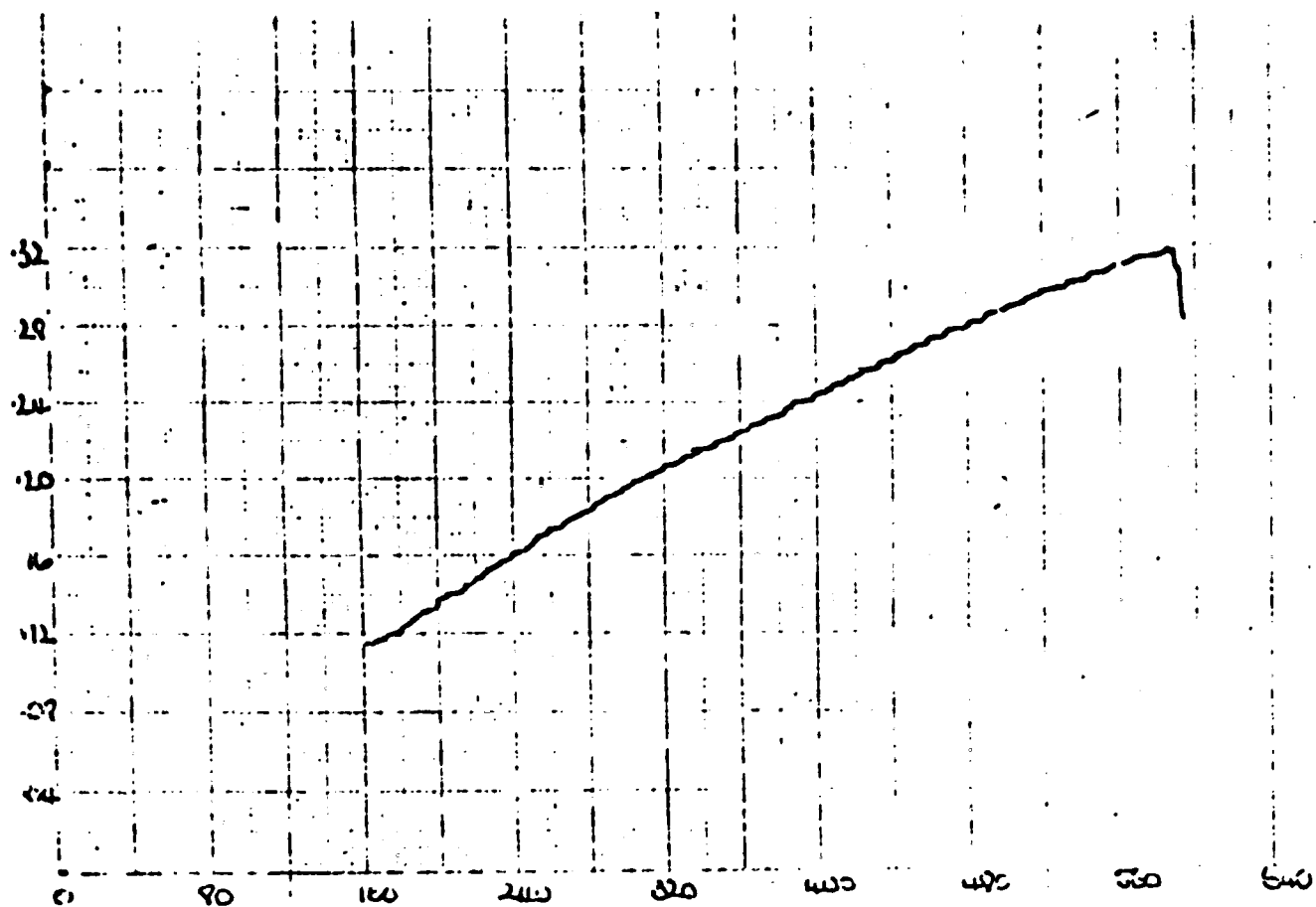


Fig. 5.10 Typical current-voltage characteristic for H-type specimen.

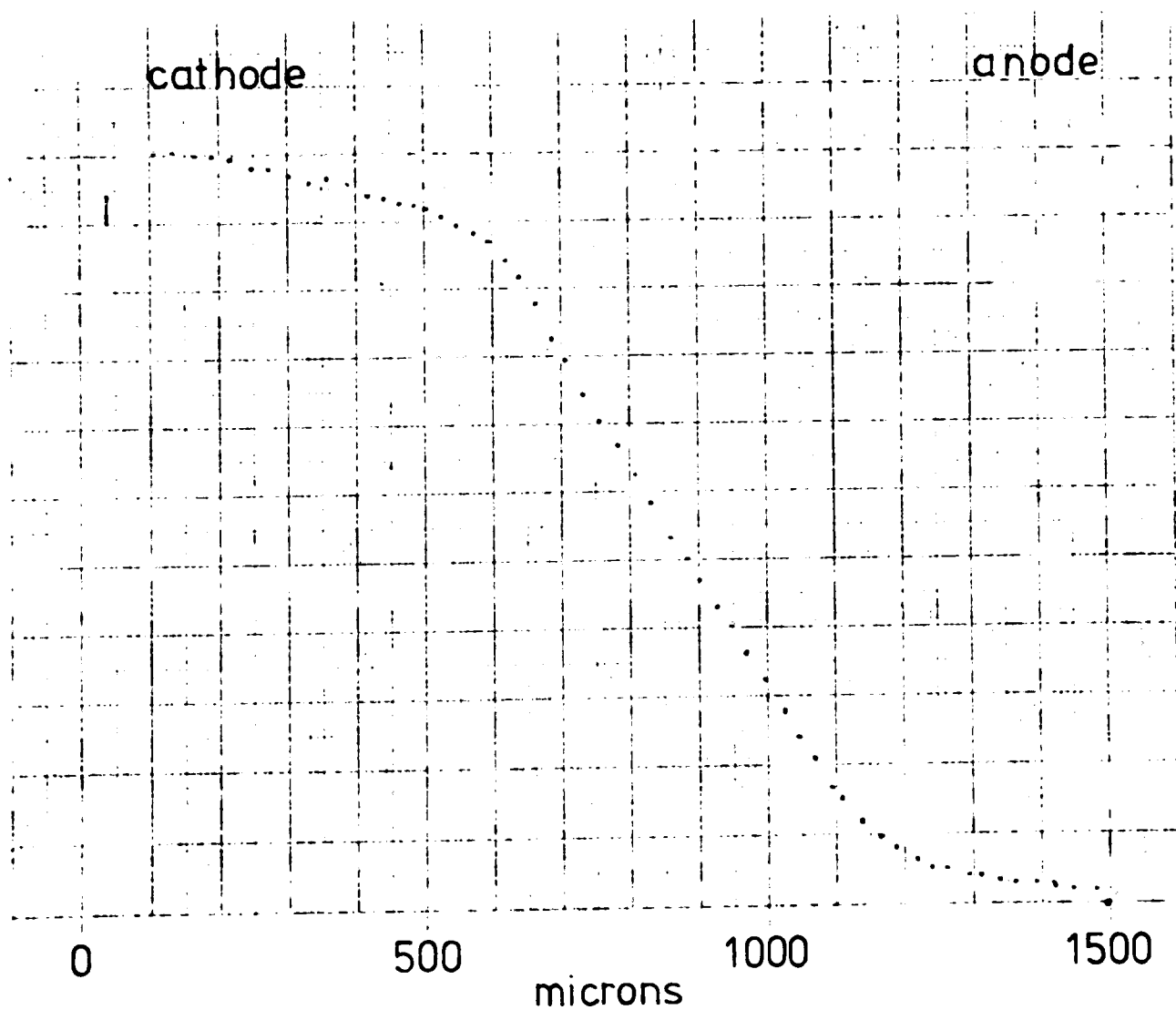


Fig. 5.11 Potential distribution along H-type specimen, measured with point-contact probe. Total voltage across specimen = 250 V.

due to the ends; this is satisfied by the bridge being narrow compared with the ends. Both these conditions are satisfied by the geometry chosen for the specimens; they are precisely the conditions which were applied towards achieving a uniform central field.

For similar geometries, the electric field distribution in a uniform epitaxial layer and a sheet of resistance paper will be identical, and hence the resistances measured between corresponding points will be proportional. If the sheet resistance s of the paper is defined as the resistance between opposite sides of a unit square, this is analogous to ρ/d in the epitaxial layer. If R_s and R_p are the resistances of the semiconductor and of the paper analogue respectively, then,

$$\frac{R_s}{R_p} = \frac{\rho}{d} \cdot \frac{l}{s},$$

or if R_p is normalised to R_p' such that

$$R_p' = \frac{R_p}{s}$$

then

$$R_s = R_p' \cdot \frac{\rho}{d} \text{ for the same geometry.}$$

Because of the symmetrical specimen shape a model of only a half-specimen need be considered; such a model was made at a scale of 254 x full size (10 inches to 1 mm). Contacts were made to the paper with silver conducting paint, and the resistance between the centre of the bridge and the edge of the contact pad measured for different lengths of contact pad x (Fig. 5.12), putting on a new contact for each successive reading.

The sheet resistance s was determined from the average of measurements on several rectangular pieces of paper and checked using a 4-point method; the value of R_p' , the normalised resistance of the analogue was plotted against x . By subtracting the resistance of the

half-bridge alone ($x=0$) the series resistance due to the contact pad was deduced (Fig. 5.13).

5.5.2 Analytical Method of Majerfeld

The same specimen geometry was analysed by Majerfeld^[60], who made the same assumption that the end regions were ohmic, and gave the following expression for the resistance of the half specimen:

$$R = \frac{\rho}{d} \left[\frac{x}{b} + \frac{1}{2\pi} \left\{ \frac{b^2 + w^2}{bw} \ln \left(\frac{b + w}{b - w} \right) + 2 \ln \left(\frac{b^2 - w^2}{4bw} \right) + \frac{\ell}{2w} \right\} \right]$$

where the last term inside the square bracket represents the resistance of the half-bridge. Inserting $\frac{b}{w} = 15$ (for specimens with a 100 μ wide bridge), and subtracting this term gives for the series resistance of the end

$$R = \frac{\rho}{d} \left(\frac{x}{b} + 0.734 \right)$$

This is compared with the results from the analogue in Fig. 5.13.

The specimens used in the experiments all had $\frac{x}{b}$ in the range 0.15 to 0.25, where the curves are within 5% of each other. As only about one quarter of the applied voltage was dropped across the end regions the discrepancy in the deduced central field would be proportionately smaller.

5.5.3 Point contact probe measurements

The field in each specimen was measured at a few values of applied voltage with the point contact probe; a large number of readings was avoided with most specimens to prevent possible surface damage caused by excessive use of the probe.

Results for one of the narrow-bridge specimens are shown in Fig. 5.14 where they are compared with the fields calculated by the analogue and conformal transformation methods, and clearly agreement is very close, being nowhere worse than $\pm 3\%$. In none of the comparisons made between the fields so measured and calculated was the

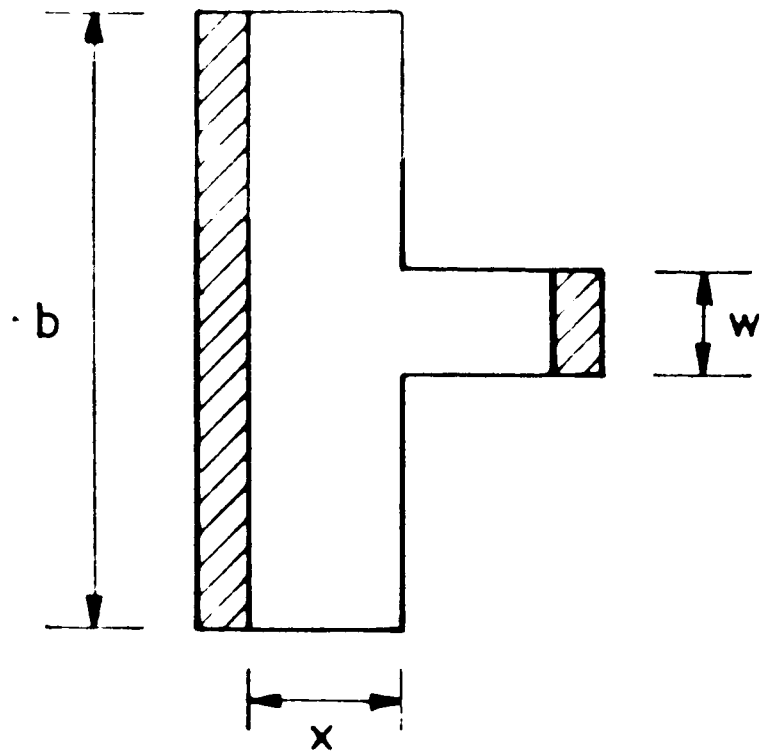


Fig. 5.12. Dimensions of specimen analogue

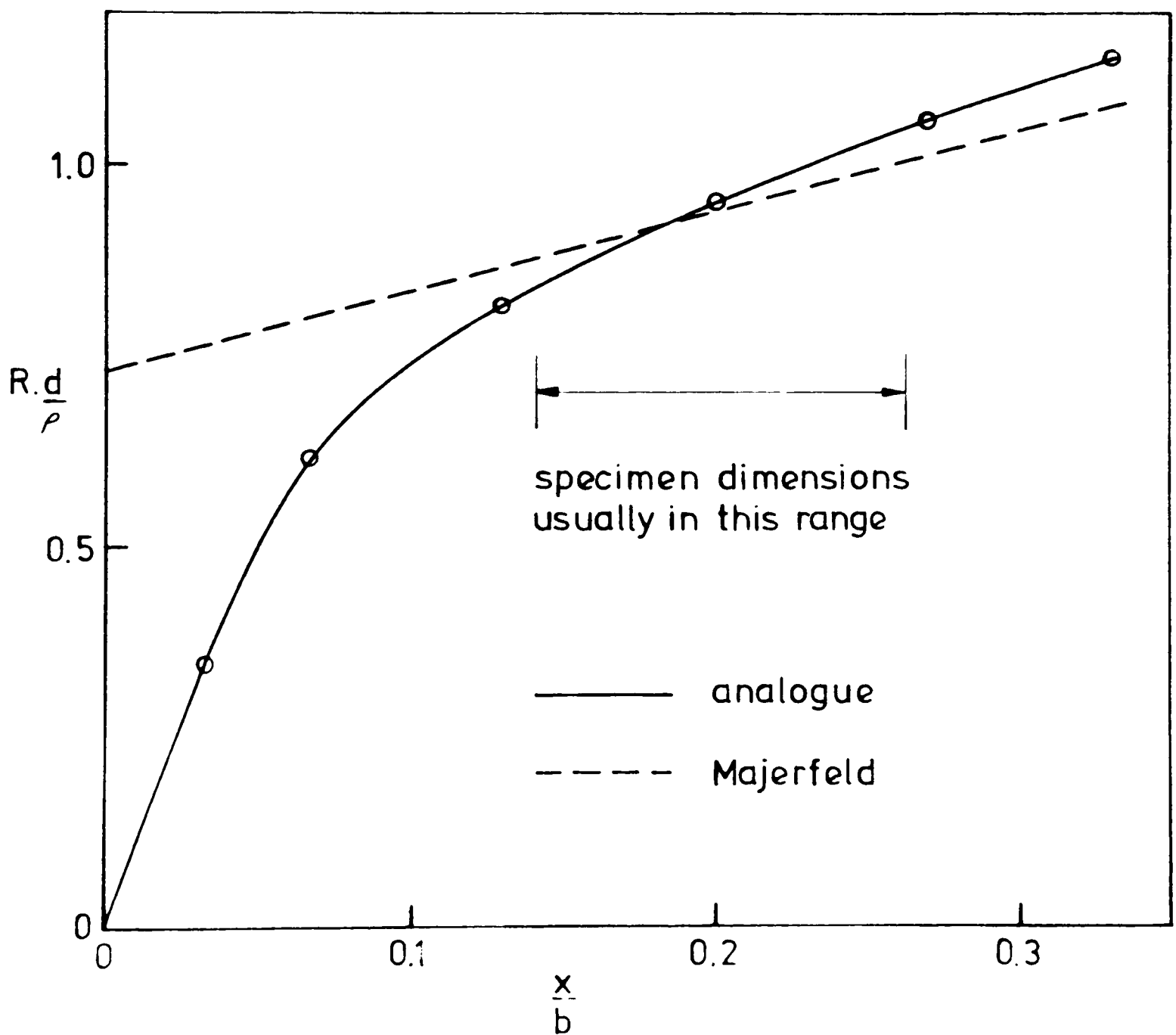
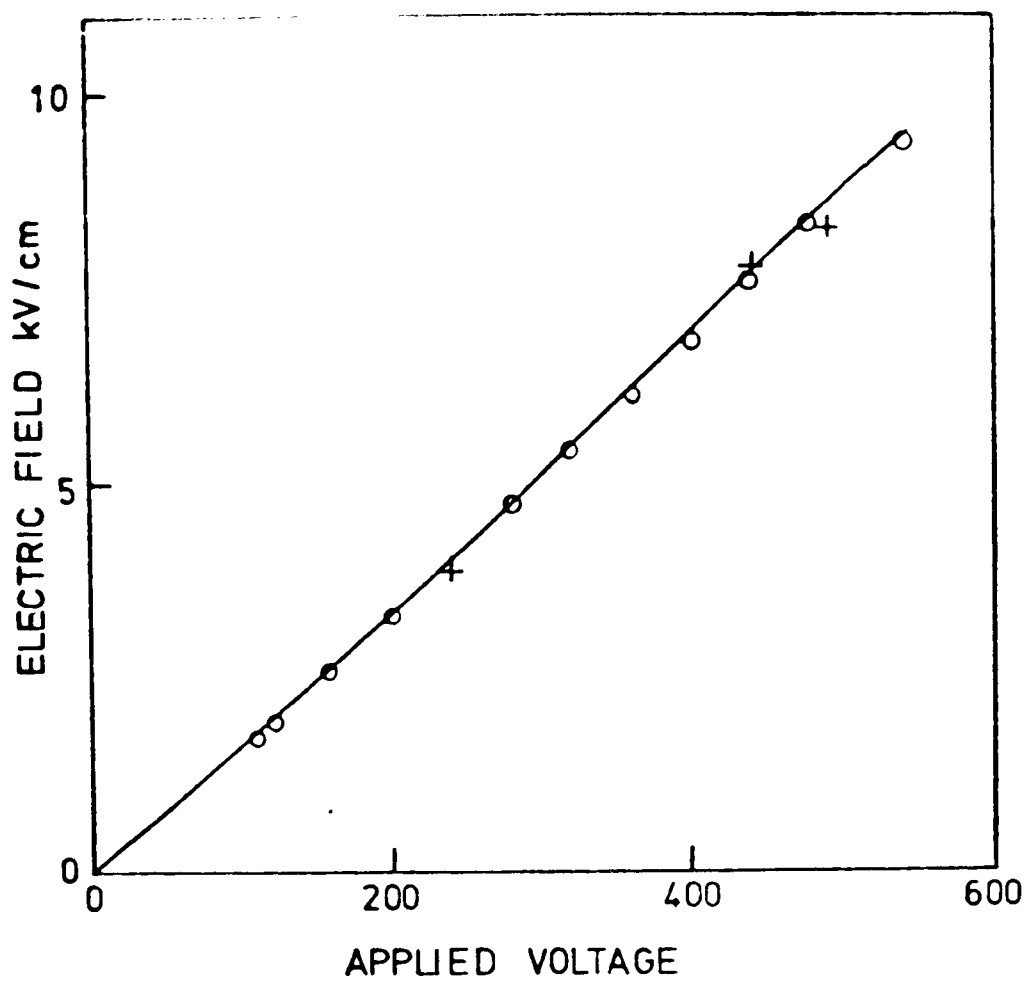


Fig. 5.13. Specimen end resistance



- calculated from analogue
- + measured with probe
- conformal transformation of Majerfeld

Fig. 5.14. Field in central part of H-type specimen

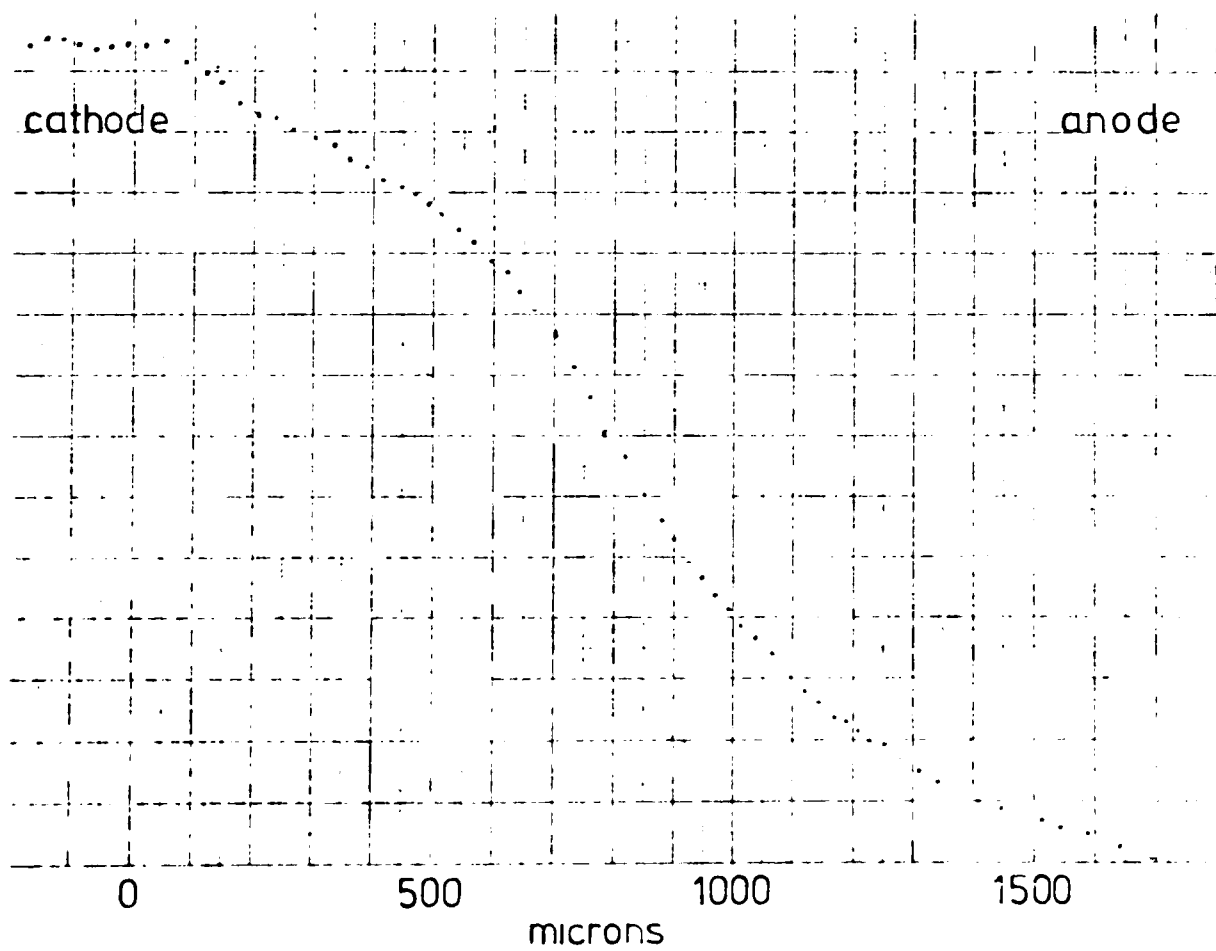


Fig. 5.15 Potential distribution along wide-bridged H-type specimen. Total voltage across specimen = 550 V.

discrepancy more than 5%, a result which would justify the deduction by the analogue method of the field values in the complete velocity-field curves.

From the analogue results and the value of $\frac{\rho}{d}$ and the dimensions for a particular specimen the end resistances R_A , R_B are calculated; the voltage across the central part of the specimen is then given by

$$V_c = V - I (R_A + R_B)$$

V and I being the terminal voltage and current. The central field is then

$$E = \frac{V - I (R_A + R_B)}{l}$$

For several points on the measured current-voltage characteristic values of voltage and current were read off and the central field calculated from (5.11.1). The voltage scale was thus transformed into a scale of electric field.

The low field Hall mobility was known from the low field Van der Pauw measurements and, divided by the scattering factor, gave the low field drift mobility. In the central bridge carrier drift velocity is proportional to current, and so a drift-velocity-field characteristic was derived by normalising the current-field curve to this low-field drift mobility.

5.5.4 Wide-bridge specimens

A small number of experiments was carried out with specimens with a 500 μ wide bridge. The electric field in the central region was measured directly with the point-contact probe.

A typical probe result is shown in Fig. 5.15, where the field is seen to change towards the ends of the bridge. Such plots were taken for a number of applied voltages, and turned into graphs of central field against applied voltage, which were used to convert the

I - V results into velocity-field relations, again by normalising to the drift mobility.

5.6 Sub-threshold velocity-field characteristic at 300 K

The results for several specimens are plotted in Fig. 5.16, and the salient points of the characteristic for the individual specimens are set out in Table 5.3. The consistency between the different samples is good: at no value of field does the standard deviation of the individual values of velocity exceed 8% of the mean, without taking into account the different low field mobilities of the various slices. If this is done by normalising all the curves to one low field mobility (a suitable value might be $4700 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$), the deviation in the velocities is reduced.

Two specimens (C1521a and C1521b) show a lower velocity than the rest at high fields, a property which might be attributable to their low-field mobility.

The averaged values of the threshold field and velocity from all the specimens are

$$E_T = 10.7 \text{ kV/cm}$$

$$\text{standard deviation } 0.93 \text{ kV/cm (8.7\%)}$$

$$v_{DT} = 2.44 \times 10^7 \text{ cm/s}$$

$$\text{standard deviation } 0.34 \times 10^7 \text{ cm/s (13.9\%)}$$

For the narrow-bridged specimens alone the averaged values become

$$E_T = 10.8 \text{ kV/cm}$$

$$\text{standard deviation } 0.98 \text{ kV/cm (9.1\%)}$$

$$v_{DT} = 2.47 \times 10^7 \text{ cm/s}$$

$$\text{standard deviation } 0.38 \times 10^7 \text{ cm/s (15.3\%)}$$

and from the wide-bridged specimens alone the averaged values are

$$E_T = 10.4 \text{ kV/cm}$$

$$\text{standard deviation } 0.96 \text{ kV/cm (9.2\%)}$$

$$v_{DT} = 2.46 \times 10^7 \text{ cm/s}$$

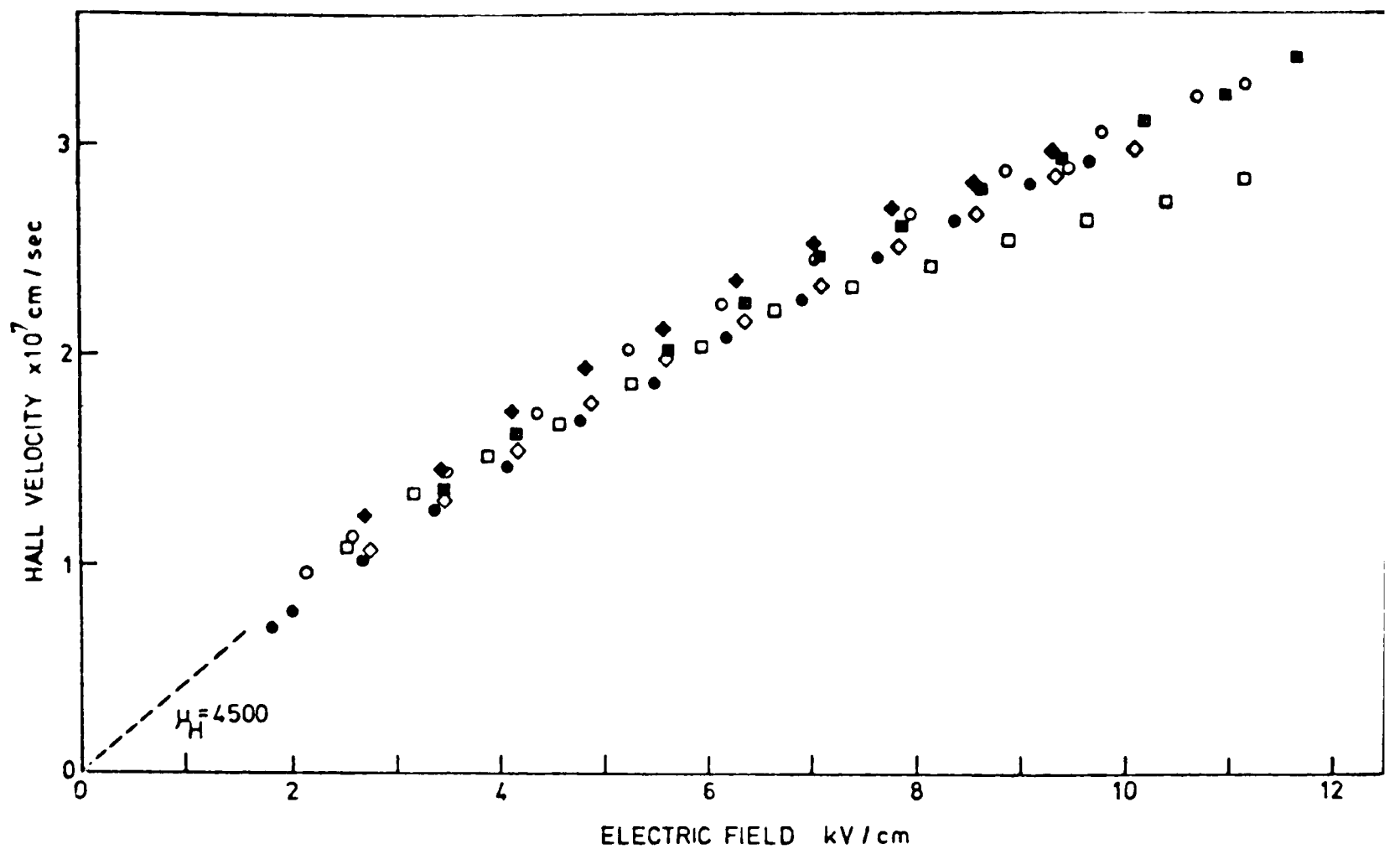


Fig. 5.16. Individual specimen results

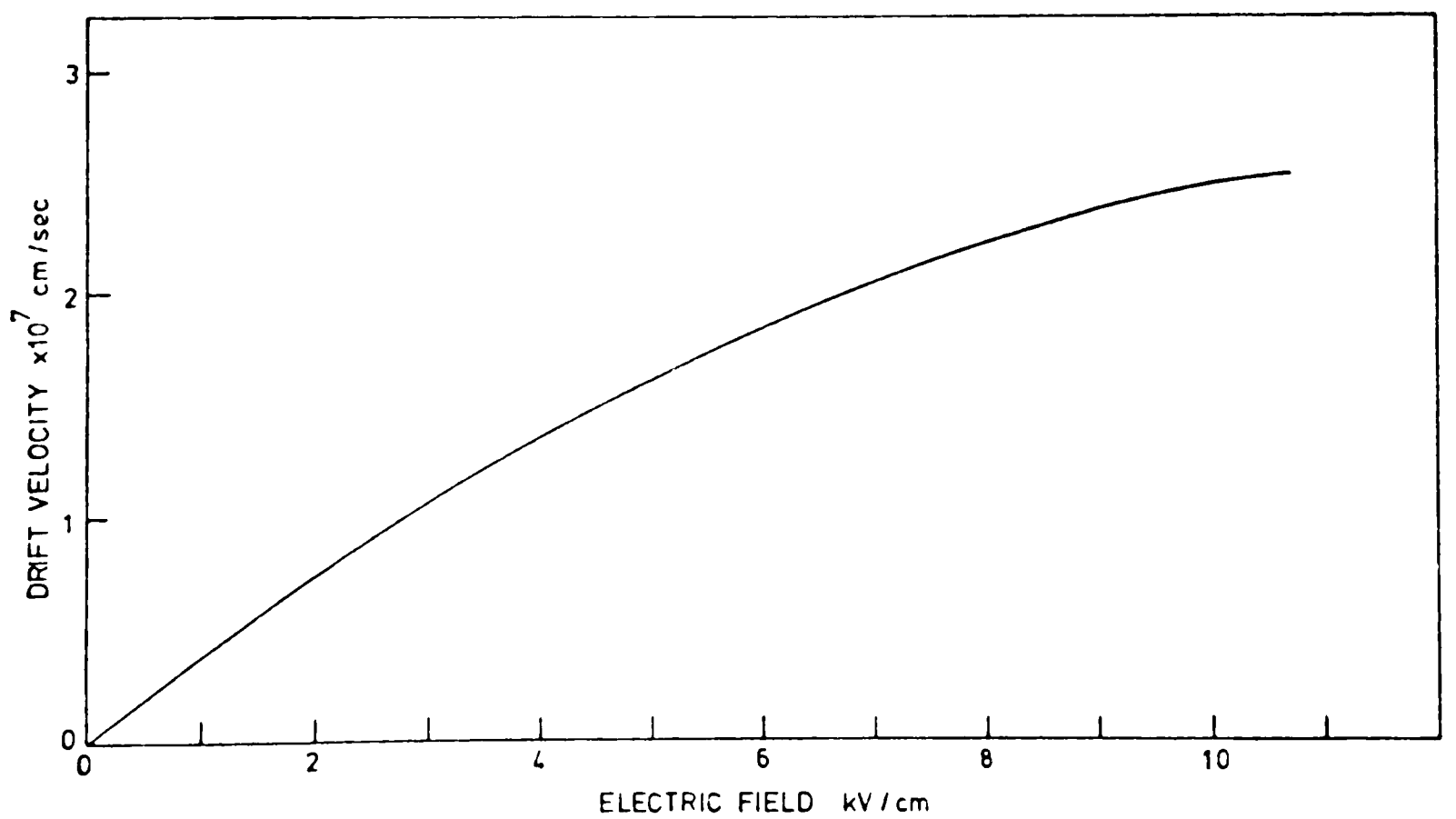


Fig. 5.17. Subthreshold velocity - field characteristic at 300 K

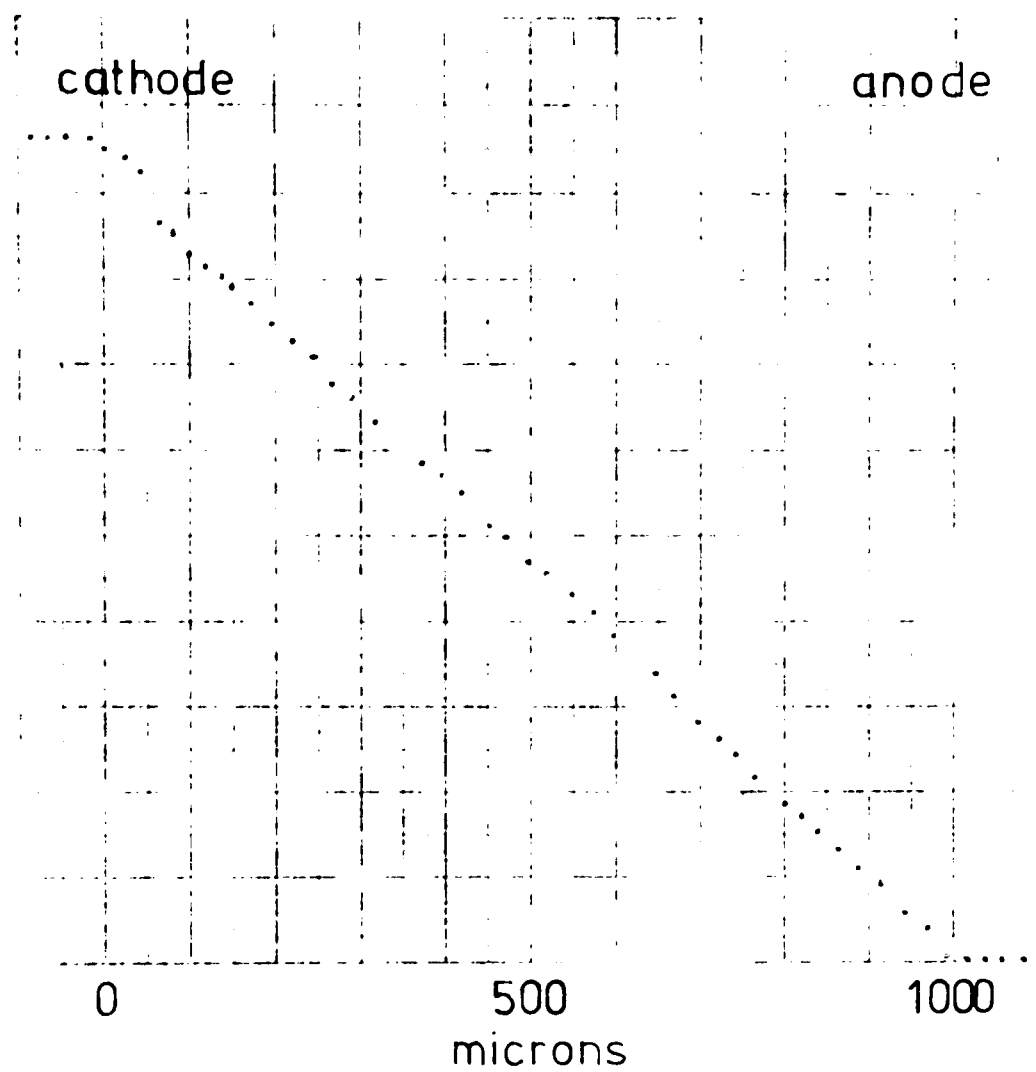


Fig. 5.18 Potential distribution along bar-type specimen, showing high field region near the cathode. Total voltage across specimen = 400 V.

There seems to be little difference between the results for E_T and v_{DT} given by the two widths of bridge - the threshold field from the wide-bridged specimens is slightly lower, but not significantly so. The overall velocity-field characteristic is shown in Fig. 5.17.

The results already given in Table 5.2 for the average threshold field shown by the bar-type specimens in the preliminary experiments indicated much lower values of E_T . Measurements made with the point-contact probe showed the presence of a high-field region adjacent to the cathode contact, similar to that observed by Gunn in early experiments on gallium arsenide (Fig. 5.18). That E_T is higher for the longer specimens (7.7 kV/cm for 1000 μ nominal length compared with 6.7 kV/cm for 500 μ nominal length) is consistent with this, as such a drop would account for a smaller proportion of the total applied voltage in the longer specimens.

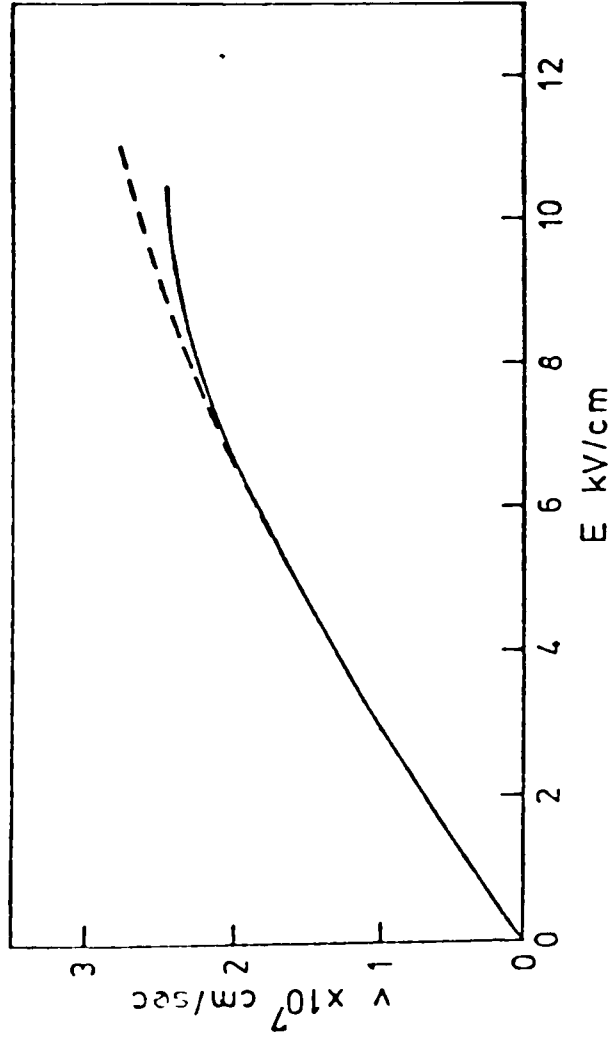
Both these results and those from the H specimens show that the threshold field decreases for higher carrier density material.

5.7 Comparison with other results

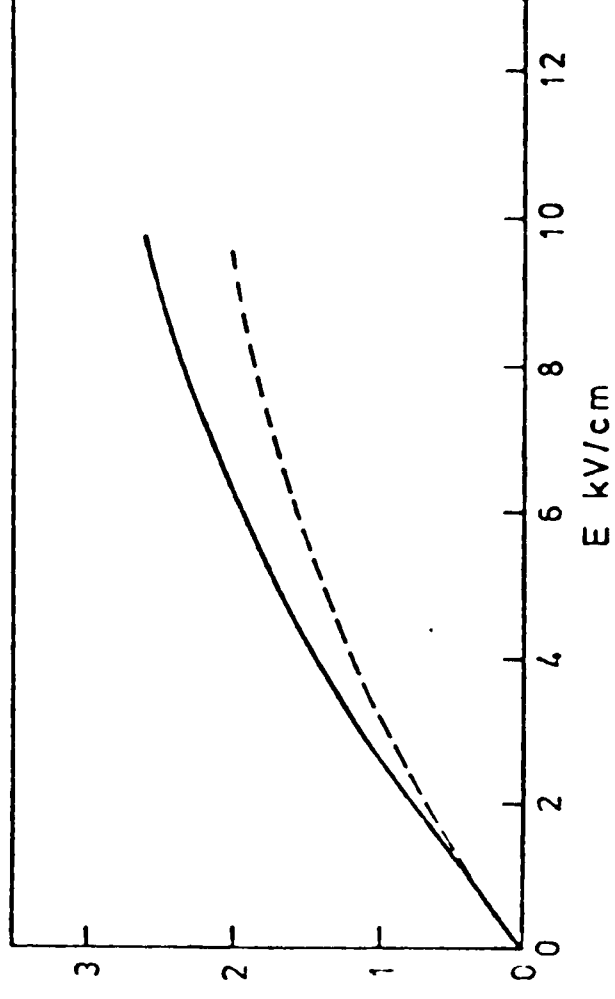
5.7.1 Comparison with microwave experiments on similar material

Experiments using the microwave heating technique of Glover to determine the velocity-field characteristic were performed by Tebbenham [53] on samples from the same four semiconductor slices as some of the samples used in the present work. The individual results are shown compared in Fig. 5.19, and the salient points of the characteristics are compared in Table 5.4.

The curves, with the exception of d) agree quite closely. In Tebbenham's results this sample showed significantly lower values of velocity than others with comparable carrier density and mobility, which may have been due to a contact causing current saturation. Therefore, perhaps, not too much importance should be attributed to this disagreement, particularly as the values of threshold field for this slice agree closely.

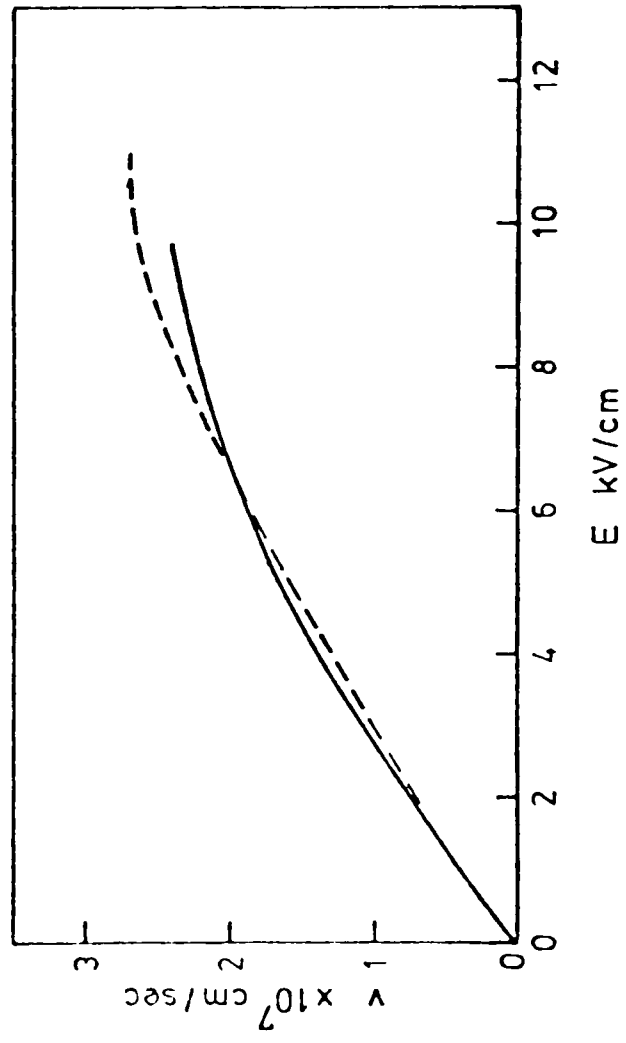


a) Slice CJ422

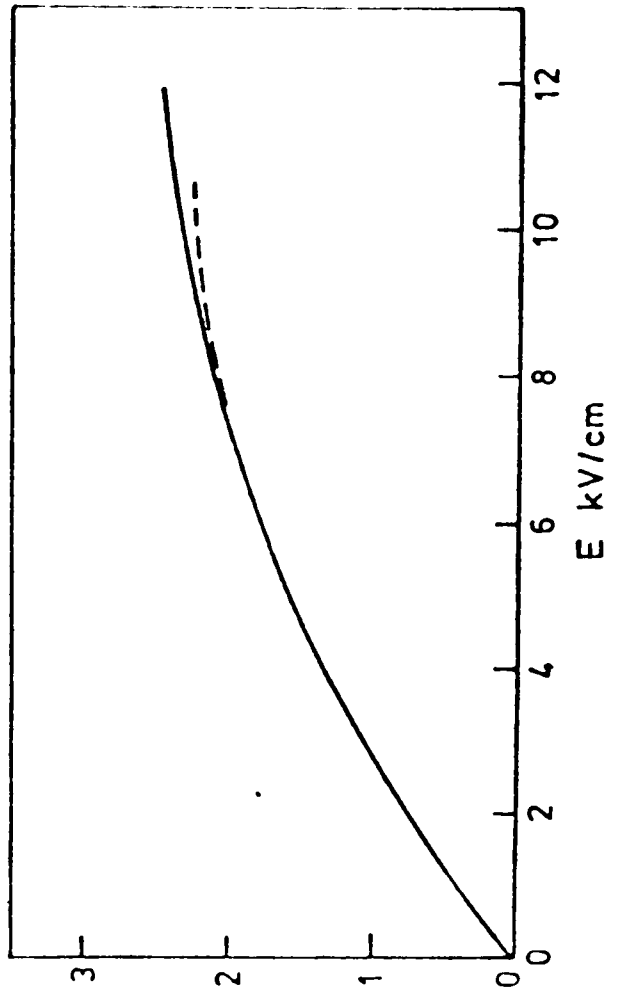


c) Slice CJ425

— This work
 ---- Tebbenham



b) Slice CJ424



d) Slice CJ462B

In all the curves the values of threshold field agree within 10% which, taking into account the quoted accuracy of the microwave measurements (15 %) and the accuracy of the present experiments, is satisfactory. It should be noted that in the microwave experiments the samples were at temperatures of 30 - 45 K above ambient, which would have the effect of increasing the measured threshold field and decreasing the measured threshold velocity by a few per cent.

Comparison of the overall threshold values gives

$$\text{this work } E_T = 10.7 \text{ kV/cm} \quad v_{DT} = 2.40 \times 10^7 \text{ cm/s}$$

$$\text{Tebbenham } E_T = 10.5 \text{ kV/cm} \quad v_{DT} = 2.44 \times 10^7 \text{ cm/s}$$

which obviously shows satisfactory agreement.

5.7.2 Comparison with theoretical calculations

Fig. 5.20 shows the experimental sub-threshold velocity-field characteristic compared with the calculated curves of the five sets of workers discussed in Chapter II (Table 2.1).

Clearly, agreement with the 3-level calculations (curves 1, 2, 5) is poor, the predicted values of both E_T and v_{DT} being lower than and outside the range of variation of the experimental results. On the other hand, the experimental curve agrees closely in shape with the 2-level calculations of James (curve 3), Fawcett and Herbert (curve 7), Maloney and Frey (curve 8), Hamaar and Vinter (curve 4), and also with curve 6 (Hamaar and Vinter) which is a 3-level calculation but with such strong $\Gamma - L$ coupling that the mechanism is effectively a 2-level one. The inference of the results, therefore, is that a 2-level mechanism is responsible for electron transfer in indium phosphide.

Whilst the shapes of these curves agree closely, their actual values differ somewhat. The most obvious point is the difference in low-field mobilities which they represent: the low field mobility of the theoretical curves is around $5000 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, which represents

particularly pure material (Chapter III), whereas that of the experimental curve is a little more than $4000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, a difference which would clearly lead to the experimental velocities being lower. Taking this into account, agreement with curves 3, 4 and 6 becomes closer.

The average measured threshold field (10.7 kV/cm) agrees very well with that predicted by Fawcett and Herbert from the calculation using unscreened pseudopotentials (10.5 kV/cm) and also with the prediction of Maloney and Frey (10 - 11 kV/cm); this is a little lower than that predicted by the other curves (11.5 - 12 kV/cm). The average threshold drift velocity ($2.5 \times 10^7 \text{ cm/s}$) also agrees most closely with these two calculations ($2.4 \times 10^7 \text{ cm/s}$ and $2.5 \times 10^7 \text{ cm/s}$ respectively).

5.7.3 Comparison with other measured characteristics

Fig. 5.21 shows the experimental sub-threshold characteristic compared with the measured characteristics of other workers. With the exception of the results of Kaul^[55] and Prew^[27] the shapes of the curves agree quite well; neglecting these the ranges of measured E_T and v_{DT} are:

$$9.5 \text{ kV/cm} < E_T < 13 \text{ kV/cm}$$

$$2.20 \times 10^7 \text{ cm/s} < v_{DT} < 2.90 \times 10^7 \text{ cm/s}$$

with the present results falling towards the lower bounds of these. The closest agreement is with the results of Nielsen^[43,44] and Tebbenham^[53] who both use measurements of d.c. conductivity in the presence of a microwave field.

Other workers using a direct measurement technique were Kaul^[55], Prew^[27] and Potter^[60]. Potter's value for threshold field agrees closely with the present work (10.5 kV/cm compared with 10.7 kV/cm), but his threshold velocity is somewhat higher ($2.90 \times 10^7 \text{ cm/s}$ compared with $2.44 \times 10^7 \text{ cm/s}$) for material with a similar low field

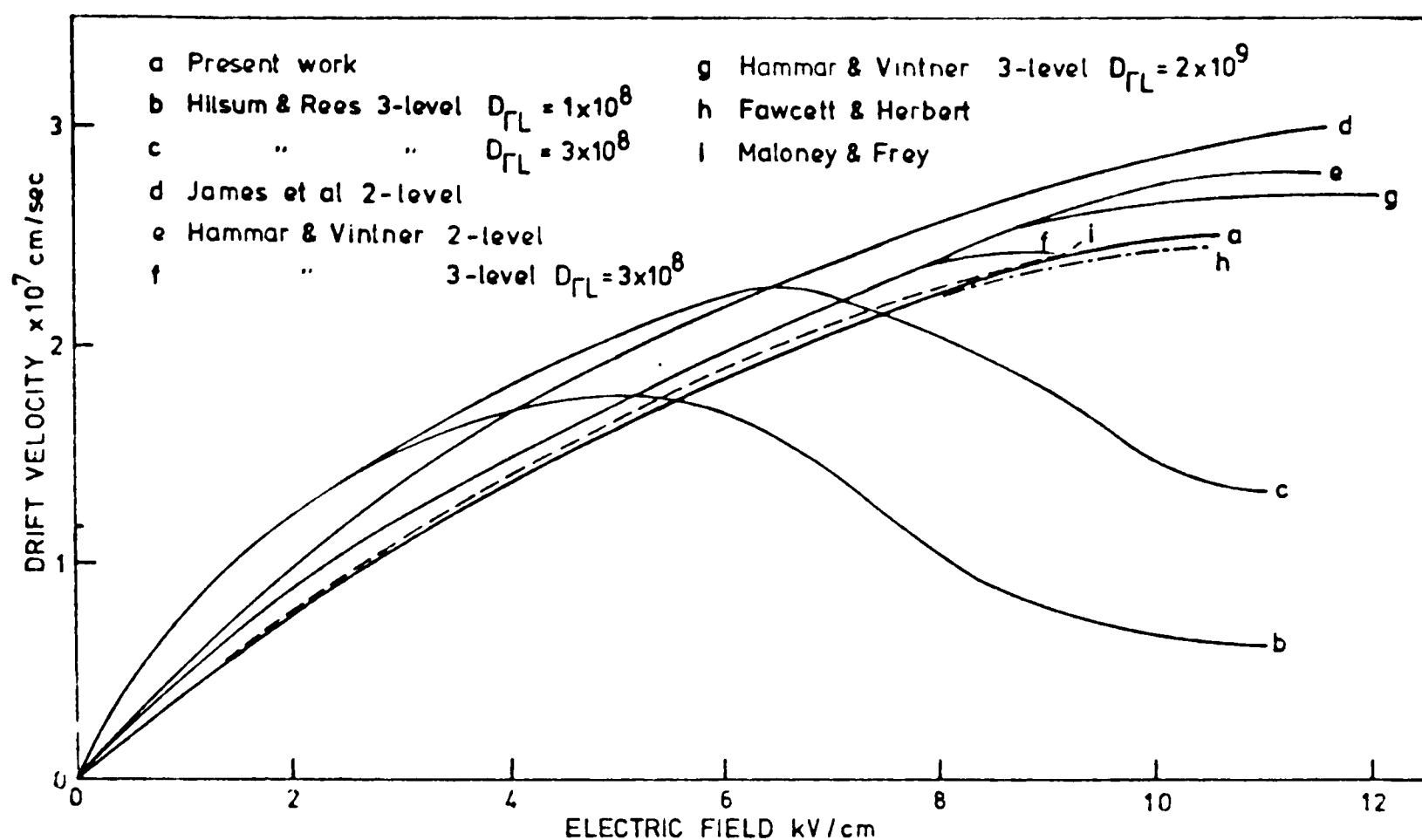


Fig. 5.20. Comparison of results with theoretical curves

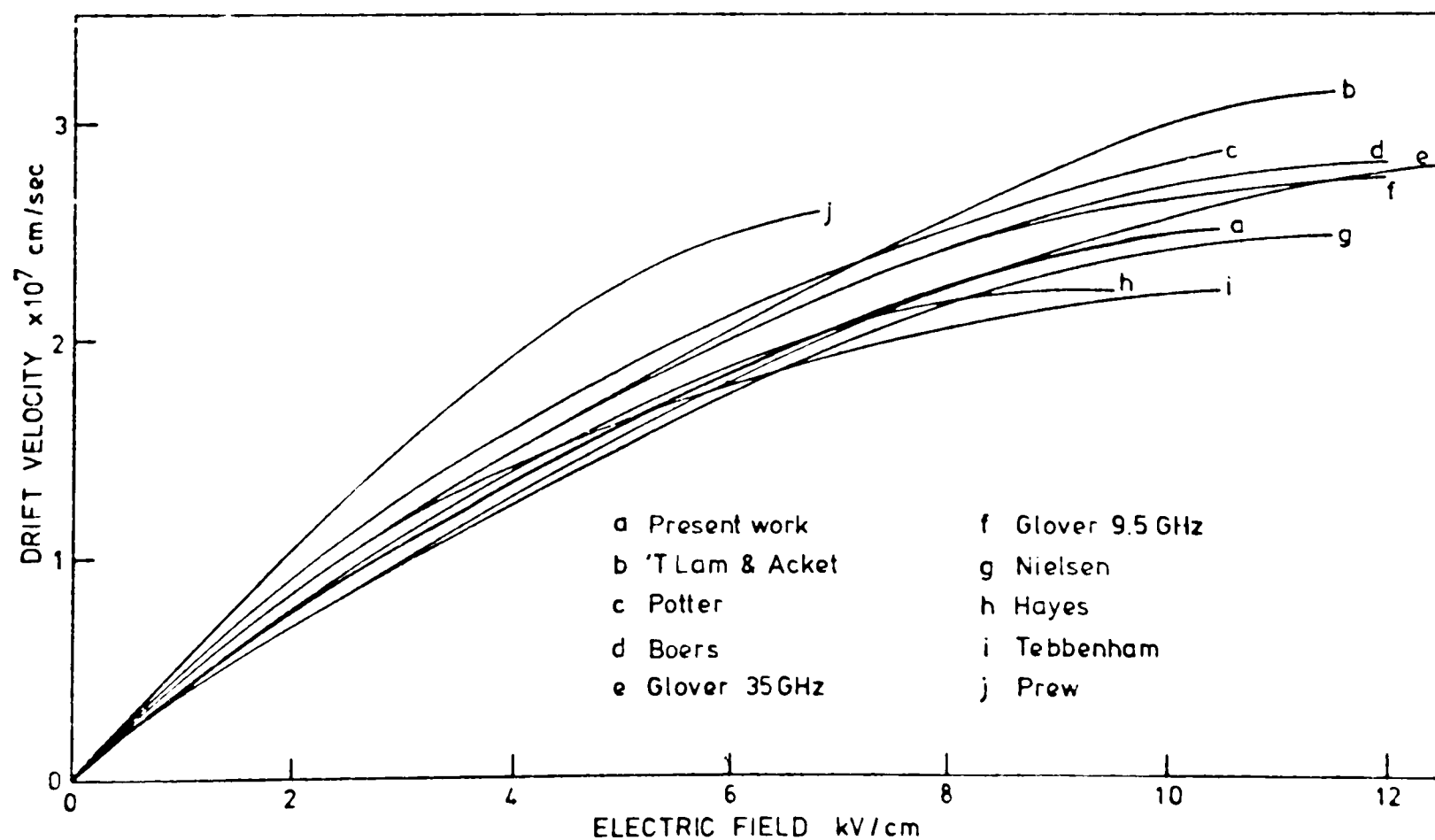


Fig. 5.21 Comparison with other experimental results

The results of Kaul ($E_T = 6.8$ kV/cm) and Prew ($E_T = 6.8$ kV/cm, $v_{DT} = 2.60 \times 10^7$ cm/s) differ very much from the others, but there seems to be no obvious explanation of this. It is perhaps significant that the same 'sculptured' shape of specimen was used here; it might be worthwhile performing further experiments on specimens of this shape and H-shaped specimens made simultaneously from the same semiconductor slice.

5.8 Sub-threshold velocity-field characteristic at 77 K

The results from four specimens, from three different semiconductor slices, are shown in Fig. 5.22, and the threshold values, together with the material data, are summarised in Table 5.5. Curves 1 - 3 show reasonable agreement, while curve 4 differs noticeably from them; the material of this specimen was clearly of poor quality, having a low field mobility at 77 K of only $17,100 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, which suggests a large amount of impurity scattering and means that the material is not typical of that which is normally of interest. A mean curve is therefore derived only from curves 1 - 3, and this gives for the threshold values

$$E_T = 6.92 \text{ kV/cm}$$

$$\text{standard deviation } 0.44 \text{ kV/cm (6.4\%)}$$

$$v_{DT} = 3.90 \times 10^7 \text{ cm/s}$$

$$\text{standard deviation } 0.34 \times 10^7 \text{ cm/s (8.7\%).}$$

5.9 Comparison with published low temperature data

Recently^[49] Maloney and Frey have calculated, by a Monte Carlo method, velocity-field characteristics at 77 K. Apart from these, the only available calculated low temperature characteristics are that of James et al.^[29], based on their 2-level model, for a minimum temperature of 150 K, and the calculations of Fawcett and Hill^[48]

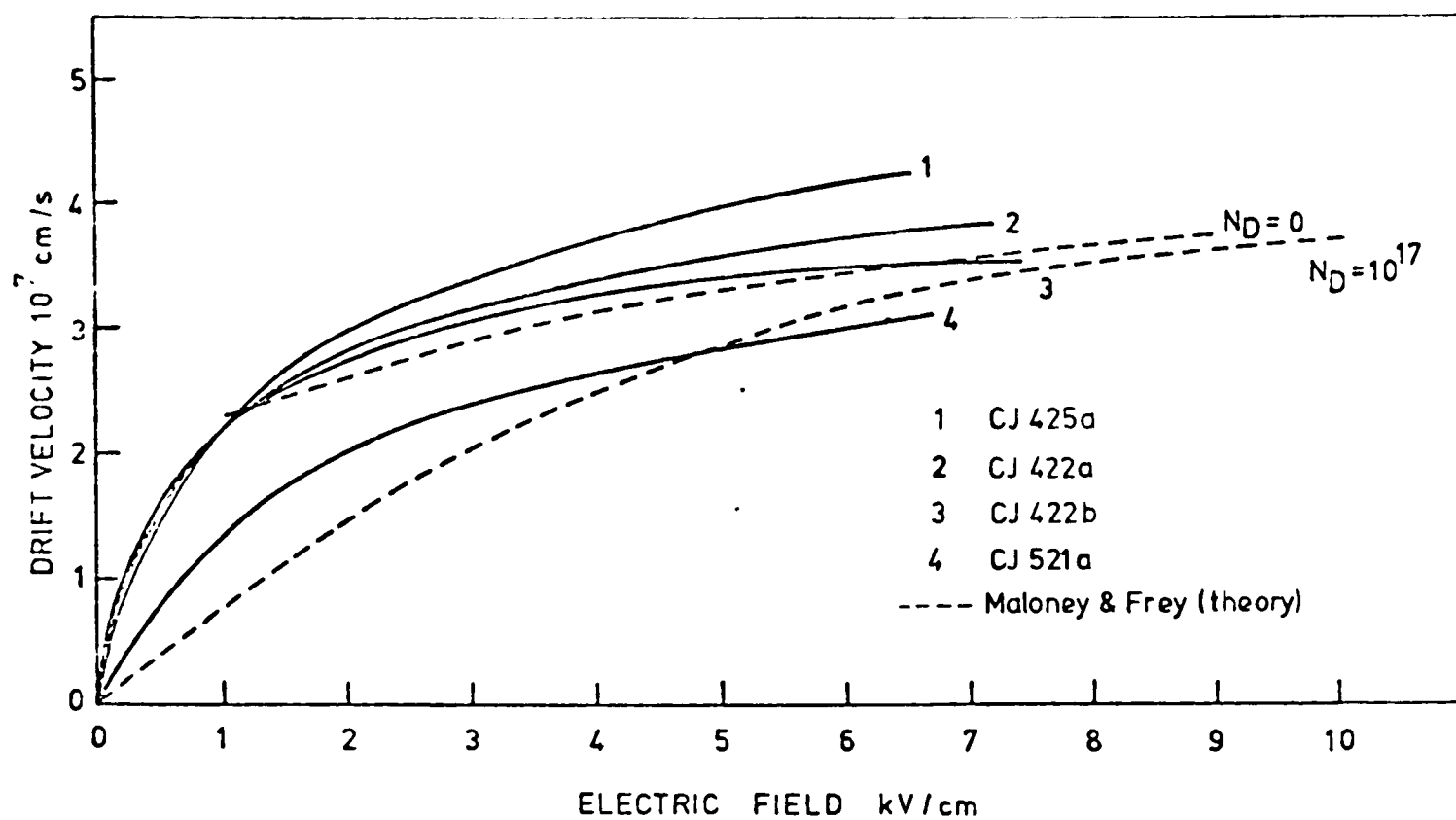


Fig. 5.22 Results at temperature of 77 K

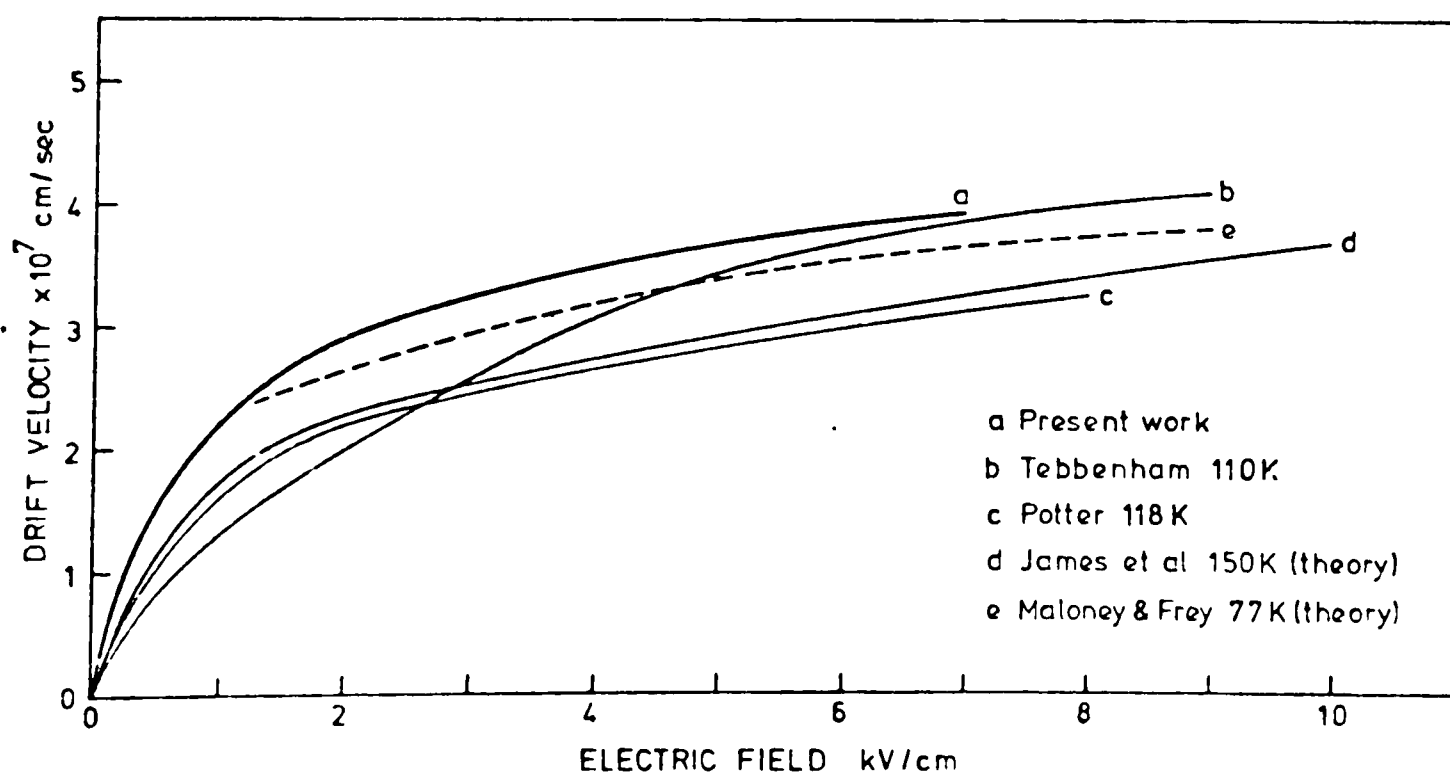


Fig 5 23. Comparison of sub-threshold low-temperature curves

which go down only to a temperature of 200 K. Experimental results have been produced by Parkes et al.^[83] from device performance data, Tebbenham^[53] from microwave measurements and Potter^[60] from direct measurements, none of these, however, being for a temperature as low as 77 K.

Parkes et al. measured a threshold field at 110 K of 7 kV/cm. The other results are shown compared with the present ones in Fig. 5.23; the shape of the measured characteristic agrees reasonably with curves 3 and 4, and quite well with curve 5, but the present results indicate a higher velocity. It must be remembered however, that with the exception of the calculation of Maloney and Frey, and particularly in the case of the calculation of James, the temperatures are quite different, and comparisons cannot be made too closely. Despite the differently shaped curve, the microwave results give a similar estimate for the threshold velocity, but a higher value for the threshold field.

The material used had a carrier density in the range $7 \times 10^{14} - 1.5 \times 10^{15} \text{ cm}^{-3}$, and therefore closer agreement would be expected with the calculated curve for $N_D = 0$ rather than with $N_D = 10^{17}$. It can be seen that this is in fact so, with the shapes of the curves agreeing well; the velocities agree closely, although the measured value of E_T (6.9 kV/cm) is somewhat lower than that predicted (9 kV/cm).

Potter^[60] performed a series of measurements over a temperature range of 446 K to 118 K; these results are shown in Fig. 5.24. Extrapolation to 77 K gives

$$E_T = 7.25 \text{ kV/cm}, v_{DT} = 3.45 \times 10^7 \text{ cm/s}.$$

Comparing the present results with these shows that agreement between the values of threshold field is good (4.6%), with a 12% discrepancy between the velocities. This extrapolation, at least for the threshold field, would seem to be justified from James' values for the

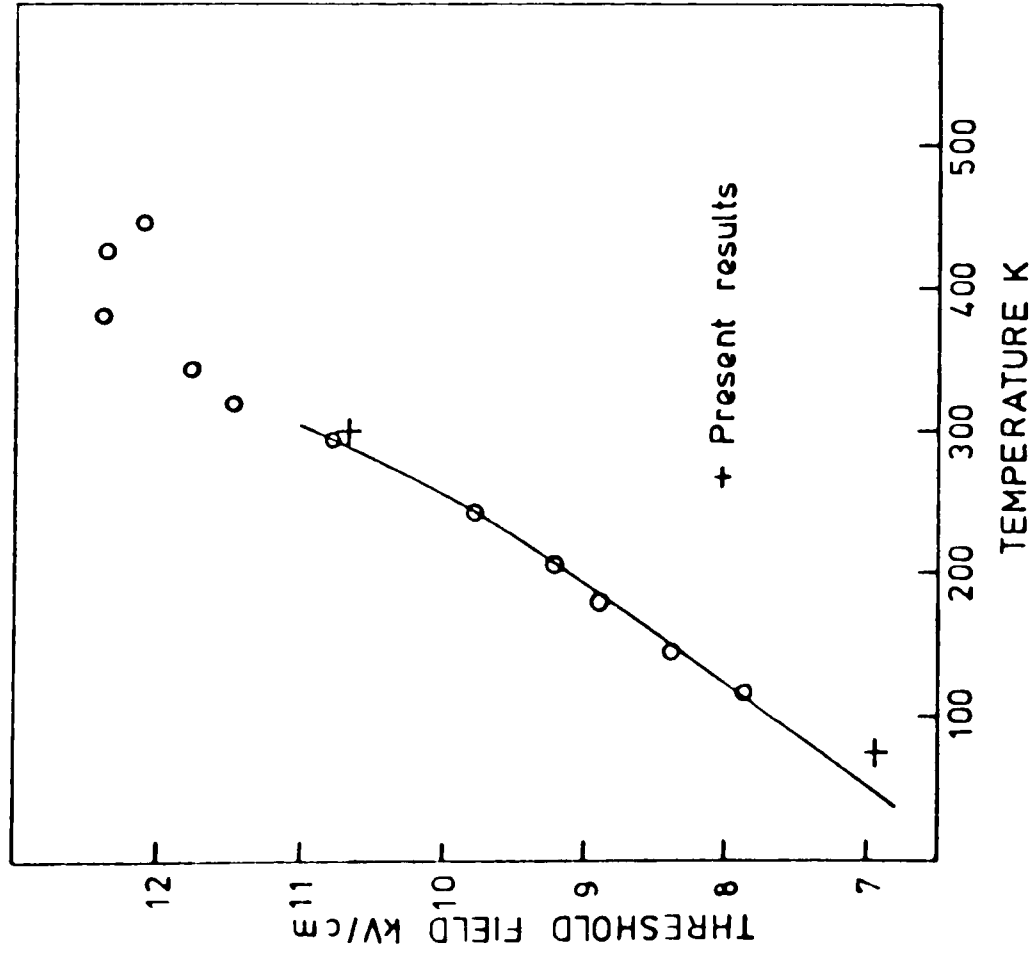


Fig. 5.24a. Temperature variation of threshold field (Potter)

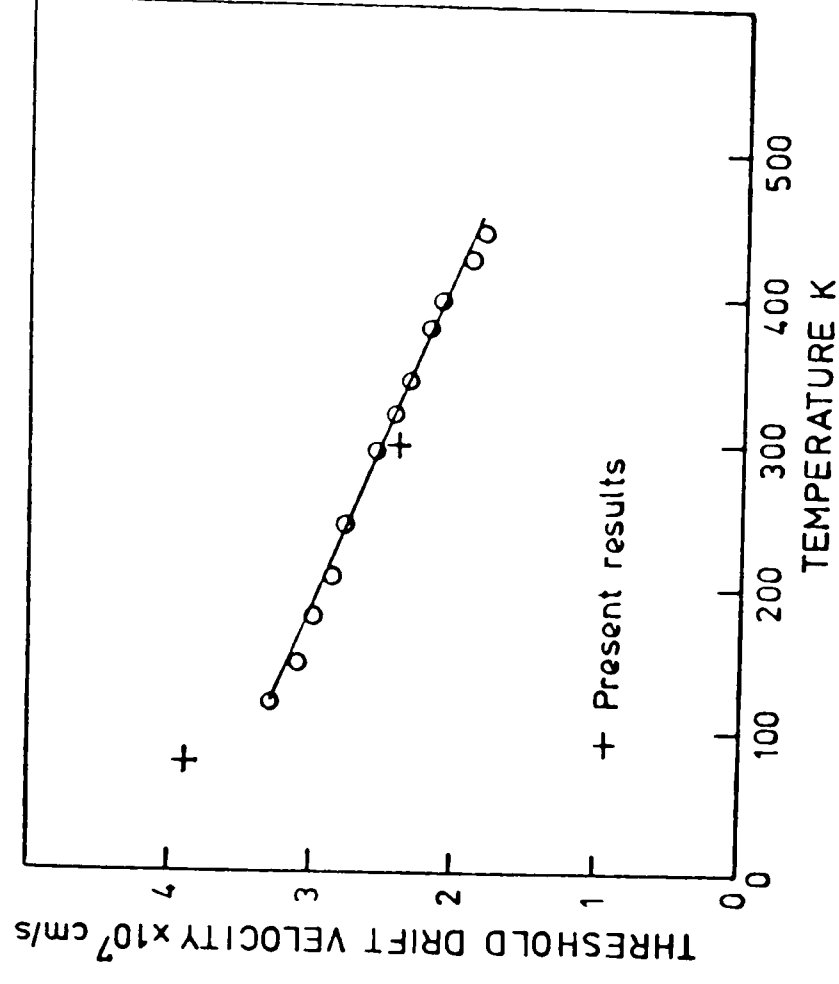


Fig. 5.24b. Temperature variation of threshold velocity (Potter)

upper and lower valley levels, which indicate that the separation between the minima continues to decrease to below 77 K.

In material with a low ionised impurity density, the low field mobility will continue to increase down to around 77 K (see Fig. 3.1) and so a difference such as that seen would be expected between the velocity-field characteristics at 110 K and 77 K, although according to the extrapolation from Potter's work, the difference should perhaps not be so great. A possible source of error here might be in the normalisation of the results to the low-field mobility; however, sufficient care was taken to ensure that an accurate V - I characteristic was measured at low voltages, and the error here should be small.

The calculated variations^[28,48,49] of threshold field and velocity with temperature are plotted in Figs. 5.25 and 5.26 respectively, along with all the experimental figures. The curves from^[29] and ^[48] are shown extrapolated to lower temperatures (curves 1, 2 and 3). The present results for E_T differ greatly from curve 1 (James) and to a lesser extent from curve 2, but appear to agree closely with the trend shown by curve 3, the unscreened pseudopotential calculation of Fawcett and Hill. There is less difference between the predicted variations of v_{DT} with temperature and Fig. 5.26 shows that agreement cannot be claimed for the 77 K result with the trend of one calculation rather than the others. However, the room temperature values of E_T (10.7 kV/cm) and v_{DT} (2.44×10^7 cm/s) have been seen to agree well with Fawcett and Hill's unscreened pseudopotential calculation (10.5 kV/cm, 2.40×10^7 cm/s) rather than with James (11.5 kV/cm, 3.0×10^7 cm/s), and hence the overall conclusion indicated is that the present results support the former.

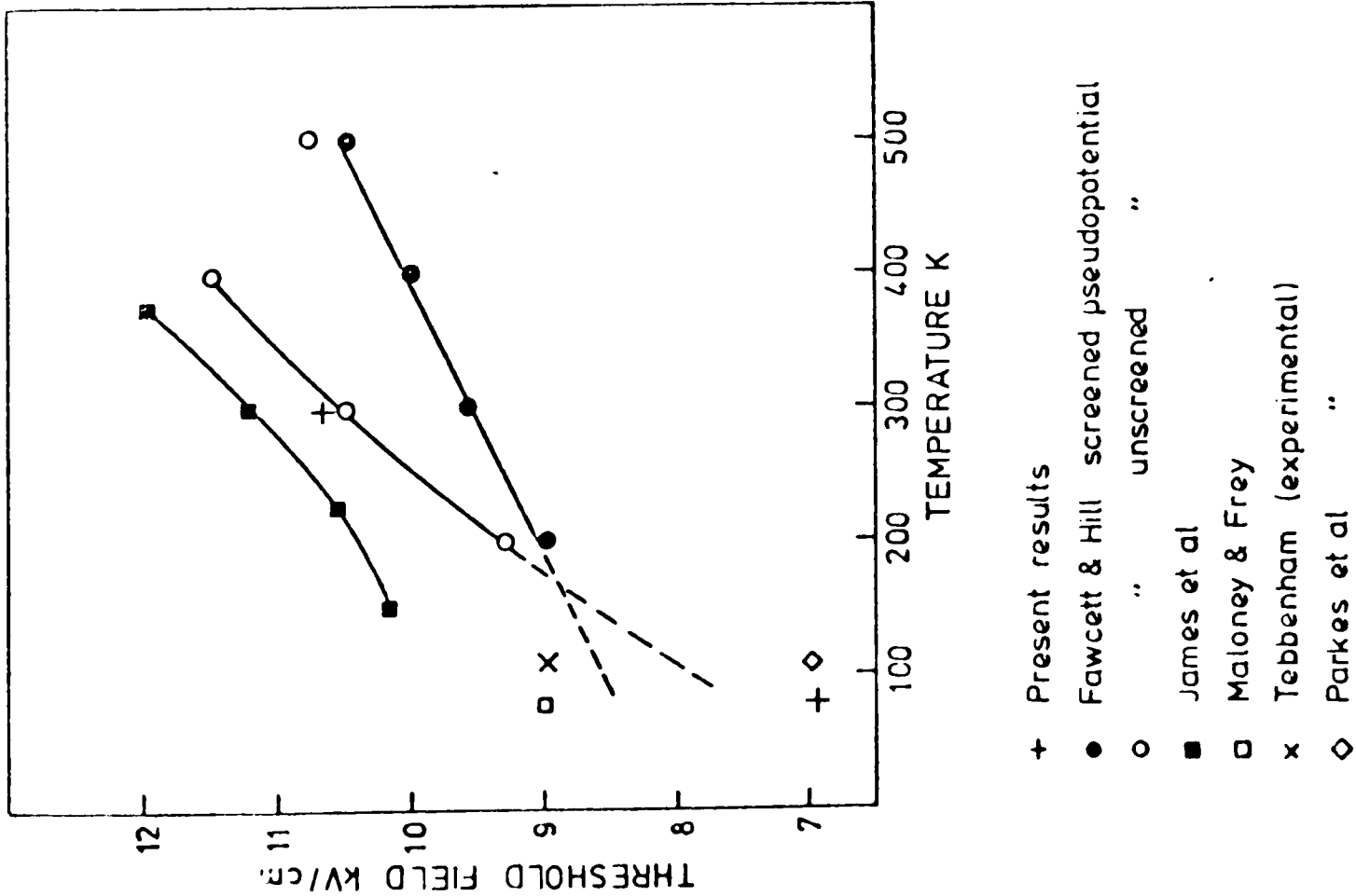
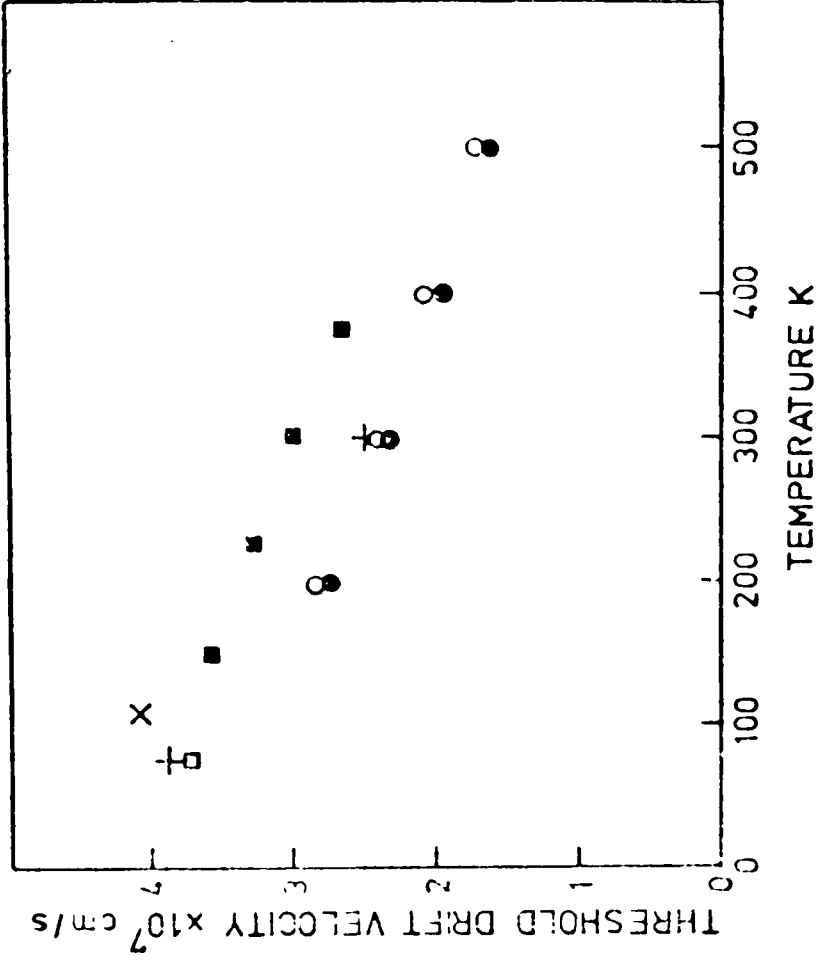


Fig 5.25. Temperature variation of threshold field



Symbols as in Fig. 5.25.

Fig 5.26. Temperature variation of threshold velocity

5.10 Substrate conduction

When current-voltage measurements are made on epitaxial slices etched so that the active regions are formed in mesa-structures from the epitaxial layer, the semi-insulating substrate appears in parallel with these regions. It was thus necessary to check the justification of the assumption that the effect of this could be neglected.

H-type specimens from the various slices were used, and the narrow bridge region was scratched away using a pointed tool, leaving just the contact pads. The resistance between these was measured using the low-field apparatus and was found at room temperature to be always of the order of 10^6 ohms, which was almost three orders of magnitude larger than that of any of the actual specimens.

5.11 Accuracy

The main sources of error in these experiments were

- 1) the calibration of the oscilloscope sampling unit and the pen recorder
- 2) the measurement of specimen length
- 3) the point contact probe
- 4) the measurement of low field mobility, used to normalise the drift velocity curve.

5.11.1 Field measurement

The probe and calculation methods of deriving the central field in the specimens always agreed within 5%. As the probe was calibrated against the applied voltage each time it was used, the accuracy here is limited by the oscilloscope/pen-recorder calibration ($\pm 2 - 3\%$) and the calibration of the potentiometer and micrometer used to measure distance. The potentiometer was quoted to be linear to within 1%, and any other error would be in the motion of the probe mounting: the probe was always moved in the forward direction to avoid backlash, and

the error here should be very small. The total error in the field measurement would therefore be around 7%.

5.11.2 Velocity measurement

The low field mobility Van der Pauw measurements were estimated to be accurate to 3%, and to this must be added the error in measuring the specimen current and field, as the slope of the E - I curve was normalised to the measured mobility. This makes the total error in velocity $\pm 12\%$.

The final results now become for the threshold values

$$\text{at } 300 \text{ K } E_T = 10.7 \pm 0.75 \text{ kV/cm}$$

$$v_{DT} = 2.40 \pm 0.29 \times 10^7 \text{ cm/s}$$

$$\text{at } 77 \text{ K } E_T = 6.92 \pm 0.48 \text{ kV/cm}$$

$$v_{DT} = 3.90 \pm 0.47 \times 10^7 \text{ cm/s.}$$

TABLE 5.1

Comparison of measured room temperature resistivities
and mobilities with manufacturer's values

Slice	Manufacturer		Measured	
	ρ (ohm cm)	μ_H (cm ² V ⁻¹ s ⁻¹)	ρ (ohm cm)	μ_H (cm ² V ⁻¹ s ⁻¹)
CJ 422	1.75	4720	1.69	4950
CJ 425	0.90	4600	0.87	4800
CJ 622	0.35	4500	0.34	4720
CJ 631	0.53	4830	0.57	4610
CJ 671	0.28	3800	0.26	3840

TABLE 5.2

Values of threshold field shown by bar-type specimens

Specimen	Length() (nominal)	n (cm^{-3})	μ ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)	E_T (kVcm^{-1})
422 05	500	7.5×10^{14}	4950	7.5
422 03	500	7.5×10^{14}	4950	6.7
425 01	500	1.5×10^{15}	4800	6.1
425 03	500	1.5×10^{15}	4800	7.4
425 04	500	1.5×10^{15}	4800	6.4
452 04	500	2.4×10^{15}	4280	5.8
422 08	1000	7.5×10^{14}	4950	7.8
424 05	1000	1.25×10^{15}	4680	6.4
425 60	1000	1.5×10^{15}	4800	7.4
462 03	1000	7.2×10^{14}	4450	8.4
462 04	1000	7.2×10^{14}	4450	8.3

Average value of E_T for 500 μ specimens = 6.7 kVcm^{-1}

Average value of E_T for 1000 μ specimens = 7.7 kVcm^{-1} .

TABLE 5.3

Details of specimens and low-field results

Specimen	Type	μ_H ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)	n (cm^{-3})	ρ (ohm cm)	d μ	E_T (kV/cm)	v_{DT} (cm/s)	mean E_T	mean v_{DT}
CJ 422.a	narrow	4950	7.5×10^{14}	1.75	19.5	11.6	2.95×10^7	10.97	2.60×10^7
CJ 422.b	narrow	4950	7.5×10^{14}	1.75	19.5	11.3	2.47×10^7		
CJ 422.c	wide	4950	7.5×10^{14}	1.75	19.5	10.0	2.37×10^7		
CJ 462'.a	narrow	4450	7.2×10^{14}	1.94	10	11.9	2.86×10^7	11.7	2.73×10^7
CJ 462.b	wide	4450	7.2×10^{14}	1.94	10	11.5	2.60×10^7		
CJ 425.a	narrow	4800	1.5×10^{15}	0.90	13	9.7	2.44×10^7		
CJ 521.a	narrow	4140	7.6×10^{15}	0.20	11	10.6	2.10×10^7	10.1	1.99×10^7
CJ 521.b	narrow	4140	7.6×10^{15}	0.20	11	9.6	1.88×10^7		
CJ 424.a	wide	4680	1.25×10^{15}	1.07	16	9.7	2.30×10^7		

TABLE 5.4

Comparison of threshold field and drift velocity measured by microwave method and in the present work

Slice	Present method		Microwave method	
	E_T (kv/cm)	v_{DT} (cm/s)	E_T (kV/cm)	v_{DT} (cm/s)
CJ 422	10.9	2.59×10^7	10.0	2.43×10^7
CJ 462B	11.7	2.72×10^7	10.6	2.22×10^7
CJ 424	9.7	2.31×10^7	10.9	2.56×10^7
CJ 425	9.7	2.42×10^7	9.5	1.97×10^7

TABLE 5.5

Values of threshold field and velocity measured at 77 K

Specimen	μ ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)	n (cm^{-3})	ρ (ohm cm)	E_T (kV/cm)	v_{DT} (cm/s)
CJ 422. b	55,400	7.1×10^{14}	0.16	7.15	3.88×10^7
CJ 422. a	55,400	7.1×10^{14}	0.16	7.41	3.57×10^7
CJ 425. a	48,000	1.4×10^{15}	0.093	6.45	4.26×10^7
CJ 521. a	17,100	5.5×10^{15}	0.066	6.67	3.31×10^7

CHAPTER VI

SURVEY OF PUBLISHED HIGH-FIELD DOMAIN RESULTS

6.1 High-field domains in indium phosphide

Contrary to the prediction of Hilsum and Rees^[35], in proposing the three-level transfer mechanism for indium phosphide, that the material would not sustain domain-mode oscillation, it has been established^[64,65,69] that in this respect indium phosphide behaves in a very similar way to gallium arsenide, producing high-field domains when biased above threshold field. Three sets of workers, Boers^[65], Prew^[27] and Robson et al.^[61] have measured field profiles in the high-field domains by probing techniques, Prew with a point-contact probe, and Boers and Robson with capacitive probes. The work by Robson includes a complete analysis of the probe-specimen system, and presents measured domain profiles corrected for the probe spatial and temporal response.

There are marked differences between the results, which seem to divide according to the type of probe used. Both capacitive probe results show asymmetrical triangular shaped domains at high domain voltages, with an accumulation layer markedly narrower than the depletion layer, as in gallium arsenide, whereas Prew's results measured with the point-contact probe show a wider, almost symmetrically shaped domain, with accumulation and depletion layers of comparable width. The measured domains in the latter case were approximately 50% wider than similar domains in gallium arsenide.

Only Robson gives detailed results, the other workers giving simply a domain profile. The domain voltages are sufficiently close however to enable some comparisons to be made.

6.2 Comparison of domain measurements

Results from all three workers are shown in Fig. 6.1, and the salient points of the domain shapes are summarised in Table 6.1.

The results can be compared, to a first approximation, by using the theory for a simple triangular domain discussed in Chapter I, which gives

$$w_D \propto \sqrt{\frac{V}{nr}} \quad (6.1)$$

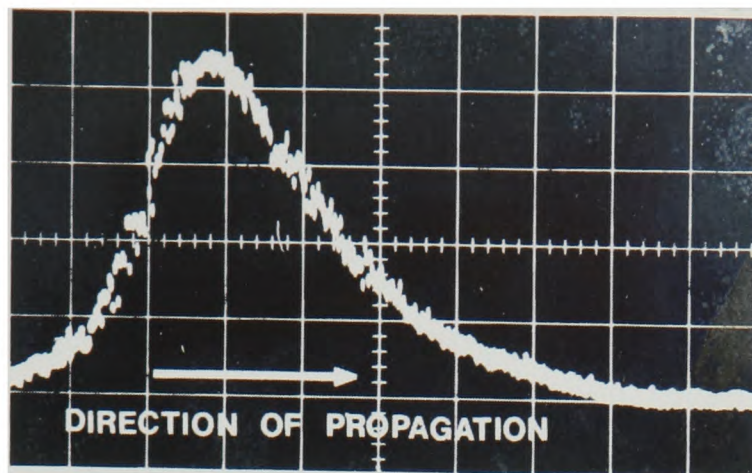
and also

$$E_m \propto \sqrt{nVr} \quad (6.2)$$

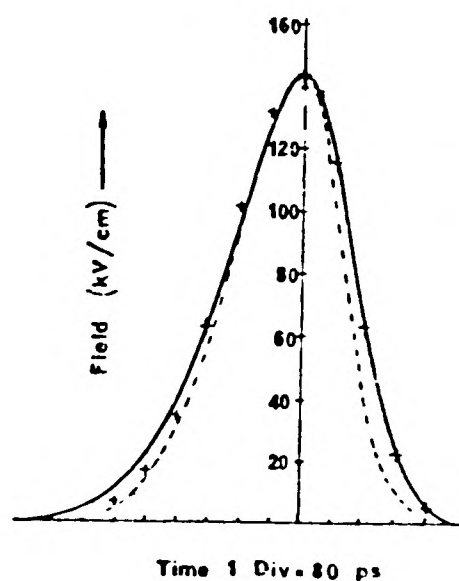
where w_D represents the width of the depletion region, r the depletion ratio, V the domain voltage and E_m the maximum domain field.

Now, the results of Robson are from material with a carrier density midway between the carrier densities of the materials used by the other workers, and an approximate comparison of the results, taking into account differences in domain voltage and carrier density may be made by normalising the other two sets of data to these, using equations (6.1) and (6.2). These results are shown in Table 6.2. The results of Boers and Robson agree well for depletion width, and less well for peak field, whereas Prew's results show a large discrepancy for both. No account has been taken of the variation of depletion, which increases with decreasing carrier density (Butcher, 23) and with increasing domain voltage (Robson, 61); this would, if taken into account, tend to reduce the differences between (1) and (2) whilst not having very much effect on (3).

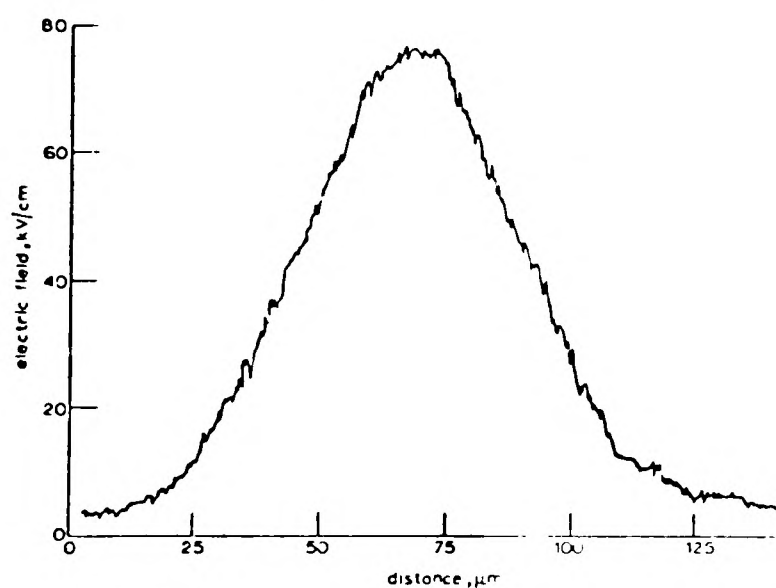
Discussion of the differences in domain shape ensued between Prew and Boers^[56,57]. Boers points out that a possible source of distortion in a point-contact probe would be the spreading resistance where the point touches the material, particularly as the resistivity of the material changes during the passage of a high-field



- (a) Boers^[67] $V_D = 380V$, $n = 1 \times 10^{15} \text{ cm}^{-3}$.
Horizontal scale: 10μ per division.
Vertical scale: 45 kV/cm per division.



- (b) Robson et al.^[94] $V_D = 392V$, $n = 8 \times 10^{14} \text{ cm}^{-3}$.
Horizontal scale equivalent to 6.4μ per division.
The domain is travelling to the left.



- (c) Prew^[64] $V_D = 325V$, $n = 6 \times 10^{14} \text{ cm}^{-3}$.
The domain is travelling to the left.

Fig. 6.1 Comparison of published domain shapes.

domain.

However it is obvious, and was indeed pointed out by Prew, that the effects of spreading resistance were unlikely to cause the observed differences. The spreading resistance modifies the response by interaction with the self capacitance of the probe tip, giving a high frequency response inversely proportional to the resistance, and a d.c. response which is modified by the additional series resistance. In the accumulation region of the high field domain the resistivity is smaller, which should therefore lead to a faster response, as well as a larger response due to the reduced series resistance. It is shown that this distortion would tend to accentuate asymmetry in the domain shape, which is contrary to the observations.

Velocity-field relations are deduced from these measurements using the method, based on the equal-areas rule, of Bastida et al.^[26], Prew and Robson using measured domain shapes to deduce peak domain fields, and Boers assuming domains with a constant 50% depletion. Measurements by Robson on material with $n = 8 \times 10^{14} \text{cm}^{-3}$ showed that the depletion ratio varied from 40% to 60% as domain voltage went from 230 V to 420 V, and was inversely proportional to domain voltage, indicating that this assumption was not entirely unjustified. The velocity-field relations have been shown in Fig. 6.2, where it is clear that the results of Boers and Robson agree with the calculated curves based on two-level theory, but Prew's results support the three-level theory of Hilsum and Rees.

6.3 Domain shapes

There is no obvious explanation to the difference between the domain shapes given in these results. The quoted resolution of both types of probe should have been adequate: Robson's capacitive probe was estimated to have a resolution of 10 - 20 μ , and Prew quoted the rise-time of his point-contact probe (point diameter 5 μ) as less than

200 ps, which assuming a domain velocity of 10^7 cm/s, gives a spatial resolution of around 20μ . However, to give an output proportional to domain field, the point-contact probe was fed into a differentiator, of which no description or performance details were given.

A possible way of clarifying the situation would be to repeat the experiments using a point-contact probe, using a probe and differentiator which have been carefully designed and characterised; this will be described in the next chapter.

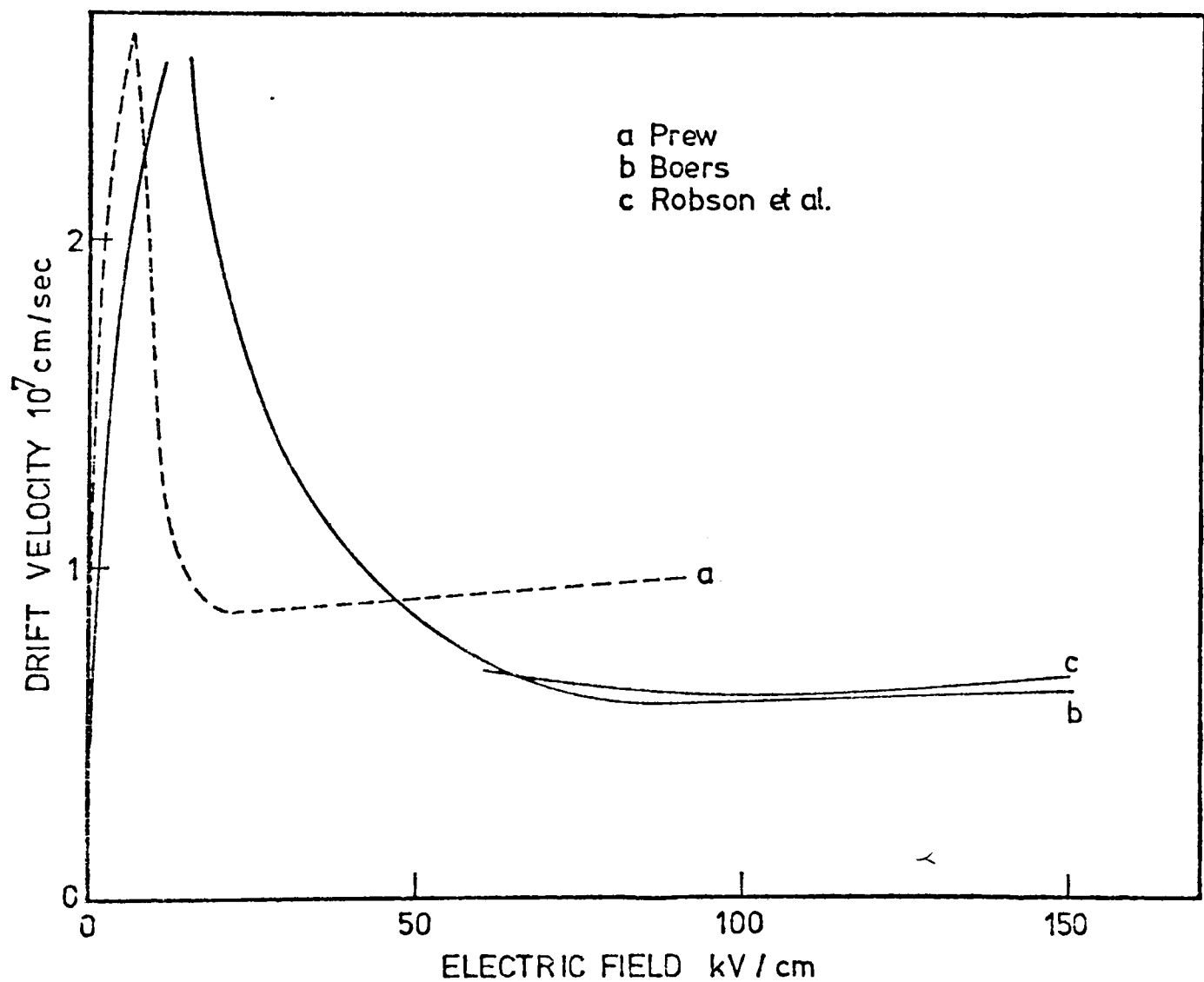


Fig. 6.2 Published velocity-field characteristics deduced from high-field domain data.

TABLE 6.1

COMPARISON OF SALIENT FEATURES OF PREVIOUS DOMAIN MEASUREMENTS

Worker	Material carrier density, n (cm^{-3})	Domain voltage (V)	Domain depletion width (μ)	Domain peak field (kV/cm)
Boers	1×10^{15}	380	50	193
Robson	8×10^{14}	392	58	140
Prew	6×10^{14}	325	75	80

TABLE 6.2

NORMALISED COMPARISON OF MAIN FEATURES OF DOMAIN MEASUREMENTS

Worker	True domain voltage (V)	Normalised depletion width (μ)	Normalised domain peak field (kV/cm)
Robson	392	58	145
Boers	380	57	172
Prew	325	75	101

CHAPTER VII

DEVELOPMENT OF POINT-CONTACT PROBE FOR HIGH-FIELD DOMAIN

MEASUREMENTS

7.1 Basic requirements for probe

The specification for a probe used for observing dynamic effects will be much more stringent than that for the probe used for the static measurements: as well as very fine spatial resolution a very fast, but well-damped, transient response is required. In order to determine accurately the high-field domain shape the probe has to give a measure of the electric field distribution along the specimen.

An estimate of the values of the probe parameters can be obtained by considering material with a carrier density of $1.5 \times 10^{15} \text{ cm}^{-3}$ with a 100 V high-field domain which, assuming it to be fully depleted, has a width of 27 microns. If this disturbance travels at 10^7 cm/s (a reasonable figure for indium phosphide, though rather high for gallium arsenide), it will take 270 ps to pass the probe.

Two types of probe, capacitive^[15,16] and point-contact^[31,27] have been used for high-field domain observations; a comparison of their most important features follows.

7.2 Capacitive probe

The coupling to the specimen is through a small capacitance, and when the probe output is fed into a 50 ohm circuit the signal is differentiated with respect to time. When a uniformly propagating disturbance is being measured, this corresponds to a differentiation of the potential distribution with respect to distance along the specimen, with the result that the observed output is proportional to electric field.

For good spatial resolution the probe must be in intimate contact with the specimen but with a very thin (of the order of 10 microns thickness) dielectric layer in between, and to maintain close contact pressure must be applied to the probe, possibly fracturing epitaxial specimens. The insulating layer, however, may reduce the possibility of specimen surface damage caused by moving the probe.

If the capacitance element is formed by the thin line of a metal edge it is essential for optimum resolution that this line be accurately at right-angles to the length of the specimen. The thin capacitance element must be supported and screened on both sides by earthed metal cheeks which will present a significant capacitance to the specimen, possibly modifying the field distribution there and causing a distorted domain shape to be measured.

7.3 Point-contact probe

If the probe consists of a metal point in contact with the specimen, fed through a high resistance to limit the current drawn from the specimen into a 50 ohm circuit, the potential distribution is measured. To obtain the field distribution a differentiating circuit must be included.

As the only part of the probe in contact with the specimen is its fine point the risk of specimen breakage is less, and as long as the point is not too hard there should be minimal surface damage. The spatial resolution is determined by the point size and the temporal response of the system - there are no problems of alignment.

Because the junction between probe point and semiconductor forms a Schottky barrier which must be forward biased for current to flow, the bias applied to the specimen must always be negative. This junction, with its associated resistance, forms part of the signal path in the probe and may modify the response.

7.4 Preliminary experiments

For preliminary experiments a capacitive probe, having a total width (insulation - capacitance element - insulation) of between 15 and 20 microns was constructed. High-field domains were resolved in both gallium arsenide and indium phosphide specimens, but the disadvantages mentioned were apparent - specimens were frequently broken and the resolution was suspect owing to difficulties of alignment.

Of the published results, the difference between those of Prew and the others suggests that the type or design of probe may have been responsible. It seemed worthwhile, therefore, to attempt to repeat these measurements using a point-contact probe system, each part of which was as thoroughly tested and characterised as possible.

Just recognisable domain measurements were obtained with the point-contact probe used for the static measurements, poor resolution being due to the probe's slow risetime. A modified version, with different resistor values and a much shorter tip, gave improved results, but the response could not be made fast enough; a new approach was needed.

7.5 Development of point-contact probe design

The design criteria for the probe were:

- 1) A tip with as small a self-capacitance as possible
- 2) A high resistance
- 3) A fast well-damped response.

The self-capacitance of the tip has to be charged from the specimen via any spreading resistance where it touches the semiconductor, and must therefore be very small to minimise the disturbance to the charge distribution in the specimen, and also to minimise any attenuation, caused by the spreading resistance, of high frequency components of the signal from the specimen. The probe resistance has

to be high to ensure that it draws as small a current as possible. Typical specimen resistances were of the order of 500 - 1000 ohms, and a minimum probe resistance of 10 kilohms was considered reasonable. Because the probe was to be fed into a differentiating circuit, it was essential that the transient response showed a minimum of overshoot or 'ringing' which, after differentiation, would lead to a very confused signal.

Thim and Barber^[31] described a potential probe constructed from two 5 kilohm resistors mounted above a ground plane, forming a 'lossy transmission line', and connected directly into a 50 ohm line. (Fig. 7.1). The bandwidth of this probe was about 5 GHz, and the results from it show high field domains in 2.5 ohm cm gallium arsenide passing in about 350 ps. The high frequency response depended on the spreading resistance of the point on the specimen, and hence on the specimen resistivity; this could be compensated by varying the amount by which the shielding of the coaxial line overlapped the adjacent resistor.

Based on this, a probe of 'open' construction and using two $1/4$ W solid carbon resistors was tested initially by applying a step of risetime about 200 ps to its point (Fig. 7.2). Under these conditions optimum results were obtained with 1.5 kilohm and 15 kilohm resistors at the top and bottom respectively, the top resistor being completely enclosed in a screen made from the body of a subminiature coaxial connector. Feeding into a sampling oscilloscope with a bandwidth of 18 GHz, this showed promise, resolving the potential distribution of a high field domain in 0.8 ohm cm gallium arsenide, but the fixed compensation provided by the screen over the top resistor was unlikely to be ideal in the presence of additional high frequency loss due to the point capacitance and spreading resistance. A second version was constructed where the capacitance from this resistor to ground was provided by an adjustable plate near it.

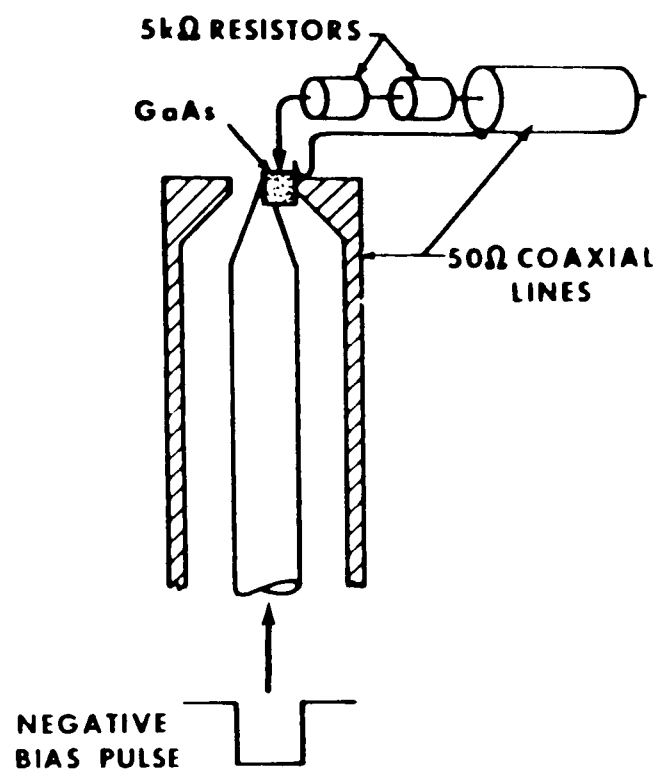


Fig.7.1. Point-contact probe of Thim and Barber.

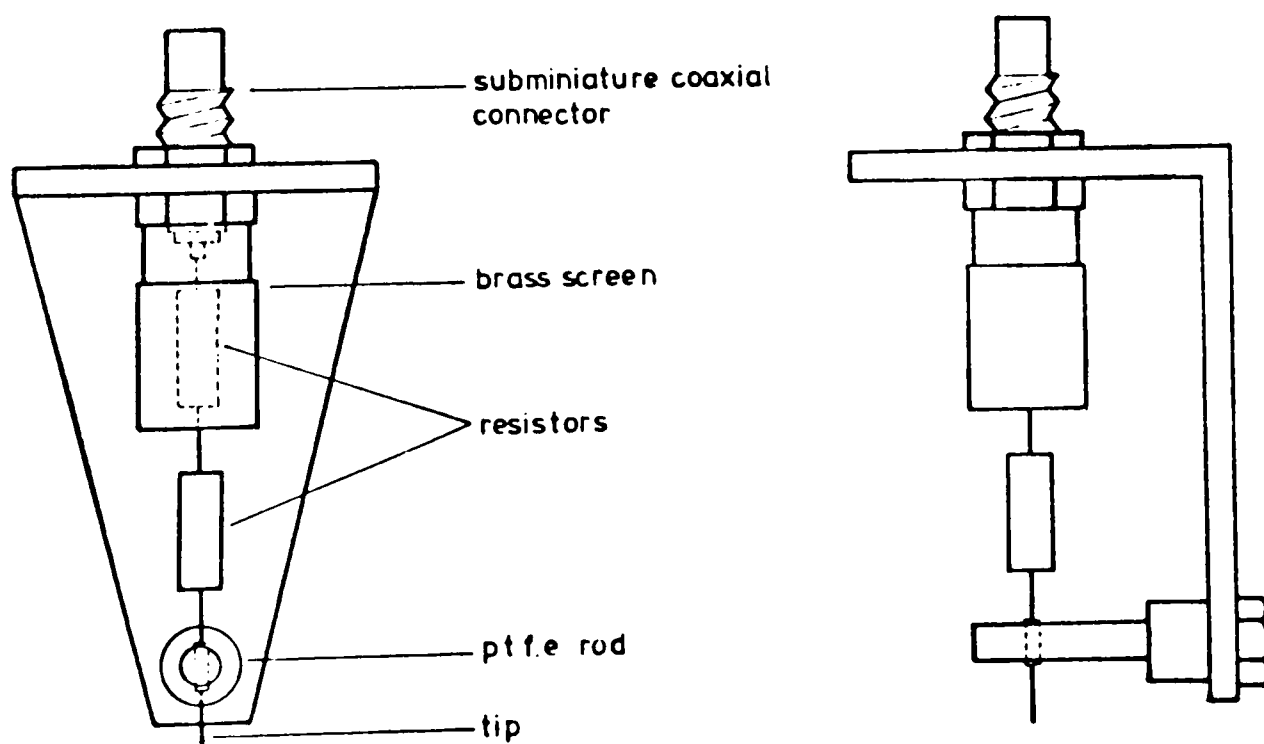


Fig. 7.2. Point-contact probe: first design.

However, with both versions, when a differentiator (see section 7.7) was included between the probe and oscilloscope the accumulation edge of the high field domain showed very severe ringing at around 5 GHz which could not be moderated by adjustment of the probe. Clearly, as had been predicted, differentiation was imposing stricter limits on the probe performance.

7.6 Point contact probe - final design

The logical development was to attempt to make the probe smaller: the two resistor design was about 2.5 cm long, which is a quarter wavelength in free space at 3 GHz, well within the passband of the measuring system. If the probe was made small compared with a quarter wavelength at, say 10 GHz, it could justifiably be regarded as a lumped circuit element. The effective bandwidth of the measuring system was limited to approximately 10 GHz by the line to the oscilloscope; this is considered in more detail later.

A single $\frac{1}{8}$ W solid carbon resistor (which was 4 mm long) was used. The probe was constructed around a subminiature panel - mounting coaxial socket, whose centre spigot had been filed almost flush with the p.t.f.e. insulation, and had a new 0.6 mm hole drilled in it to accept the resistor wire, which was cut so short that the resistor body fitted closely up to the spigot. The wire at the other end of the resistor was also cut off very short (about 1mm) and had a fine nickel wire soldered directly to it (Fig. 7.3). Experiment showed that making these resistor wires as short as possible was crucial in reducing ringing. A screen for the resistor was again made from the body of a subminiature coaxial connector with its inside threaded to accept an insert having a hole closely fitting the resistor, and which could be screwed up and down to be positioned anywhere along it. The probe was mounted above the copper specimen table, and a phosphor bronze leaf spring attached to the table was arranged to make an earth

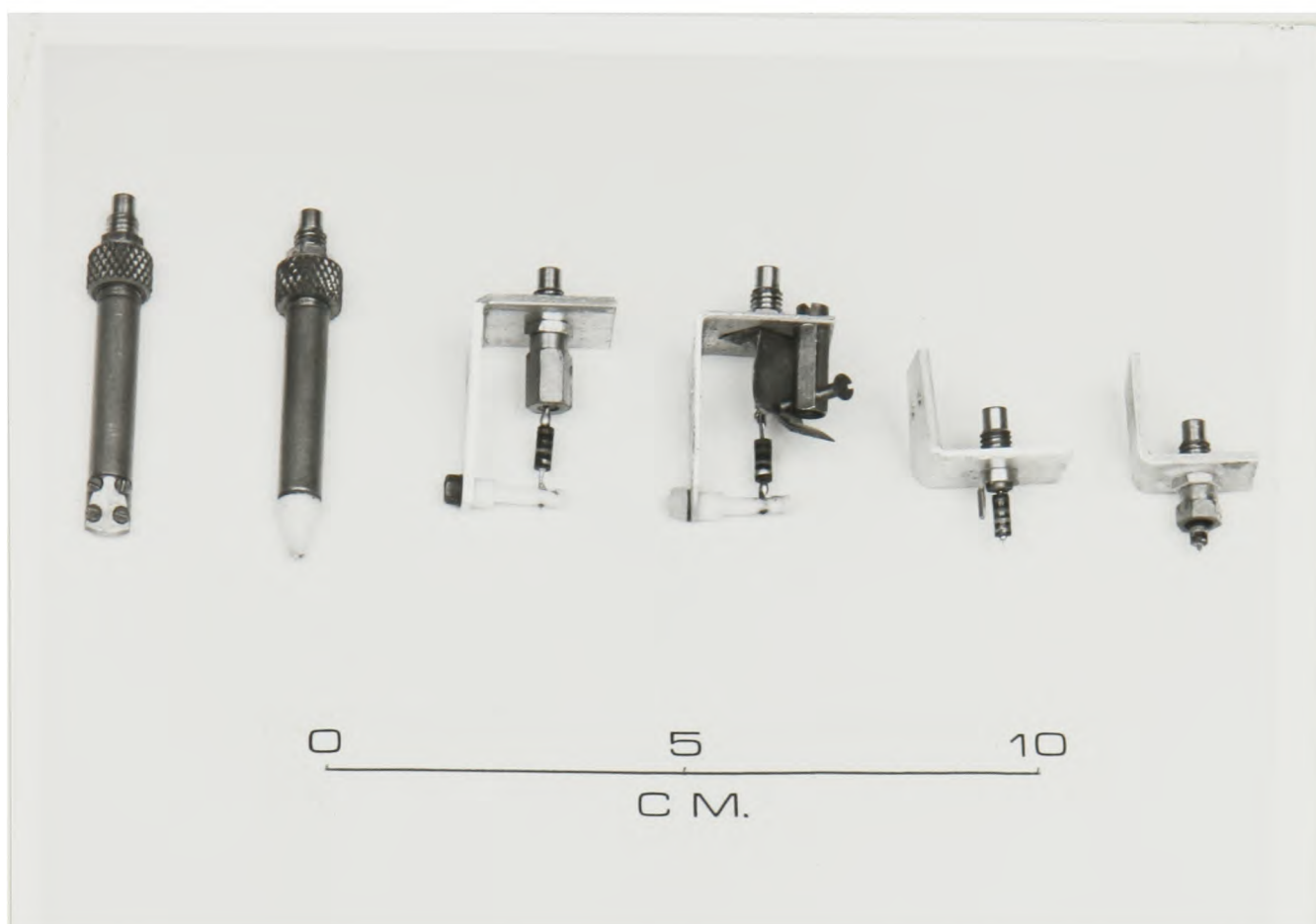


Fig. 7.3a Different probes constructed during the course of the work, being, from left to right,

- 1) Capacitive probe,
- 2) Point-contact probe used for sub-threshold measurements,
- 3) Point-contact probe with two resistors with fixed response,
- 4) Point-contact probe with two resistors with adjustable response,
- 5) } Final versions of point-contact probe using a
- 6) } single resistor.

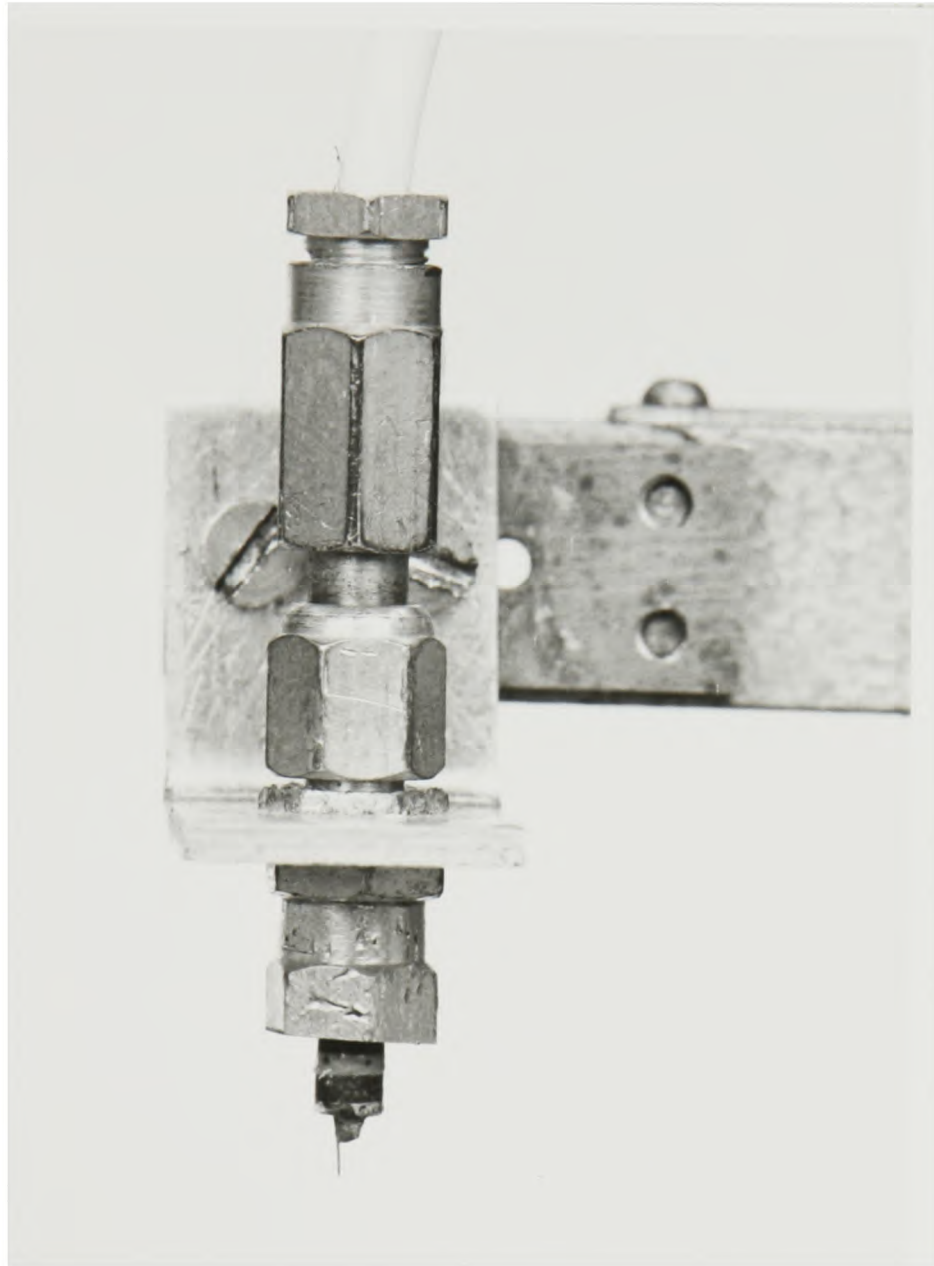


Fig. 7.3b Final version of point-contact probe.

connection to the probe body.

Again using a high-field domain in 0.8 ohm cm gallium arsenide specimens as a test signal, this design performed well, resolving a domain width of around 300 ps which agreed well with theoretical predictions. Without the compensating insert the response to the domain showed a single small overshoot with no oscillations, presumably caused by the end-to-end capacitance of the resistor. Adjustment of the insert removed the overshoot.

A final version was constructed using a $\frac{1}{4}$ W resistor which was approximately 6 mm long and should therefore have less end-to-end capacitance. Without compensation the overshoot was indeed significantly less, and could be compensated by a thinner insert. This design was used for the measurements as it was found to be easier to set up and adjust to give reproducible results.

The nickel point on the resistor was made as short as possible (1 - 2 mm). An advantage of the accessibility of the point was that the electrolytic etching (section 5.3.5) could be performed with the probe in situ, a wire simply being clipped on to the resistor end, very much reducing the possibility of damage to the tip. Otherwise the electrolytic etching was carried out in the same way as previously. Any traces of sodium hydroxide remaining after etching tended to increase the resistance between the tip and the specimen; to remove these, after etching, the tip was dipped briefly in dilute sulphuric acid and then washed in clean water. This usually left the tip completely uncontaminated.

7.7 Differentiating circuit

A differentiating circuit had to be incorporated in the 50 ohm line between the probe and the oscilloscope input. Lumped element circuit theory suggested inserting either a shunt inductor or a series capacitor in the line.

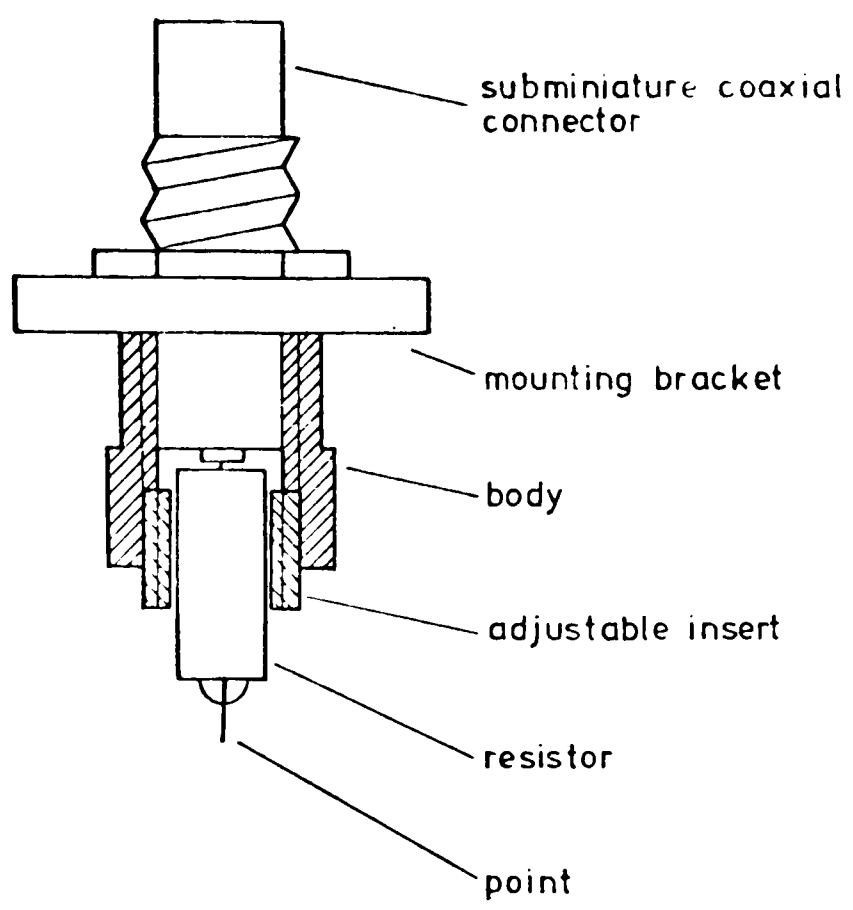


Fig.7.4. Final design of high-field probe.

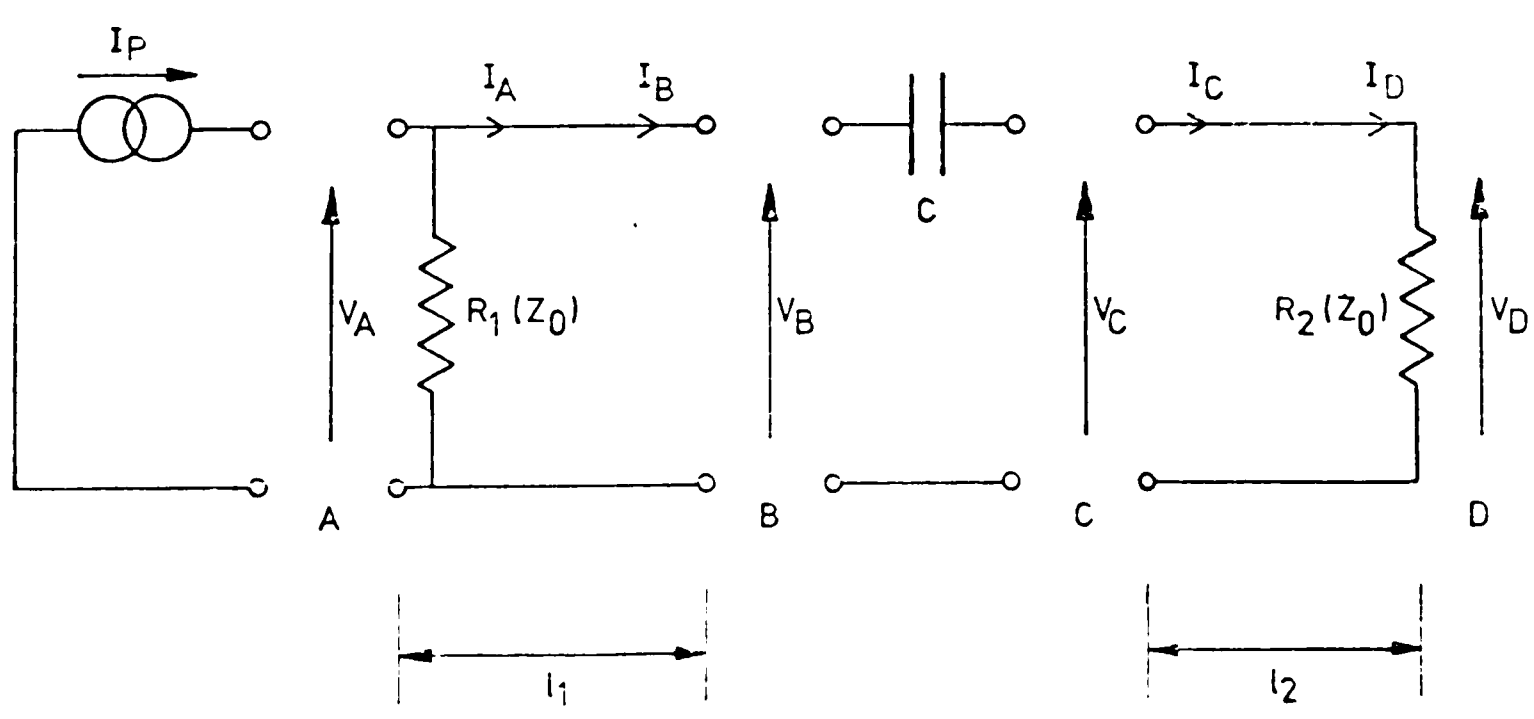


Fig 75 Equivalent circuit of probe and differentiator

A shunt inductor was thought at first to be the easier to engineer, as probably the only way to realise a suitably small inductance would be simply to put a conductor across the line. Let r (typically 1 mm) be the radius of this conductor. At 1 GHz, the skin depth (δ) in copper is 2×10^{-3} mm, and it is known^[86] that for values of r/δ greater than about 10, the impedance of such a conductor becomes

$$\frac{f\mu}{4\pi r^2\sigma} (1 + j) \text{ ohms/m}$$

which has equal inductive and resistive parts. The values quoted make r/δ equal to 500, and clearly therefore such an arrangement would be a poor approximation to an inductor. On the other hand a small series capacitor can be realised very easily and effectively by making a break in the centre conductor of the coaxial line.

The circuit of the system is shown in Fig. 7.5. The probe itself, comprising the physically small high resistance, is represented by current generator I_p , and is terminated in a 50 ohm load R_1 . AB and CD represent sections of 50 ohm coaxial line (assumed lossless), BC represents the capacitor and R_2 represents the 50 ohm input resistance of the sampling oscilloscope. The resistance R_1 is necessary to terminate line AB, so that the reflected wave from the discontinuity in BC is not re-reflected at A.

Writing in matrix form the equations for the voltages and currents defined in Fig. 7.5 gives:

$$\begin{bmatrix} V_A \\ I_A \end{bmatrix} = \begin{bmatrix} \cos\beta\ell_1 & jZ_0\sin\beta\ell_1 \\ j\frac{\sin\beta\ell_1}{Z_0} & \cos\beta\ell_1 \end{bmatrix} \begin{bmatrix} V_B \\ I_B \end{bmatrix}$$

$$\begin{bmatrix} V_B \\ I_B \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{sC} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_C \\ I_C \end{bmatrix}$$

$$\begin{bmatrix} V_C \\ I_C \end{bmatrix} = \begin{bmatrix} \cos\beta\ell_2 & jZ_0\sin\beta\ell_2 \\ j\frac{\sin\beta\ell_2}{Z_0} & \cos\beta\ell_2 \end{bmatrix} \begin{bmatrix} V_D \\ I_D \end{bmatrix}$$

Combining these and noting that $I_D = \frac{V_D}{Z_0}$,

$$V_A = \left[e^{j\beta(\ell_1 + \ell_2)} + \frac{1}{sCZ_0} \cos\beta\ell_1 e^{j\beta\ell_2} \right] V_D \quad 7.7.1$$

$$I_A = \frac{1}{Z_0} \left[e^{j\beta(\ell_1 + \ell_2)} + \frac{j}{sCZ_0} \sin\beta\ell_1 e^{j\beta\ell_2} \right] V_D \quad 7.7.2$$

$$\text{Now, } I_p = I_A + \frac{V_A}{Z_0} \quad 7.7.3$$

$$= e^{j\beta(\ell_1 + \ell_2)} \left(2 + \frac{1}{sCZ_0} \right) V_D \quad 7.7.4$$

Because the probe resistance R_p is much larger than Z_0 ($= R_0$),

$$V_p = I_p R_p$$

Hence,

$$V_D = e^{-j\beta(\ell_1 + \ell_2)} \cdot \frac{R_0}{2R_p} \cdot \frac{2sCR_0}{1 + 2sCR_0} \cdot V_p \quad 7.7.5$$

which indicates that as long as $2\omega CR_0 \ll 1$, where ω is the signal frequency, the voltage measured by the oscilloscope will be a delayed, attenuated differentiated version of the voltage at the probe tip.

This calculation assumed that the line is perfectly terminated at A where it joins the probe. The only way this could be done with a standard 50 ohm termination (a feed-through type not being available) was by putting a T-adaptor on the probe and connecting the line and termination to the two arms. This gave distorted signals due to the lengths between the probe and T and the T and termination having a

significant transit time. The simplest solution was to omit the termination and feed the probe directly into the line.

In this case, equation 7.7.3 becomes

$$I_p = I_A = \frac{V_P}{R_p},$$

and so from 7.7.2,

$$I_p = e^{j\beta(\ell_1 + \ell_2)} \frac{1}{R_0} \left[1 + \frac{1}{2sCR_0} (1 - e^{-2j\beta\ell_1}) \right] V_D$$

The term $e^{-2j\beta\ell_1}$ indicates a reflected wave which will arrive at D twice the transit time of AB later than the direct wave. If AB is made long enough, this reflected signal will not interfere with the direct signal, which can be written

$$V_D = e^{-j\beta(\ell_1 + \ell_2)} \cdot \frac{R_0}{R_p} \cdot \frac{2sCR_0}{1 + 2sCR_0} \cdot V_p \quad 7.7.6$$

and is exactly twice the value given in equation 7.7.5. The shunt inductance differentiator can be analysed in an exactly similar way.

7.8 Construction of differentiator

Using the criterion derived in the previous section for correct operation of the differentiation, let

$$2\omega CR_0 = 1 \text{ at } 10 \text{ GHz,}$$

which gives a value of 0.1 pF for C.

The differentiator was constructed from two type N panel-mounting sockets by filing their centre spigots almost down to the insulation, and mounting them in a short brass tube so that the centre spigots were a suitable distance apart. Taking the spigot diameter as 2.5 mm, a capacity of 0.1 pF requires a spacing of about 0.5 mm, which was easily manageable. The construction is shown in Fig. 7.6.

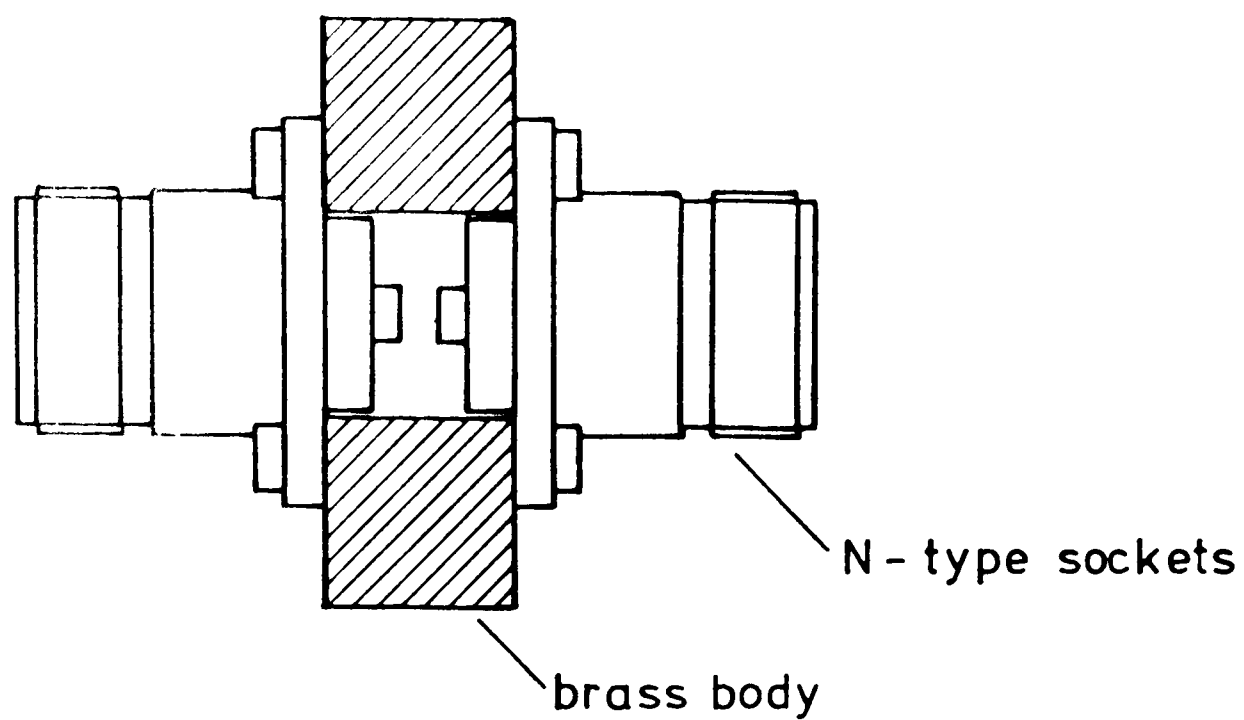


Fig. 7.6. Construction of capacitive differentiator.

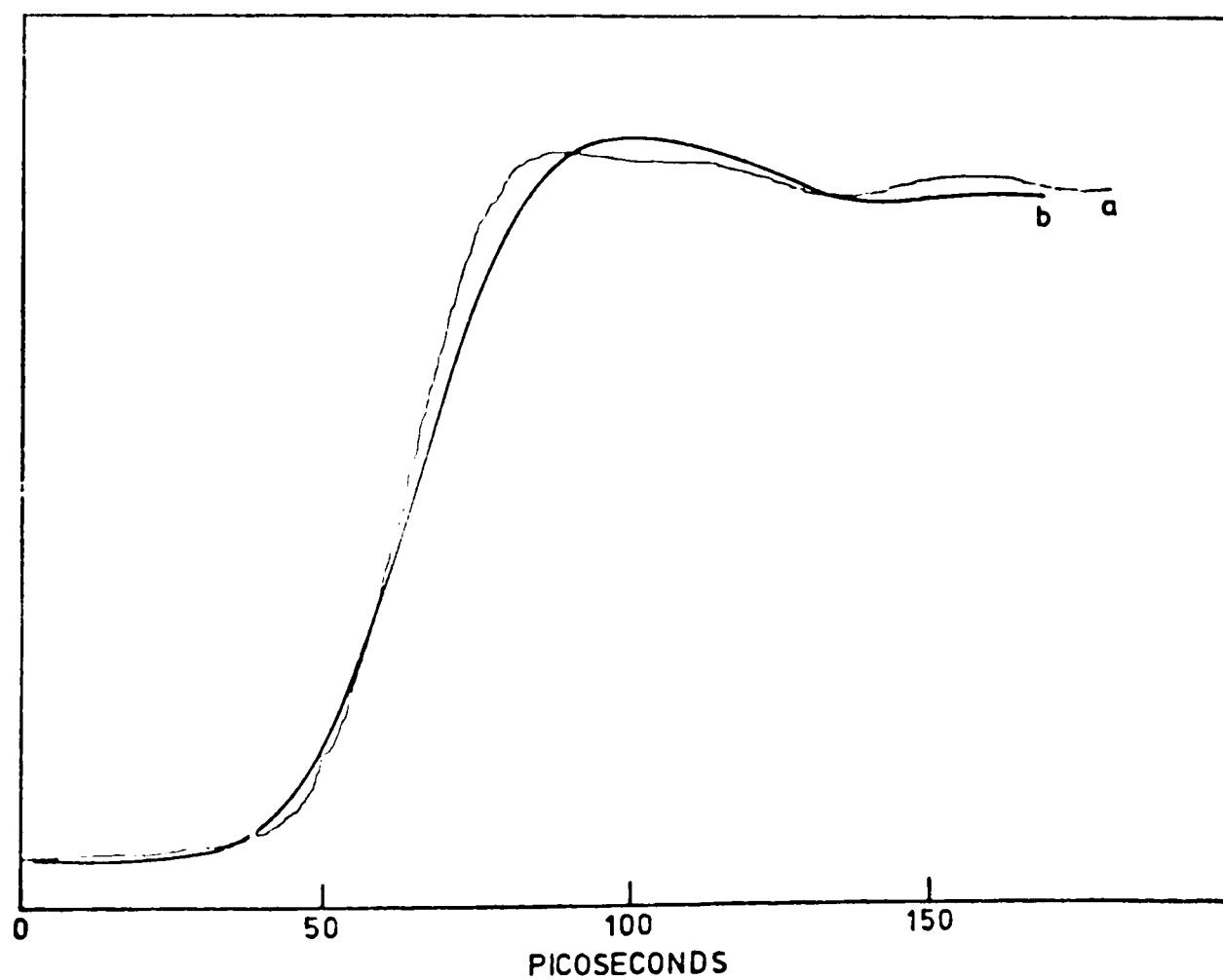


Fig. 7.7. Performance of differentiator.

- a) original pulse
- b) reconstucted pulse

7.9 Testing of differentiator

The 20 - 30 ps rise-time pulse from a tunnel diode pulse generator was observed on the 18 GHz sampling oscilloscope, and the trace was recorded on a chart recorder. The differentiator was then inserted between the tunnel diode and the oscilloscope, and the resulting waveform was recorded and then integrated graphically with respect to time. If the differentiation was accurate this, when normalised to the correct amplitude, should give the original pulse back. The two curves are shown in Fig. 7.7 and can be seen to agree well, the reconstructed pulse being a little slower than the original.

Because of the very fast rise time of the pulse this is a stringent test, and indicates that when high-field domains, which can be regarded as voltage steps with a rise time of 200 ps or more are being observed, the error in the differentiation should be negligible. The test also gave a calibration constant for the differentiator.

A frequency response plot between 3.2 and 8.5 GHz for the differentiator was attempted, but there was a scatter of about ± 2 dB on the results, presumably due to non-uniformities in the coaxial line being used. However, a line drawn through the mean of the points had a slope of -21 dB/decade, suggesting that the response was as expected.

7.10 Probe bias

The probe of Thim and Barber had a direct current of 2 mA flowing through the tip, intended to reduce the contact resistance with the specimen. A modified version of the differentiator was constructed, and included a 4.7 kilohm resistor passing through a hole in the body to the inner contact of one of the N-type sockets. Connected to a low voltage d.c. supply, this enabled a few milliamps to be passed through the probe.

As long as precautions were taken to ensure that the probe tip

was clean and in firm contact with the specimen, the effect of the bias was minimal: otherwise, the speed of response increased very slightly. More discussion of the effects of bias on the probe performance appears in Chapter IX.

7.11 Probe system - rise time measurements

The line from the probe to the differentiator had to be made long enough to avoid interference from reflections (Section 7.7), but could not be made indefinitely long because of the possibility of introducing distortion. The specimens to be used had high-field domain transit times of about 5 ns., and to observe the first two transits, therefore, the total delay of the line (go and return) had to be at least 10 ns. Tests on such a length of subminiature cable with the tunnel diode pulse generator showed a rise time of 50 ps. and a 'droop' at the top of the step of less than 5%, which was considered acceptable.

The tunnel diode generator was also used in an attempt to measure the rise time of the probe and cable together. The probe was positioned close to the 'live' end of a specimen to which the pulse was fed, but the very small amplitude of the probe output (~ 1 mV) together with oscilloscope noise and spurious effects caused by the specimen connections made the display very difficult to interpret: the rise-time of the observed signal was estimated to be approximately 80 ps.

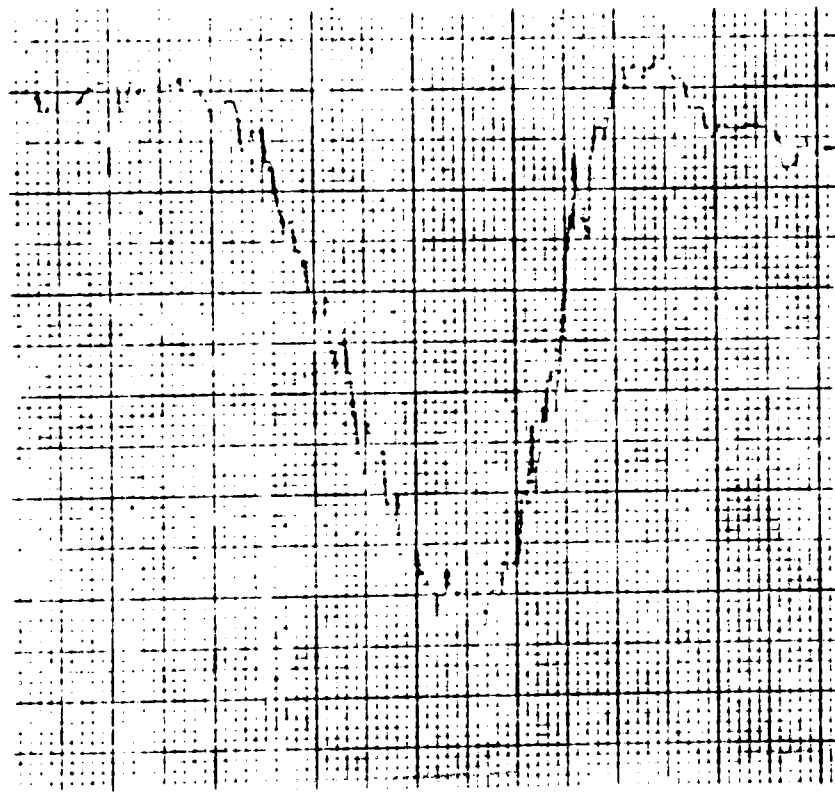
7.12 Probe system - tests on gallium arsenide

The probe and differentiator were tested using samples of 0.8 ohm cm gallium arsenide, about 500 microns long and containing high field domains. Measurements were made both with and without the differentiator, and results from a 52 volt domain are shown in Fig. 7.8. A series of potential measurements at 25 micron intervals



a) Potential

Horizontal scale: 100 ps./cm.
Vertical scale: 10 V/cm.



b) Electric field

Fig. 7.8. Probe measurements of high-field domain in gallium arsenide.

along the specimen gave the velocity as 7×10^6 cm/s: this allows the time scale to be transformed into one of distance. The domain width is measured as 24 microns, which compares well with the calculated width of 19.8 microns for a fully depleted domain.

The rise-time of the potential steps caused by the high field domains is about 300 ps, but in order that details of the domain shape, which are contained in the higher frequency components of the signal, can be resolved, the probe must have a rise time faster than this. Because of the rising response with frequency of the differentiator these components become more significant when it is included in the circuit, and a better estimate of the response of the probe and cable may be obtained from the differentiated signal. The measured width of the accumulation layer is 100 ps. (corresponding to a width of 7 microns) which can be regarded as an upper limit on the risetime of the whole system.

7.13 Tests on higher resistivity material

The next tests performed were on 2 ohm cm indium phosphide; the larger spreading resistance at the point given by the higher resistivity material required that the probe response be re-optimised. Optimum results were obtained using a 27 kilohm resistor with the screening round it reduced to a minimum: only enough of the screen was left down one side of the resistor to make contact with the earthing spring on the specimen holder. According to the model of the probe developed in Chapter VIII, this arrangement should produce a good response.

In the course of this modification, at first, higher values of the original $1/8$ W subminiature type of resistor were used, and an inconsistency between measurements made with different values of resistor was found to be due to non-linearity of this type of resistor at the higher voltages needed to bias the indium phosphide

specimens above threshold. Results from pulsed current-voltage measurements on these resistors (made using the method of Chapter 5) are shown in Fig. 7.9, where a nominally 22 kilohm resistor shows a differential resistance between 400 and 500 volts of 14.5 kilohms, and a lower resistance at higher voltages. A slightly larger type of carbon composition resistor was found to be linear up to 600 volts (Fig. 7.9) and was therefore substituted; this was the type used in the modified probe described in Section 7.6.

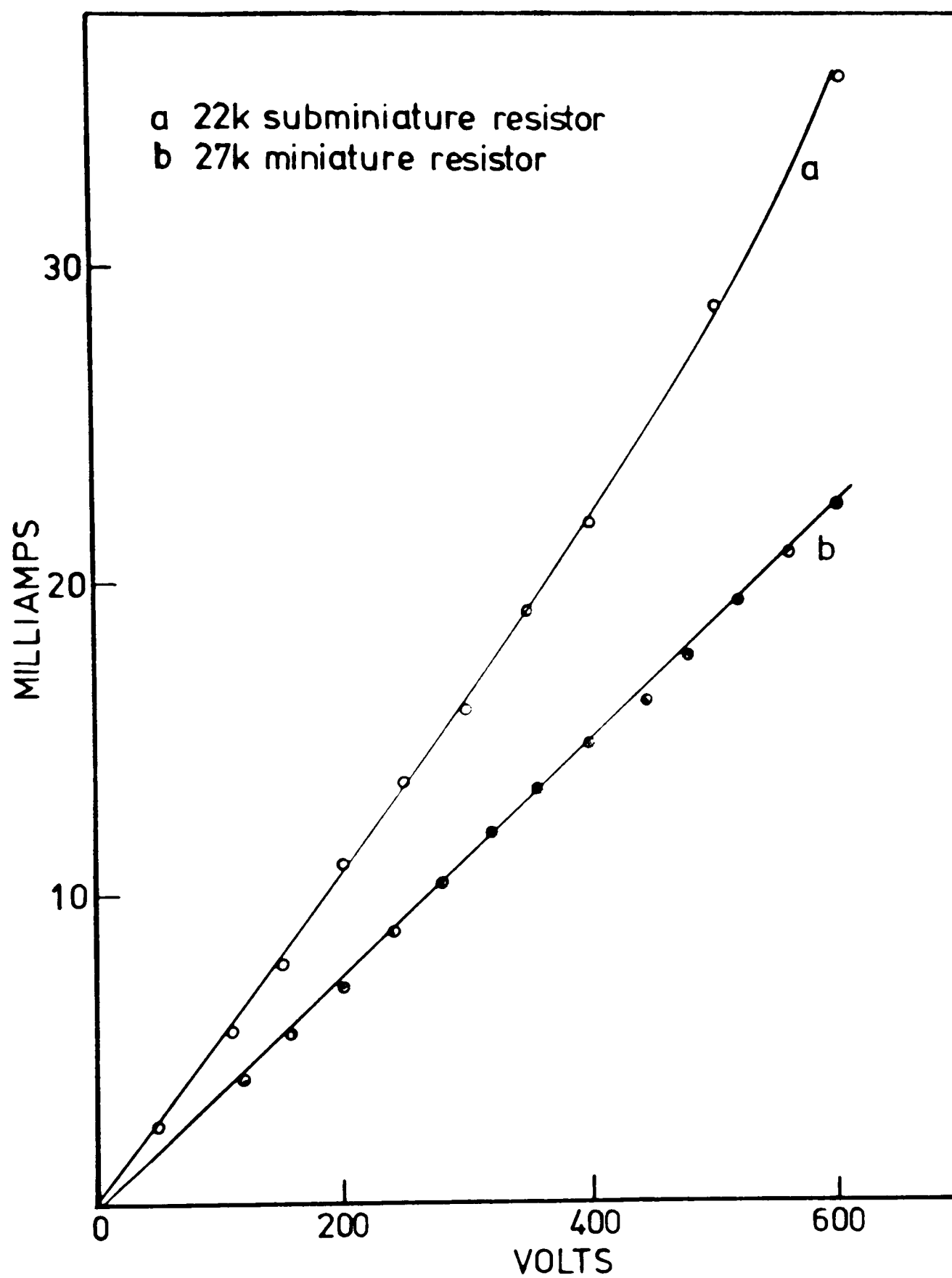


Fig. 7.9. Current-voltage characteristics of resistors tested for high-field probe.

CHAPTER VIII

MODEL OF PROBE-SPECIMEN SYSTEM

8.1 Introduction

Experimental work had shown that the probe characteristics needed to be altered to take into account different material resistivities, which clearly indicated that the effect of the spreading resistance at the point was not negligible. Whilst it was thought that satisfactory results had been achieved empirically, a model of the probe system seemed necessary fully to understand probe operation and to investigate the limitations of any particular probe.

8.2 Equivalent circuit

An equivalent circuit for the specimen and probe is shown in Fig. 8.1. The voltage on the specimen is represented by V_1 , the spreading resistance at the point by R_1 and the capacitance of the probe tip, including the wire inside the resistor, by C_1 . Apart from R_3 , which corresponds to the input impedance of a 50 ohm line, the remainder of the circuit represents the probe resistor and its spurious reactances, which, ideally, should be considered as a distributed parameter circuit. Replacing this by a three-section network as shown greatly simplifies the analysis, and represents a compromise between accuracy and ease of analysis; experiments with analogues of these circuits indicated that the error in this approximation, certainly as far as the shape of the step response is concerned, is likely to be quite small. (A network with more sections could be more easily analysed using difference equations.) In this part of the equivalent, the series resistance is represented by the resistors R_2 (each equal to one third of the total resistance), the

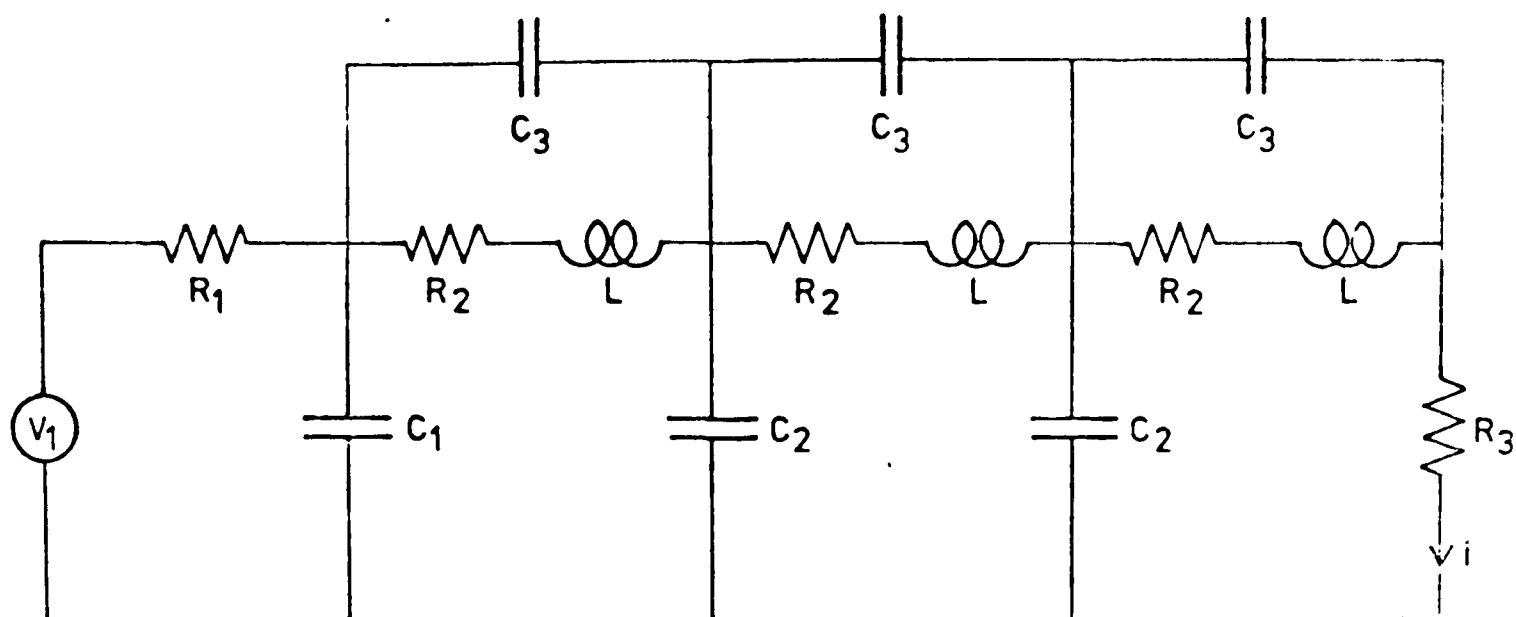


Fig.81 Equivalent circuit for specimen and probe

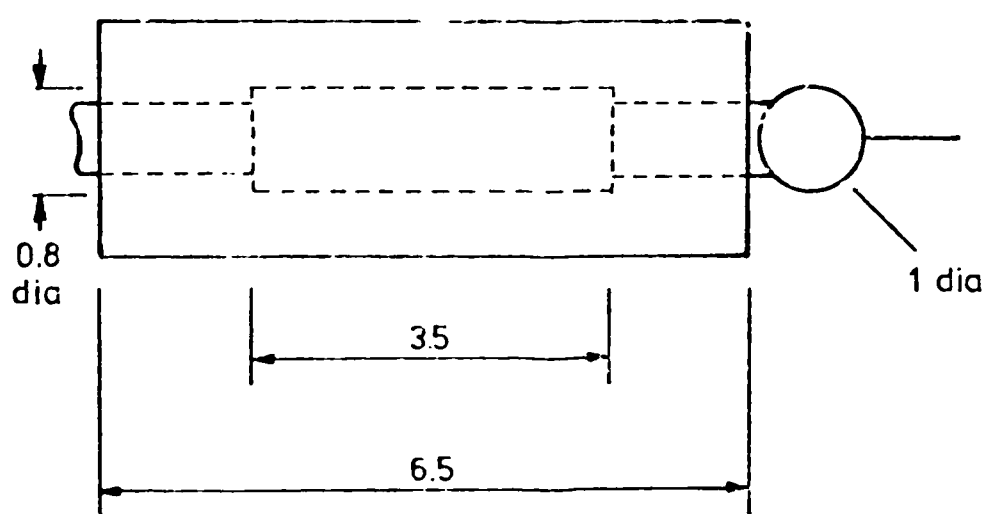


Fig.8.2 Dimensions of probe resistor.

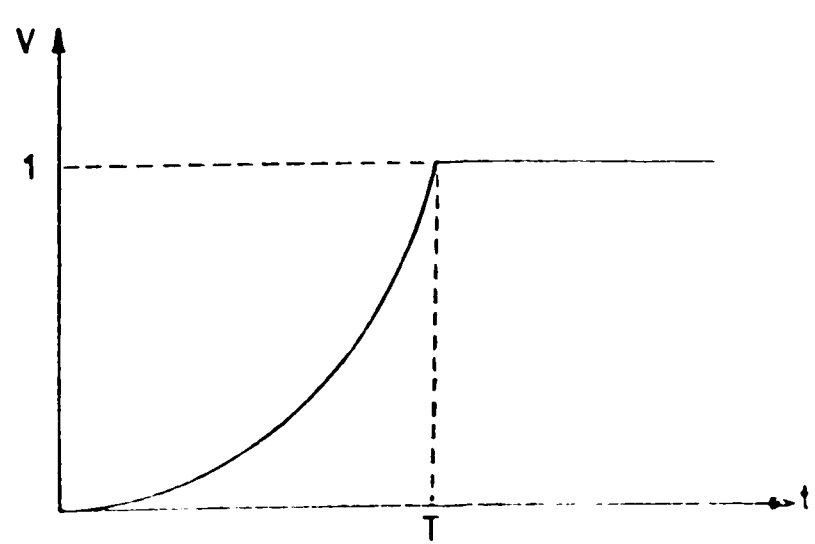


Fig 8 3 Ideal domain simulation:

$$0 < t < T, \quad V = t^2 / T^2$$

$$t > T, \quad V = 1$$

end-to-end capacitance of the resistor by the capacitors C_3 (each equal to three times the total capacitance) and the distributed capacitance from the resistor to ground by the capacitors C_2 . L represents the self inductance of the resistor and will, in fact, be shown to be negligibly small.

As the values of R_2 used in the probes were always much greater than 50 ohms, R_3 can, with a negligible loss in accuracy, be replaced by a short-circuit; the problem then reduces to the calculation of the current at this point.

8.3 Component values in the probe model

The values of the separate components in the model were estimated from the geometry of the resistor, which is shown in Fig. 8.2. The predominant contribution to C_1 is from the blob of solder joining the tip to the resistor wire, and this was treated as a sphere of radius 1 mm, giving a capacitance of 1.1×10^{-13} F. This is almost certainly an underestimate, as the proximity of earthed metal surfaces, particularly the specimen mounting plate and the contact springs, has been neglected. The value of C_1 was therefore made 2×10^{-13} F.

To estimate the end-to-end capacitance of the resistor, a value for the relative permittivity of the resistor material is needed. Carbon composition resistors are manufactured from a mixture of carbon and a refractory material, the proportions being varied to control the resistance^[87], and a calculation based on the resistivity of carbon^[85] and the geometry of the resistor indicated the percentage of carbon to be a small fraction of 1%; the relative permittivity can therefore be taken as that of the additive, which places it in the range 4 - 8^[85]. A value of 6 will be assumed, making the value of end-to-end capacitance 6×10^{-15} F, and hence C_3 1.8×10^{-14} F

The self-inductance of a cylindrical conductor is $\mu_0/8\pi$ H/m which, for a resistor 4 mm long, gives an inductance of 2×10^{-10} H. In conjunction with the estimated value for the end-to-end capacitance of the resistor, this resonates with a period of around 10 ps, which is almost an order of magnitude smaller than the time scale on which measurements are being made. The inductance can therefore justifiably be neglected.

C_2 is easily adjusted in practice by changing the metal shroud around the resistor. It is hence treated as a variable parameter.

8.4 Transfer function of probe-specimen model

Conventional analysis of the circuit in Fig. 8.4.1 is as follows:

In Section 8.4, from equation 8.4.2 onwards, R_3 should be read as R_2 .

$$\frac{i}{V_1} = \frac{(1 + Zs)^3}{as^3 + bs^2 + cs + d} \quad 8.4.1$$

where a, b, c, d, z are given by

$$a = R_1 R_2^3 [C_3^2 \{3(C_1 + C_2) + C_3\} + C_2(C_1 C_2 + C_2 C_3 + 4C_1 C_3)]$$

$$b = R_2^2 [R_2(3C_3^2 + 4C_2 C_3 + C_2^2) + R_1(6C_1 C_3 + 6C_2 C_3 + 3C_3^2 + C_2^2 + 4C_1 C_2)]$$

$$c = R_2 [R_2(6C_3 + 4C_2) + 3R_1(C_1 + C_2 + C_3)]$$

$$d = 3R_2 + R_1$$

where s is the Laplace transform variable.

A special case arises if $C_2 = 0$, when the transfer function becomes

$$\frac{i}{V_1} = \frac{1}{R_1 + R_3} \cdot \frac{1 + sC_3 R_3}{1 + s(C_1 + C_3) \frac{R_1 R_3}{R_1 + R_3}} \quad 8.4.2$$

The self-inductance of a cylindrical conductor is $\mu_0/8\pi$ H/m which, for a resistor 4 mm long, gives an inductance of 2×10^{-10} H. In conjunction with the estimated value for the end-to-end capacitance of the resistor, this resonates with a period of around 10 ps, which is almost an order of magnitude smaller than the time scale on which measurements are being made. The inductance can therefore justifiably be neglected.

C_2 is easily adjusted in practice by changing the metal shroud around the resistor. It is hence treated as a variable parameter.

8.4 Transfer function of probe-specimen model

Conventional analysis of the circuit in Fig. 8.1, with $L = 0$ and $R_3 = 0$, gives the transfer function

$$\frac{i}{V_1} = \frac{(1 + Zs)^3}{as^3 + bs^2 + cs + d} \quad 8.4.1$$

where a, b, c, d, z are given by

$$a = R_1 R_2^3 [C_3^2 \{3(C_1 + C_2) + C_3\} + C_2(C_1 C_2 + C_2 C_3 + 4C_1 C_3)]$$

$$b = R_2^2 [R_2(3C_3^2 + 4C_2 C_3 + C_2^2) + R_1(6C_1 C_3 + 6C_2 C_3 + 3C_3^2 + C_2^2 + 4C_1 C_2)]$$

$$c = R_2 [R_2(6C_3 + 4C_2) + 3R_1(C_1 + C_2 + C_3)]$$

$$d = 3R_2 + R_1$$

where s is the Laplace transform variable.

A special case arises if $C_2 = 0$, when the transfer function becomes

$$\frac{i}{V_1} = \frac{1}{R_1 + R_3} \cdot \frac{1 + sC_3 R_3}{1 + s(C_1 + C_3) \frac{R_1 R_3}{R_1 + R_3}} \quad 8.4.2$$

If the time-constants in the numerator and denominator of this expression are made equal, that is,

$$C_3 R_3 = (C_1 + C_3) \frac{R_1 R_3}{R_1 + R_3}$$

or $C_3 R_3 = C_1 R_1$ 8.4.3

the probe response is independent of frequency. It should be noted that in this case, with the distributed shunt capacitance removed, this model represents an exact equivalent of the probe resistor and its end-to-end capacitance.

It is interesting to compare the condition derived in 8.4.3 with some empirical results obtained during the probe development, using the capacitances calculated in the previous section. On 2 ohm cm material the optimum probe performance was obtained with a 27 kilohm resistor, which made R_3 9 kilohms. The spreading resistance at the point (which will be discussed in more detail later) is given by [88]

$$R_1 = \frac{\rho}{4a} \quad \text{8.4.4}$$

where a is the radius of the tip and ρ is the material resistivity. Assuming a probe tip diameter of 10 microns, and 2 ohm cm material gives $R_1 = 1$ kilohm; putting these values in 8.4.3 gives

$$C_1 R_1 = 1.5 \times 10^{-13} \times 10^3 = 1.5 \times 10^{-10} \text{ s},$$

$$C_3 R_3 = 2 \times 10^{-14} \times 9 \times 10^3 = 1.8 \times 10^{-10} \text{ s},$$

a good agreement. With 1 ohm cm material a 10 kilohm resistor performed well, and the agreement here with the model is also reasonable.

A way has been described of obtaining the optimum probe response by using the unavoidable spurious reactances C_1 and C_3 to counteract the effects of one another. However, the probe described

by Thim and Barber^[31] and the first probes designed for the present work were equalised by varying the shunt capacitance between the resistor and ground, and it is therefore necessary to calculate the effect of this on the probe response, and find the extent to which excess overshoot can be compensated by it.

8.5 Probe response calculations

Calculations were carried out, using standard Laplace transform methods, to predict the step response, and the response to a simulated ideal domain signal of the complete equivalent circuit with the transfer function (8.4.1). In order to make the model correspond more closely with the measuring system used, a term representing the response of the sampling oscilloscope and the line coupling the probe to it was included.

The step response of the oscilloscope was quoted as 20 ps, and this increased to around 50 ps when the input coaxial line was included. A reasonable approximation to the combined response is given by a fourth-order transfer function:

$$\frac{\omega^4}{(s + \omega^4)}, \text{ with } \frac{1}{\omega} = 10 \text{ ps.}$$

The overall transfer function for the specimen-probe-oscilloscope system is thus

$$\frac{(1 + Zs)^3}{(as^3 + bs^2 + cs + d)} \frac{\omega^4}{(s + \omega^4)} \quad 8.5.1$$

The function used for the high-field domain simulation is shown in Fig. 8.3 and represents the input signal to the probe system from an ideal uniformly depleted triangular domain passing the probe tip at uniform velocity. Its Laplace transform is

$$\frac{2}{s^3} - e^{-sT} \left(\frac{2}{s^3} + \frac{2T}{s^2} \right) \quad 8.5.2$$

where T represents the time-width of the domain. The derivation of

this expression, and the detailed solutions for the responses, both to it and to a step input for the transfer function (8.5.1) are given in Appendix A 2.1 and Appendix A 2.2.

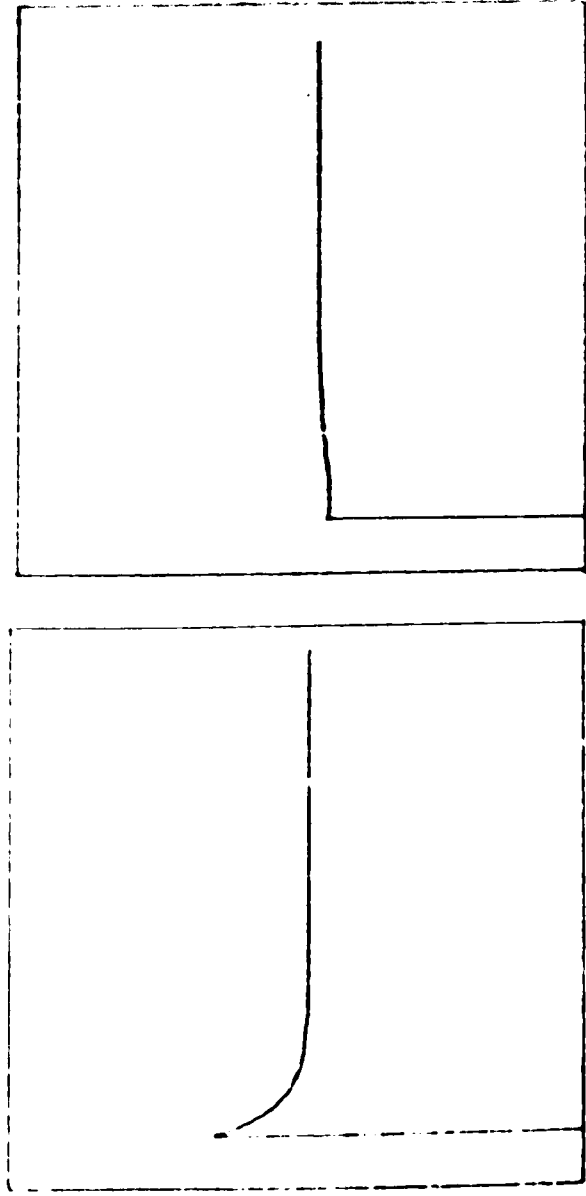
To make the calculations numerically less cumbersome, resistances were divided by 10^3 , and capacitances multiplied by 10^{10} for use in the model, giving an effective time scale multiplied by 10^{13} . The value of T was chosen to represent a high-field domain 400 ps wide (4000 s on the scale in the calculation), a value typical of those that had been measured.

To measure the domain field distribution, the probe signal is passed through the differentiator before being modified by the oscilloscope response. In the simulation, however, it is obviously more convenient to calculate the response due to the combined transfer function of the probe and measuring system (8.5.1), in other words the measured domain voltage, and then differentiate it numerically. It can be shown that, in a linear system, the order in which the operations are carried out is immaterial, and that hence the calculation method is valid. (Appendix A 2.3).

8.6 Probe response equalisation by shunt capacitance

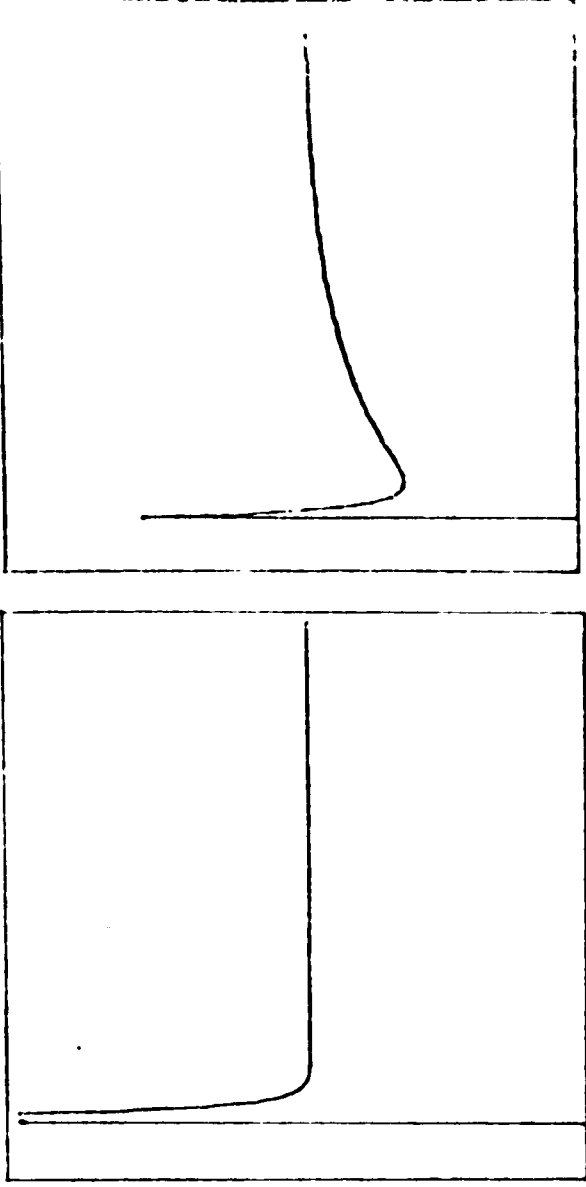
Two sets of calculated responses are shown in Fig. 8.4, which shows the step response of the specimen-probe system without and with the capacitors C_2 , and the response of the whole system to the high-field domain simulation. Both domain voltage and domain field responses are included in the latter.

Fig. 8.4 a) shows a small amount of overshoot in the unequalised step response, which is almost correctly compensated by the addition of an appropriately-valued C_2 . The domain responses are good. As the overshoot is increased by making C_1 smaller and C_3 larger (a situation which might arise with a physically smaller resistor), increasing C_2 gives the badly distorted response of



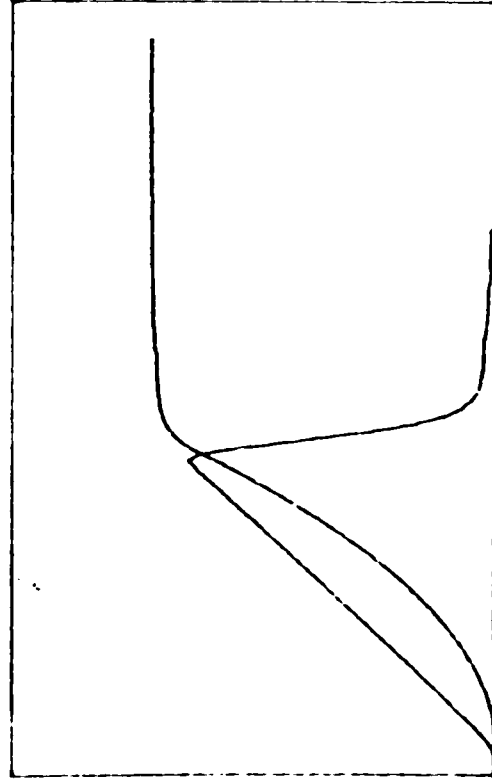
Step response
without C_2

Step response
with $C_2 = 20$

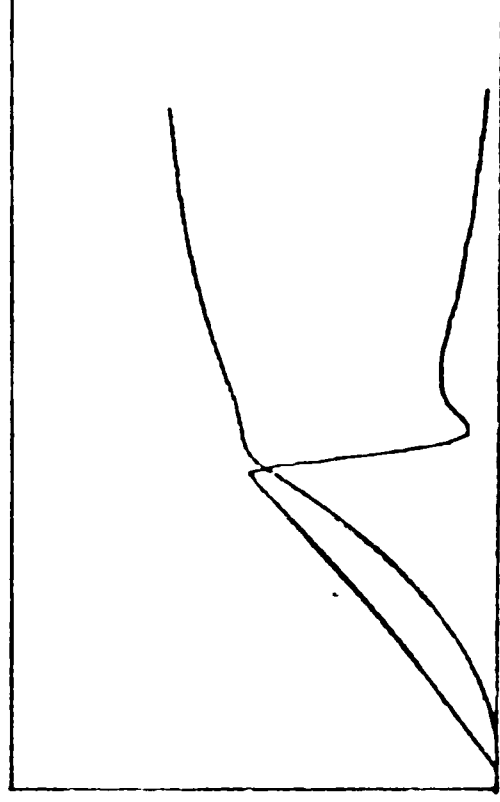


Step response
without C_2

Step response
with $C_2 = 140$



Response to domain simulation.



Response to domain simulation.

Fig. 8.4a Simulated responses of probe with small amount of overshoot, showing correct compensation by slant capacity ($R_1 = 1$, $R_2 = 9$, $C_1 = 500$, $C_3 = 75$).

Fig. 8.4b Simulated responses of probe with large amount of overshoot, showing effect of slant capacity ($R_1 = 1$, $R_2 = 9$, $C_1 = 100$, $C_3 = 100$).

Fig. 8.4 b); no value of C_2 would give an accurate response. This form of distorted response, with the second peak in the domain field plot, and the slowly sloping top to the domain voltage plot, was observed many times during early experiments with the sub-miniature $1/8$ W resistors, and the findings here were in agreement with the theoretical prediction that the correct response could not be obtained, larger values of C_2 merely slowing down the trailing edge.

8.7 Change in spreading resistance during domain passage

A simulation by Prew^[57] indicated the distortion of observed domain shape to be expected because of the change in spreading resistance at the probe tip during the passage of a high field domain (Fig. 8.5); the domain shape is badly distorted at the high field point. However, during extensive experiments with many different designs of probe nothing resembling this shape was observed. A possible explanation, at least for the reduction of the significance of the effect, lies in the nature of the probe-semiconductor contact.

The expression 8.4.4 for the spreading resistance at a point assumes an ohmic contact between metal and semiconductor. This spreading resistance will, in fact, be modified because the contact forms a Schottky barrier, and the material immediately below the metal will form a depletion layer to a depth of a micron or two. As a high field domain passes the probe the carrier density in the material is first depleted and then enhanced; the effect of this will be to make the extent of the depletion region respectively greater and smaller, the depletion depth being given, assuming complete depletion by^[89]

$$d = \sqrt{\frac{\epsilon_r \epsilon_0 \phi}{2en}}$$

ϕ being the barrier height and n the carrier density in the material. The effect on the depletion layer will be as shown in Fig. 8.6: as n

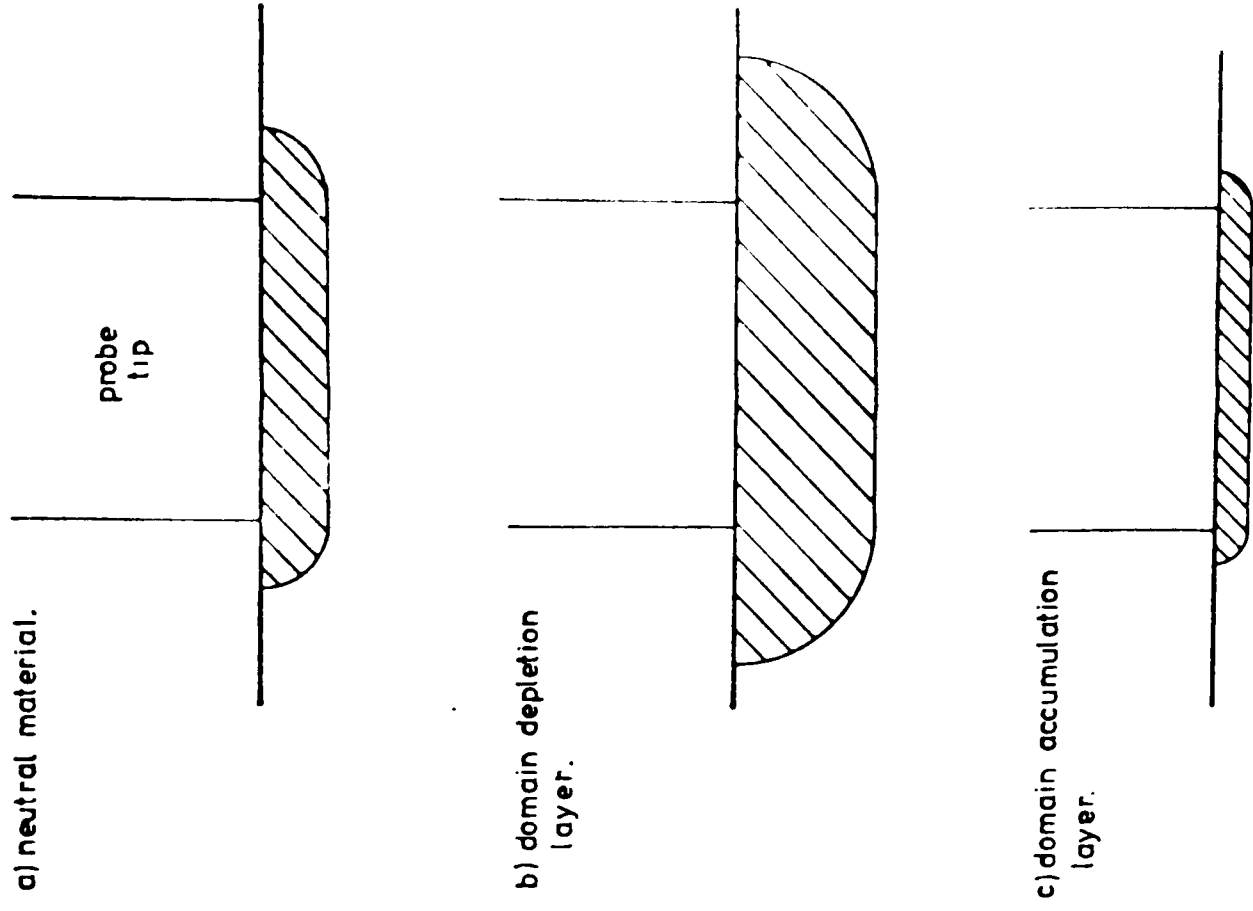
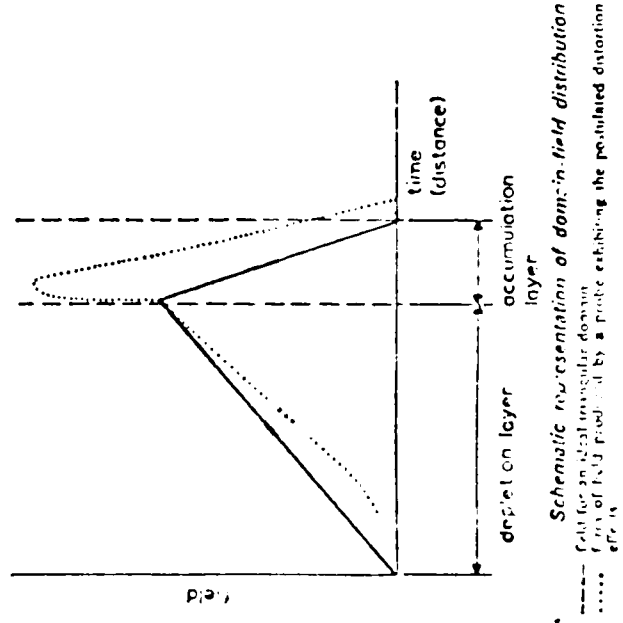
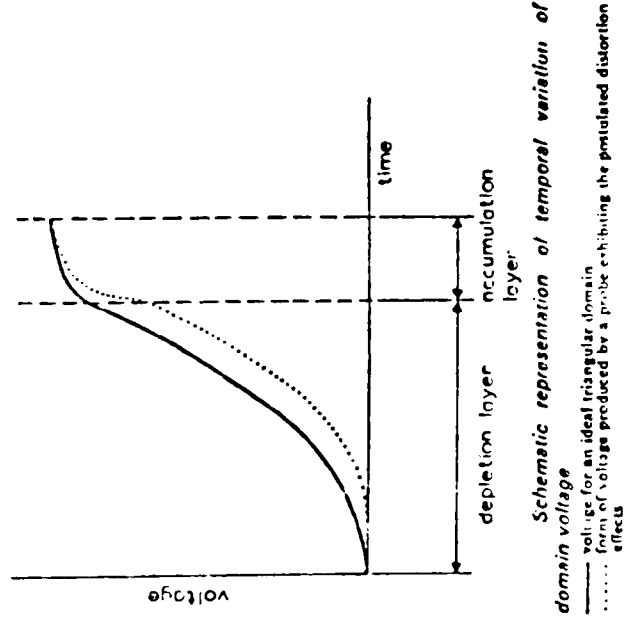


Fig. 8.5 Effect on measured domain shape of material resistivity variation across domain (Prew).

Fig. 8.6, Depletion region under probe.

changes the effective area from which the current spreads out is being changed so that when the resistivity of the material is larger, the area is also larger, with the result that changes in series resistance are reduced.

8.8 Conclusions

Practical work having indicated that the effect of spreading resistance is significant, an analysis of an equivalent circuit representing the probe system has shown that, with a fixed resistor geometry, it is possible to construct suitable probes for different material resistivities by using different values of resistor. In the case where there is no shunt capacitance, the spurious reactances associated with the resistor are being used to offset each others' effects.

However, in any practical probe there will be a small amount of distributed capacitance from the resistor to earth, which is unavoidable, and the analysis has also shown that, as long as this capacitance is small (or the amount of residual overshoot which it has to equalise is only a few per cent) the response is not seriously distorted. If there is a large amount of overshoot, it is impossible to obtain an accurately equalised response by adding shunt capacitance.

The results of the analysis also suggest that the response time of the probe should be very short (probably limited in practice by the series inductance which was neglected in the analysis), and with a properly equalised probe, the limiting factor on the response time can be taken as that of the measuring system. This will be particularly so if the probe output is fed to the oscilloscope through a low-pass filter of known characteristics, as it was with the final probe design.

CHAPTER IX

HIGH-FIELD DOMAIN MEASUREMENTS

9.1 Apparatus for domain measurements

This is shown in Fig. 9.1 and is very similar to that used for the room-temperature low-field measurements, with some additions and alterations. A digital voltmeter measured the input voltage to the pulse generator to allow any voltage setting to be quickly and accurately repeated, and a second digital voltmeter monitored the probe position along the specimen, using the circuit of Fig. 5.6 with the voltage set to give a convenient calibration.

Because the bar-type specimens used for these measurements had a lower resistance than those used for the low-field measurements the current-measuring line was shunted, adjacent to the specimen, with a subminiature 10 ohm carbon resistor. This made the effective current-measuring resistance 8.33 ohms nominally, and kept the circuit impedance low compared with the specimen resistance.

The pen-recorder could be connected to record either specimen current against specimen voltage from the dual trace sampling unit or probe output (direct or differentiated) against time from the fast sampling unit. The specimen and probe mounts were identical to those used previously. The applied pulses to the specimens were kept as short as possible - 5-6 ns - to allow only one domain transit and so avoid impact ionisation on further transits.

9.2 Measurement of domain velocity

Domain velocity was measured by fixing the probe position at successive points 50 microns apart along the specimen and, for each point, recording the variation of voltage as the domain passed. The

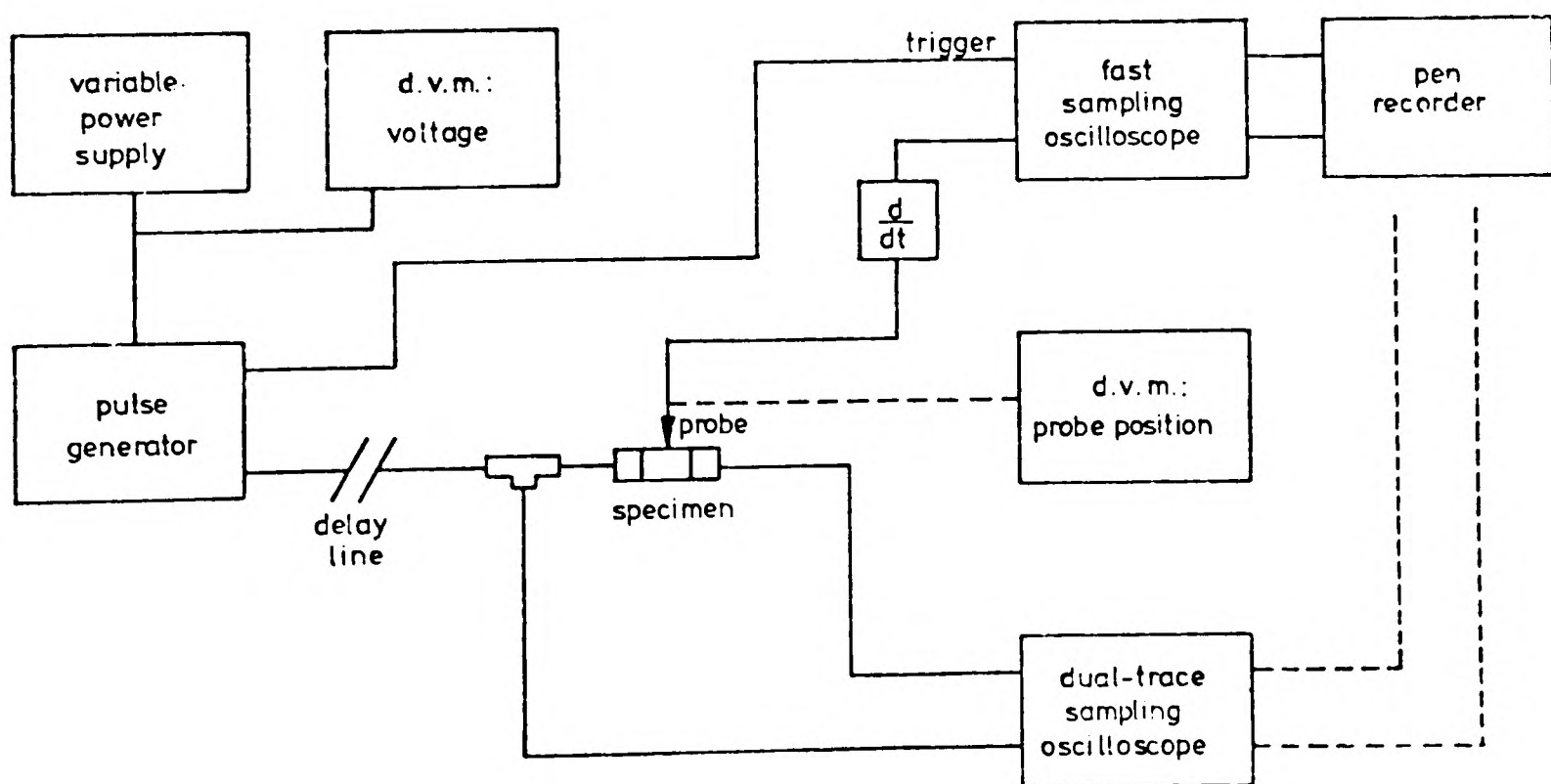
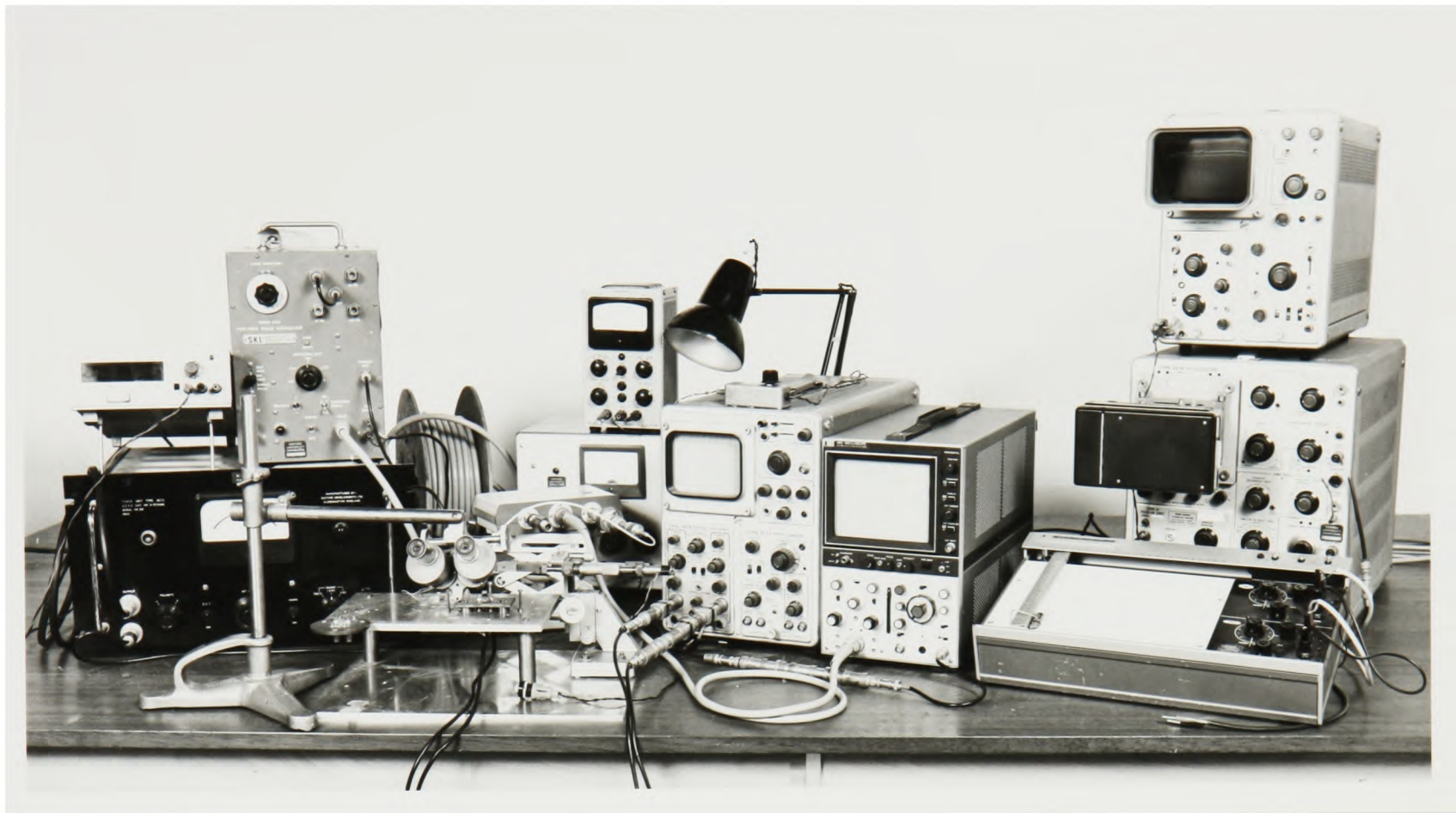


Fig. 9.1 Apparatus for high-field measurements.

velocity was then deduced from the average time taken to travel the 50 microns, this method being considered preferable to the alternative of keeping the sampling instant fixed and scanning the probe along the specimen for each of several sampling instants, which would have caused much more specimen damage.

9.3 Measurement of domain field profile

9.3.1 Difficulties with point-contact probe

When the differentiator was included in the circuit to measure the domain field profile, the sensitivity of this type of probe to the nature of the contact between probe tip and semiconductor (which might be inferred from the analysis of the previous chapter) became apparent. The observed domain shape varied very significantly with changes in contact quality, particularly in respect of the measured width of the accumulation layer. A poor contact, thought to be due to a large contact resistance, broadened the observed peak field. This effect was often found to vary randomly with the actual probe position on a specimen, points only a few microns apart giving dramatic changes in measured domain shape. Fig. 9.2 shows a 260 V domain measured at two different points, and demonstrates the effects described.

That the effect varied, apparently randomly, with position on the specimens suggests strongly that it is the contact resistance between probe and specimen which is changing. A similar, but temporal, variation at any one point was also observed. When the probe was first put into contact with the specimen a relatively large, narrow domain shape would be observed, but after a period of time varying between a few seconds and a minute or so the domain would start broadening as though the contact resistance were increasing. Again, moving to a new point on the specimen restored the original shape.

An alternative reason for the broadening might be that the initially fine probe point is being blunted by its contact pressure

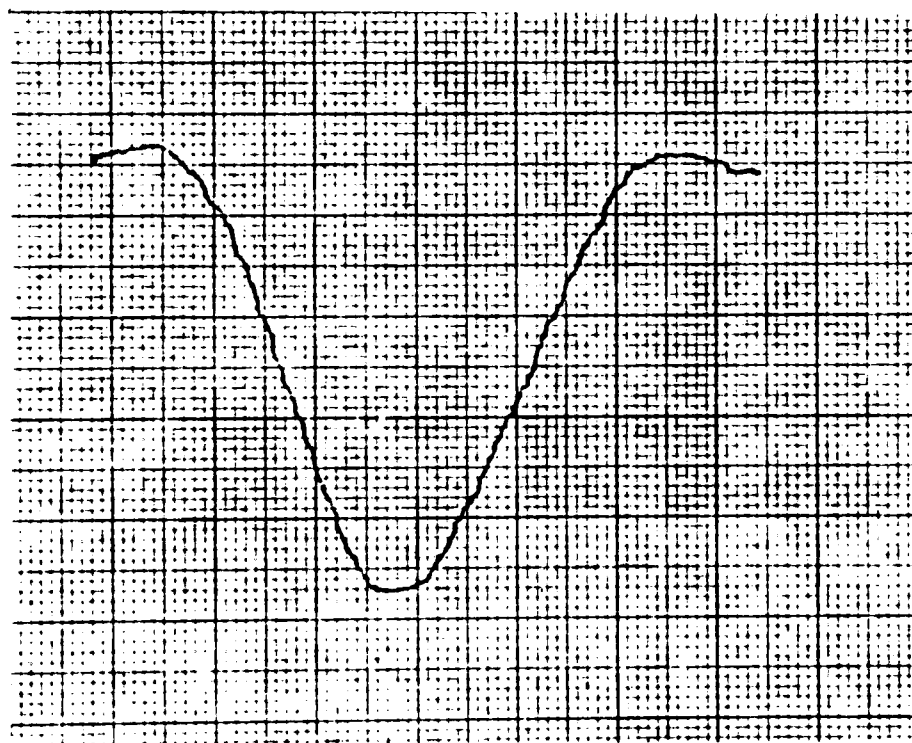
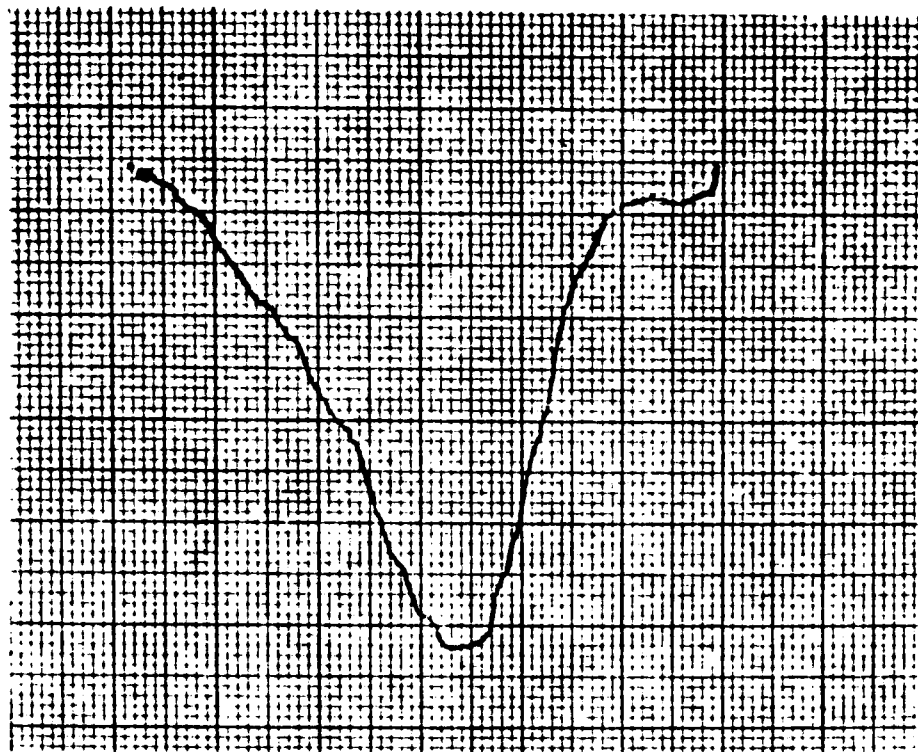


Fig. 9.2 High field domain measured at two closely separated points on indium phosphide specimen showing change in shape owing to contact resistance variation.

on the specimen, reducing its spatial resolution. This seemed unlikely, not only because moving to a new point on the specimen usually improved the response, but also because the change in measured signal occurred before any significant deformation of the probe tip was visible through a microscope. Change in contact resistance or localised surface damage seemed more likely explanations.

9.3.2 Localised specimen heating

The temporal variation occurred much more quickly (in a few seconds) when the probe was used with d.c. bias applied, suggesting that the current flow through the point was somehow responsible, perhaps by causing localised heating. If the voltage on the specimen is 400 volts and the probe resistance 27 kilohms, a current of 15 mA will flow during the applied pulse. This current is concentrated into a very small area under the point, where it may be regarded as flowing through the spreading resistance (around 1000 ohms in 2 ohm cm material), dissipating around 0.2 W peak power. With a duty cycle of 10^{-6} the mean power is correspondingly smaller. With a bias current of 2 mA d.c. flowing, the mean power dissipated is approximately 4 mW. Much of the heat produced will be conducted away into the semiconductor and the probe point, but assuming that as little as $1/1000$ of it is dissipated in a hemisphere of radius 20 microns under the probe gives a rate of temperature rise (calculated using the material constants quoted in Appendix 1) of around 100 K s^{-1} . The melting point of indium phosphide is $1320^{\circ} \text{ C}^{[84]}$, so localised surface damage seems likely. Without bias current the mean power dissipated is much less even though the peak power is greater, suggesting that damage might take longer to occur, and for this reason the probe was always used without bias.

9.3.3 Precautions

It was found that the most consistent results were obtained if

the probe point were re-etched frequently in fresh sodium hydroxide solution. Precautions were taken to ensure that it was as little contaminated as possible by rinsing, after etching, successively in dilute sulphuric acid, water and alcohol, and to reduce mechanical surface damage as much as possible by always bringing the probe gently into contact with the specimen. This was particularly important with specimens of epitaxial material as more than a micron or two of damage on the surface might seriously upset the field distribution in the specimen. This type of damage was in fact observed in specimens which had been much probed. Visual inspection of the specimen surface revealed the damage, and the period of domain current oscillation decreased, suggesting domain nucleation at a high field region away from the cathode. In view of the potential distortion of the domain field profile, several plots of each domain shape were attempted to ensure repeatability.

9.4 Stray coupling to probe

Because of the short length of the specimens, the probe point was necessarily located quite close to the spring contact supplying the input pulses to the specimen cathode. The amplitude of this pulse was typically 500 volts (for a 500 micron long specimen) and so the capacitance from the contact to the probe point, and to the top end of the probe resistor caused a serious amount of coupling. Because of the high attenuation given by the resistor and the consequent low signal level at its top end, this was a very sensitive point, and could not easily be screened owing to the need to minimise the resistor's capacitance to earth.

This stray coupling was unavoidable and had the effect of producing a decaying transient superimposed on the measured signal, due to the leading edge of the applied pulse, and emphasised by the differentiator. The only way of minimising its effect was to look at

the high field domain as it approached the specimen anode, when the signal was being measured as long after the beginning of the pulse as possible, when the spurious transient had decayed somewhat.

Assuming the breakthrough to be due to the applied voltage pulse enabled the measured domain signal to be corrected, when necessary, for the remainder. The domain shape having been recorded, the applied voltage to the specimen was turned down just below threshold without moving the probe, and the probe output corresponding just to breakthrough recorded on the same time scale. This signal, scaled up in the ratio of the two applied voltages, could then be subtracted from the measured domain signal, leaving the true signal due to the passage of the domain. This correction had not been necessary in the early experiments on gallium arsenide, where the applied pulse voltage to the specimens was much less for the same amplitude domain signal, making the breakthrough less significant.

The stray signal picked up by the probe resistor apparently contained much high frequency noise which, differentiated, overloaded the sampling oscilloscope input. This effect had been absent with previous probes which had screened resistors and was removed by incorporating a 6 GHz low pass filter between the probe and the differentiator.

9.5 Filter response

The characteristics of the 6 GHz low-pass filter were investigated by measuring its response to the step (rise-time ~ 20 ps) from the tunnel diode pulse generator, both step and response being measured under the same conditions. These waveforms having been digitised, using digital filter techniques it was possible to fit a fourth-order transfer function to the filter. The step response corresponding to this transfer function was then derived, and had a rise time of around 75 ps, followed by some ringing. The rise time

of the sampling oscilloscope, quoted as less than 20 ps, could be neglected in comparison.

A programme for an inverse filter was developed to attempt to correct the experimental results. Because of the rising response at high frequencies, however, this was very sensitive to noise on the measured signal, much of which may have been due to small errors in quantisation. The results obtained from the filter were difficult to interpret (Fig. 9.3), suggesting that the domain width was being very little altered by the filter, with perhaps a small reduction in height.

Fig. 9.4 shows the spectra, obtained by Fourier transformation of the measured domain signal and of this signal processed by the inverse filter. The filtering has increased the energy content of the signal above about 6 GHz as would be expected, but the spectrum here is fairly uniform, suggesting that the energy is due to noise, and that little extra information is being gained.

Confirmation of this result was obtained by taking the measured domain shape and processing it by the transfer function of the low pass filter, so that the true signal was effectively passing through the filter twice. The results are shown in Fig. 9.5 where, ignoring the delay between the traces, the output shape is seen to be virtually the same as that of the input. The width and height of the domains are equal to within 2%, and the only difference is a small amount of overshoot at the end of the accumulation region.

The conclusion to be drawn is clearly that the distortion of the domain shape by the filter is negligible, and that the measured domain shapes may be taken, within the limits of experimental accuracy, as the true shapes.

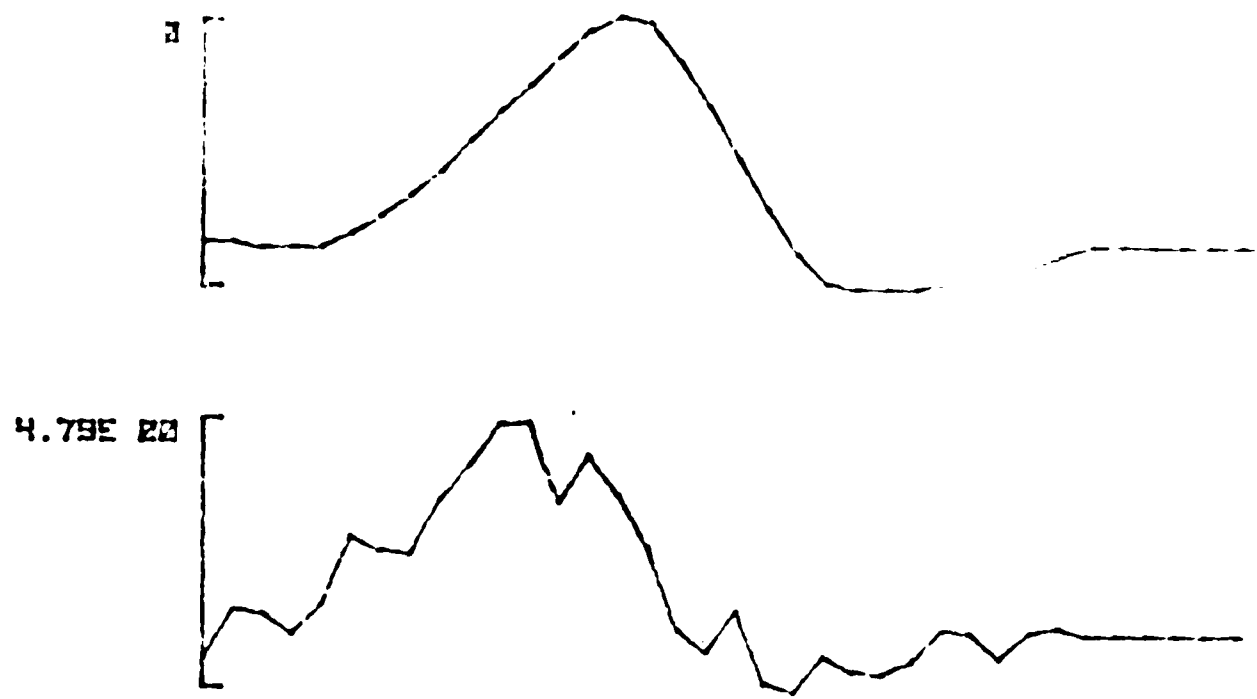


Fig. 9.3 Upper trace: measured high field domain signal.
Lower trace: measured high field domain signal after inverse filtering.

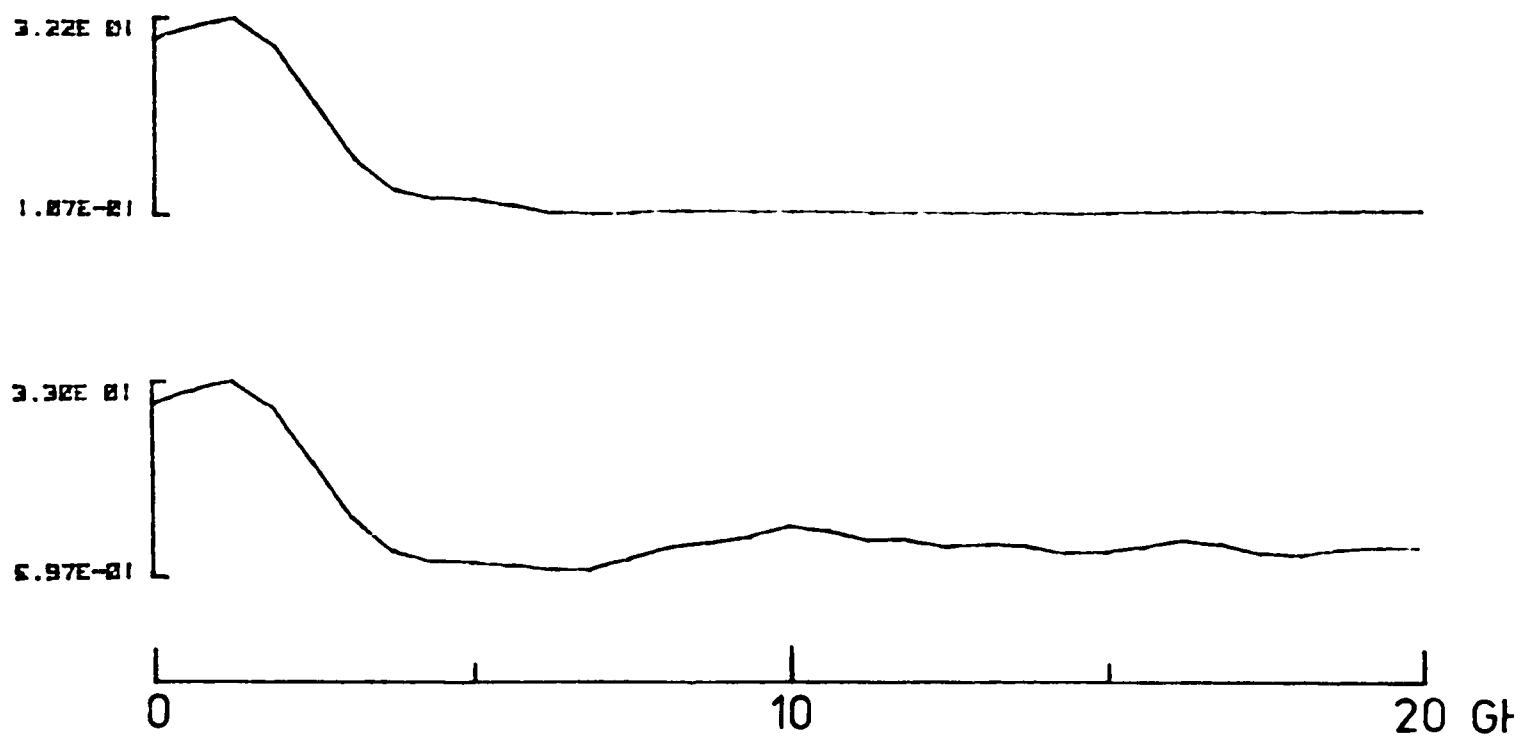


Fig. 9.4 Amplitude spectra of signals in Fig. 9.3

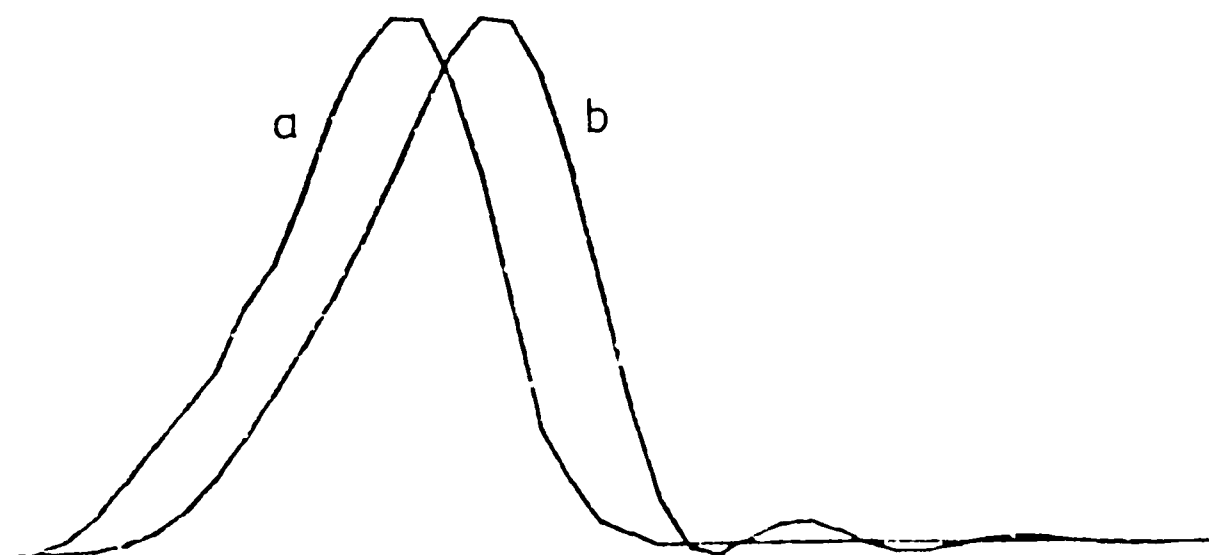


Fig. 9.5 (a) Domain signal measured via 6 GHz filter.
(b) Domain signal measured via 6 GHz filter after processing by computer simulation of 6 GHz filter.

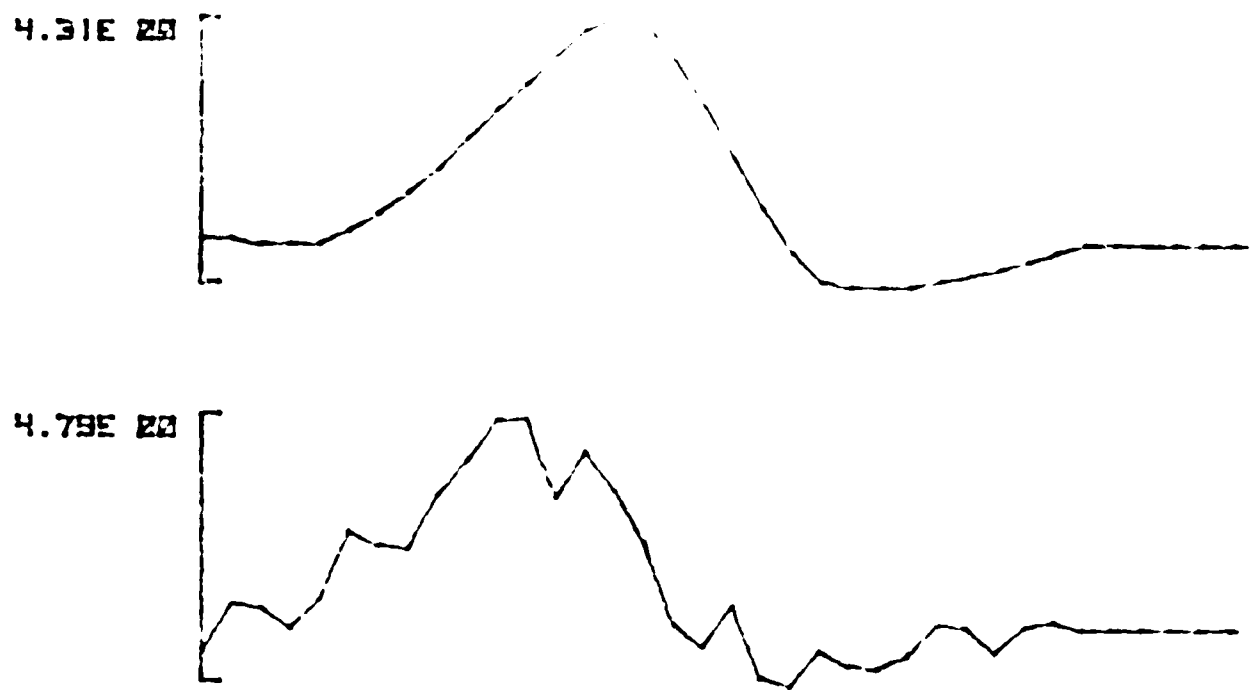


Fig. 9.3 Upper trace: measured high field domain signal.
Lower trace: measured high field domain signal after
inverse filtering.

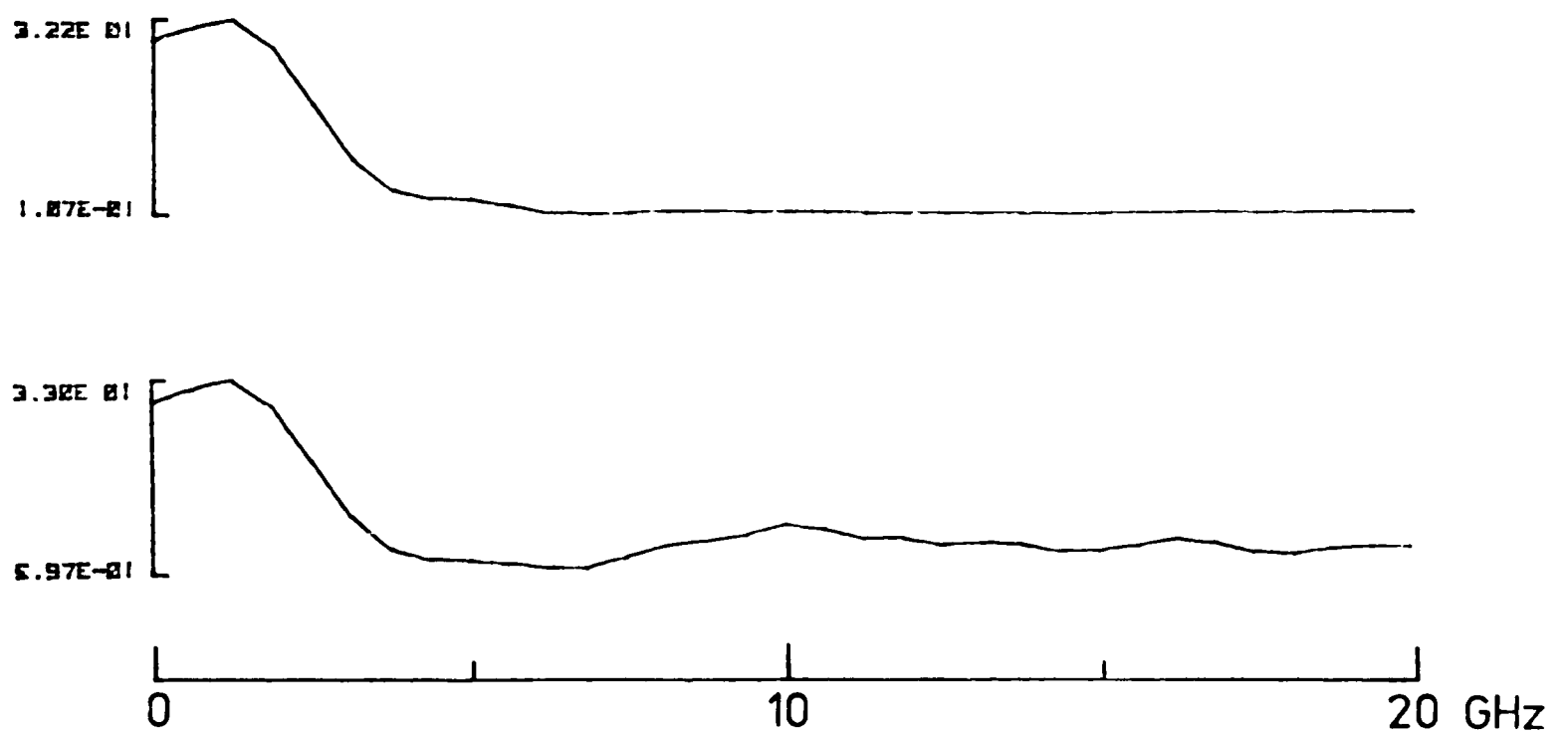


Fig. 9.4 Amplitude spectra of signals in Fig. 9.3

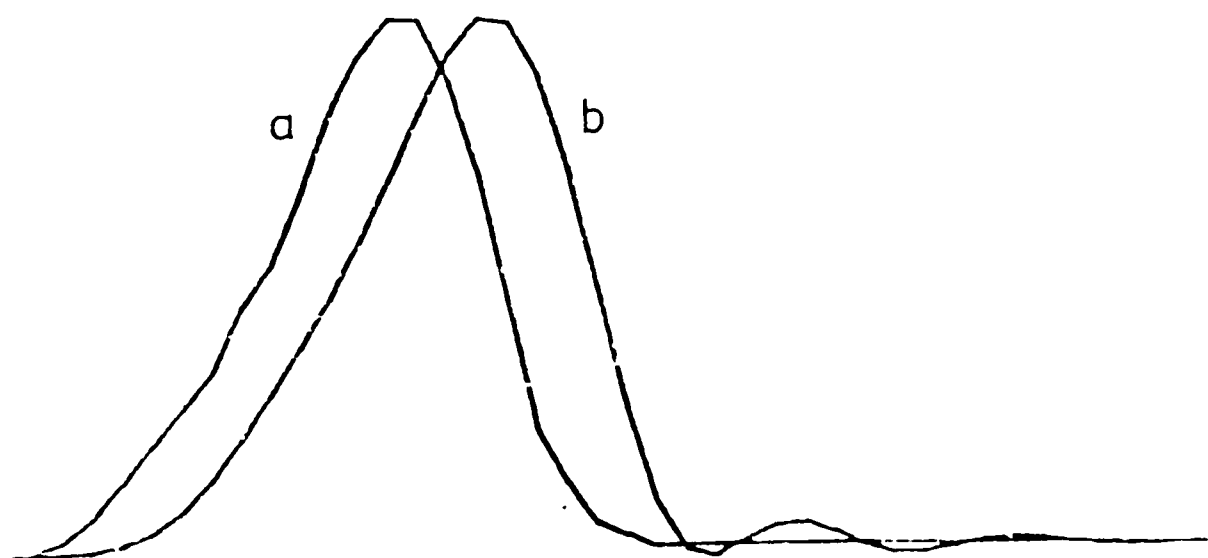


Fig. 9.5 (a) Domain signal measured via 6 GHz filter.
(b) Domain signal measured via 6 GHz filter after
processing by computer simulation of 6 GHz filter.

9.6 Derivation of domain field, voltage and depletion ratio

a) Field

The differentiator had been calibrated from step measurements, such that

$$V_{\text{diff}} = k_d \frac{dV_{\text{in}}}{dt}$$

where V_{diff} is the differentiator output voltage, k_d is the differentiator time constant (found experimentally to be 4.4×10^{-14} s), and V_{in} is the input voltage. If the voltage on the specimen is denoted by V , then

$$V_{\text{diff}} = k_p k_d \frac{dV}{dt}, \quad 9.6.1$$

k_p being the probe attenuation. As the high field domain is moving at uniform velocity v_d ,

$$\frac{dV}{dt} = v_d \frac{dV}{dx} = v_d E \quad 9.6.2$$

and from this and 9.6.1

$$E = \frac{1}{v_d} \frac{1}{k_p} \frac{1}{k_d} V_{\text{diff}} \quad 9.6.3$$

b) Voltage

The time scale of the plot of field against time as the domain passes the probe may be converted into one of distance via the velocity v_d :

$$dx = v_d dt$$

The area under this plot may therefore be written, using 9.6.3:

$$\int V_{\text{diff}} dt = \int E v_d k_p k_d \frac{dx}{v_d} = k_p k_d \int E dx = k_p k_d V_d$$

which shows that the domain voltage may be deduced from it independently of v_d . This domain voltage could be checked against a potential measurement, and against the domain voltage derived from a current-

voltage curve for the specimen, thus giving a check on the probe calibration.

c) Depletion ratio

Integration of Poisson's equation gives for the carrier density,

$$\frac{dE}{dx} = \frac{(n_0 - n)}{\epsilon} e$$

Hence, from the gradient of the field plot in the depletion region, the value of n in this region can be deduced.

9.7 Domain results

Because of the experimental difficulties with the probe and specimens, the amount of reliable data measured was limited, and was all from material with carrier density $8.2 \times 10^{14} \text{ cm}^{-3}$ and room temperature low-field Hall mobility $4360 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$. Domain profiles corresponding to domain voltages of 260 V and 370 V are shown in Fig. 9.6 ((a) and (c)), along with results of Robson et al.^[61] for domain voltages of 272 V and 392 V ((b) and (d)) from material with $n = 8 \times 10^{14} \text{ cm}^{-3}$, and results of Prew^[27] for a 325 V domain in material with $n = 6 \times 10^{14} \text{ cm}^{-3}$.

The domain voltages are close enough to enable a meaningful comparison to be made between the present results and those of Robson. The widths agree fairly well, but the peak fields are somewhat lower in the present work. Robson's detailed results give peak fields of 95 kV/cm and 140 kV/cm respectively for 260 V and 370 V domains, compared with 83 kV/cm and 126 kV/cm here. This may be taken as reasonably close agreement, which was maintained over the full range of domain voltages (Fig. 9.8). As might be expected from the smaller peak fields, the depletion ratios are also less: 23% and 41% respectively, compared with 35% and 50%. The width of accumulation layer remained constant at around 20 microns. The measured domain

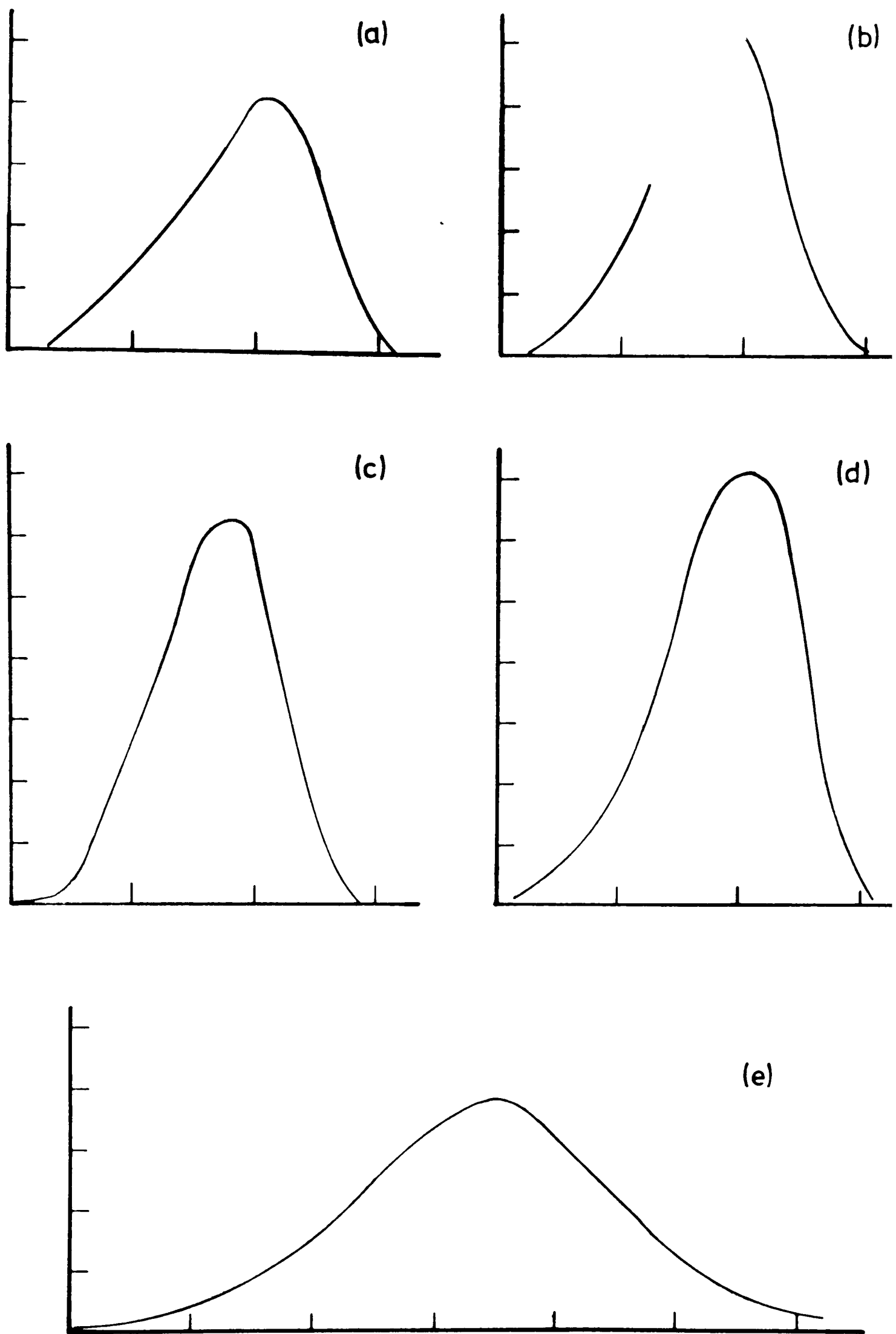


Fig. 9.6 Comparison of present domain field measurements with other published data.

Present results: (a) 260 V domain (b) 370 V domain
 Robson et al.: (c) 272 V domain (e) 392 V domain
 Prew: (d) 325 V domain
 Scales: Horizontal: 1 division = 20μ
 Vertical: 1 division = 20 kV/cm.

widths were approximately one half the width measured by Prew; consequently the peak fields were much greater.

Several measured domain velocities are plotted against domain voltage in Fig. 9.7, and show a scatter of around 10%; the straight line has been fitted to the data using a least squares fit. The velocities measured lie in the range 1 to 1.4×10^7 cm/sec., compared with 0.75 to 1×10^7 cm/sec as measured by Robson, whose results are included in Fig. 9.7 for comparison.

Fig. 9.8 shows the variation of peak domain field with domain voltage. Again results of Robson for a similar carrier density are shown for comparison and agreement is seen to be fairly good, with the present results showing somewhat lower peak fields. Two points are also included corresponding to the measured domain shapes of Boers and Prew. The apparently linear variation of peak field with domain voltage is in qualitative agreement with results of Prew^[90] who measured total domain change (and hence peak field) varying linearly with domain voltage.

9.8 Derivation of velocity-field characteristic

The 'equal areas rule' for high field domains is given in equation 1.8.5 and shown diagrammatically in Fig. 1.6, where, for the case of a field independent diffusion coefficient the two shaded areas are equal. It was expressed by Bastida et al.^[26] as

$$\int_{E_1}^{E_2} v(E) dE = (E_2 - E_1) v(E_1)$$

and differentiated with respect to E_1 , giving

$$\begin{aligned} v(E_2) &= v(E_1) + \frac{dv(E_1)}{dE_1} (E_2 - E_1) \\ &= v(E_1) + \frac{dv(E_1)}{dE_2} (E_2 - E_1) \end{aligned} \tag{9.8.1}$$

If $E_2 \gg E_1$, as was usually the case in these experiments, this simplifies to

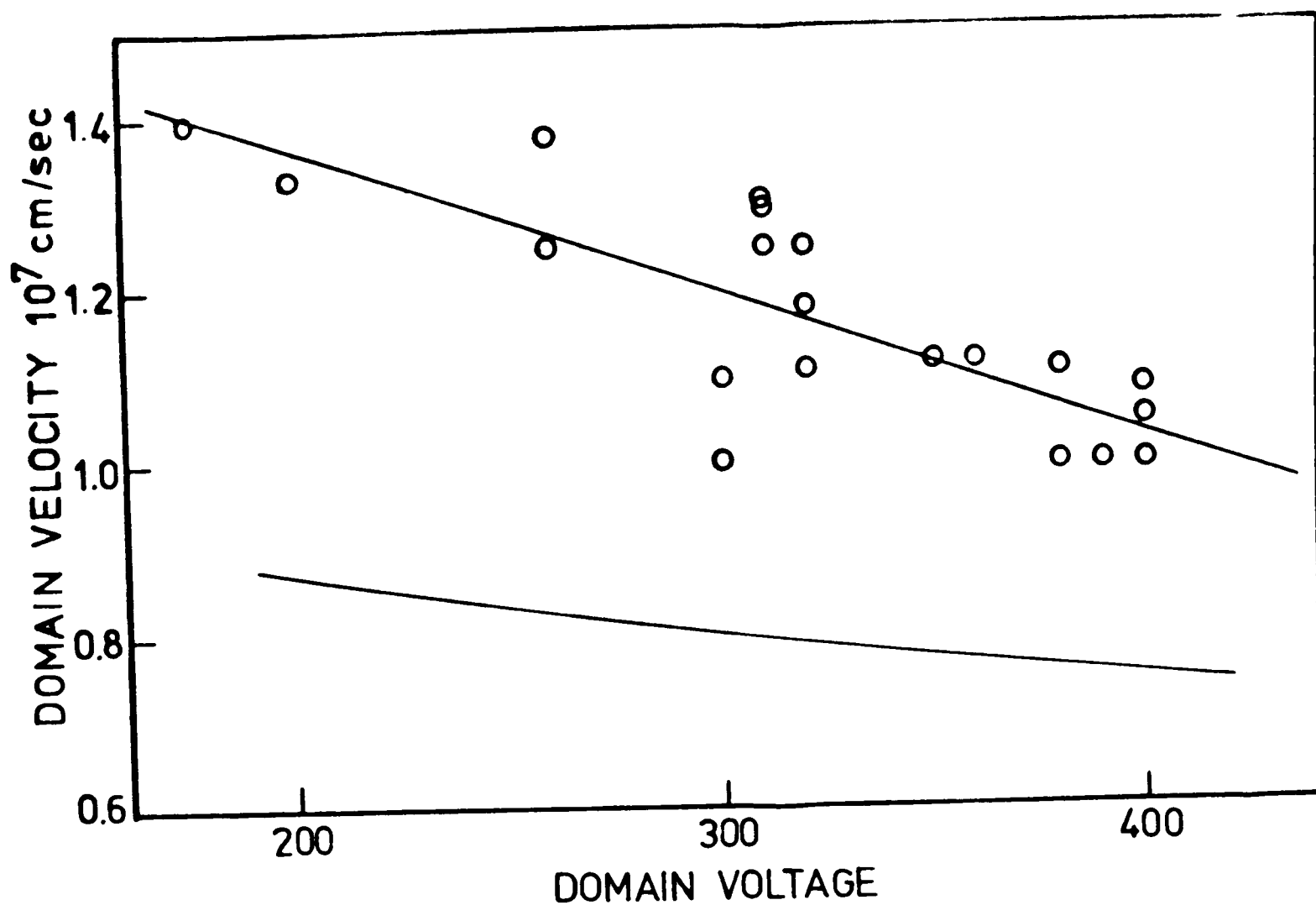


Fig. 9.7 Measured domain velocity plotted against domain voltage.

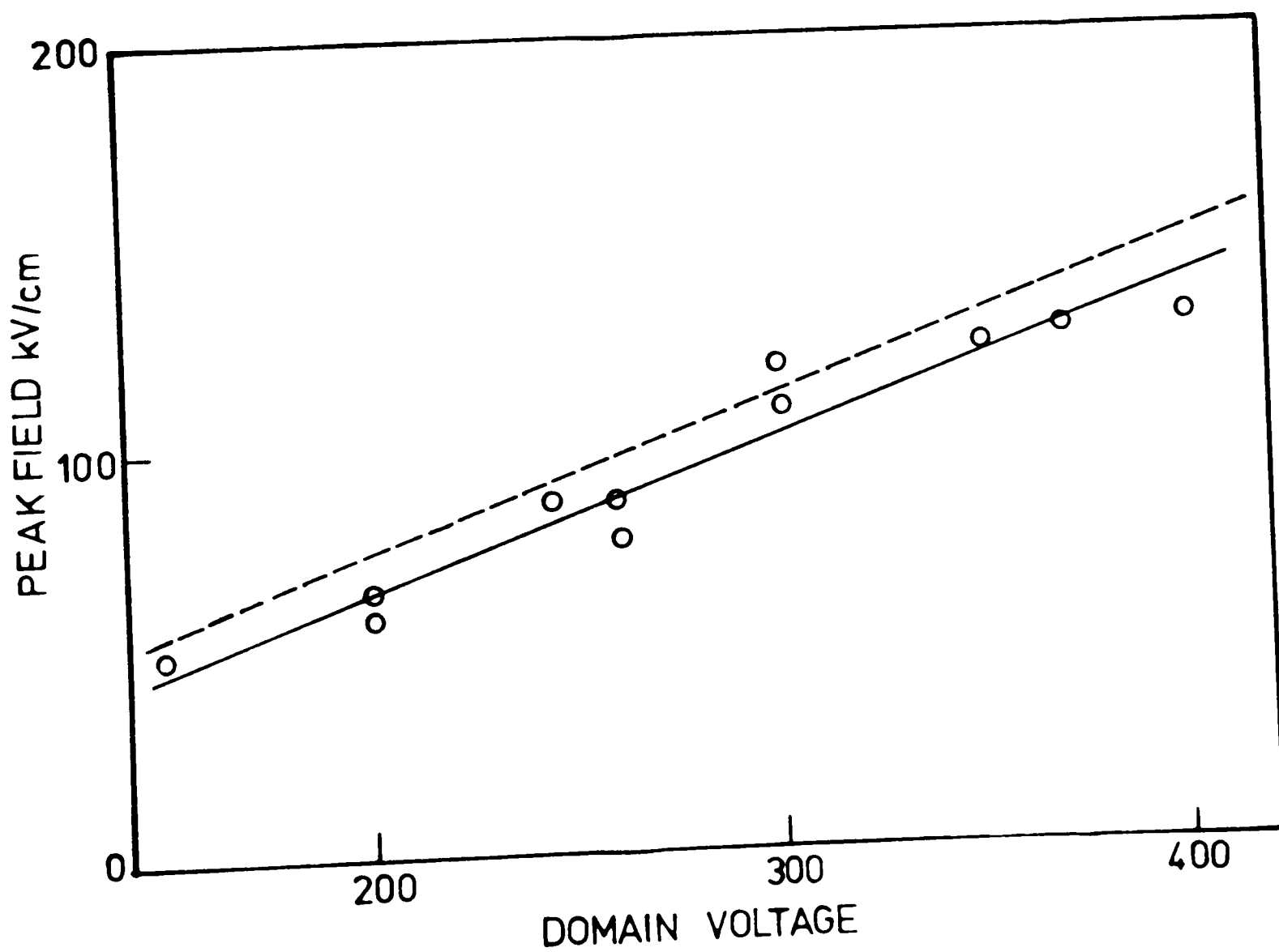


Fig. 9.8 Measured domain peak field plotted against domain voltage.

$$v(E_2) = v(E_1) + \frac{dv(E_1)}{dE_2} E_2 \quad 9.8.2$$

The values of $v(E_1)$ and V_D were obtained from the specimen current-voltage characteristic. Electric field was deduced by dividing the applied voltage by the specimen length; with such comparatively high resistivity material the voltage drop across the 10 ohm current measuring resistor could be neglected. The current scale was then transformed into one of drift velocity by normalising to the low-field drift mobility, and after normalisation a check was made to ensure that the resulting curve followed the sub-threshold characteristic of Fig. 5.17 as a precaution against specimens with anomalous contacts.

Peak domain field, E_2 was obtained from the measured domain voltage via Fig. 9.8, and hence the $v(E_1) - E_2$ relation of Fig. 9.9 resulted. Results are included here from several specimens. This data was then used in equation 9.8.2 to obtain $v(E_2)$, leading to the velocity-field relation shown in Fig. 9.10, which also includes the sub-threshold characteristic of Fig. 5.17.

9.9 Effects of diffusion

The calculations so far have been based on a diffusion coefficient assumed to be field independent, in which case the domain velocity is predicted (Section 1.8) to be equal to the electron velocity in the low-field part of the specimen. Measured domain velocities indicated that this was not so, and hence that neglecting the field dependence of D was unjustified.

Robson et al.^[61] obtain from the analysis of Bastida et al.^[26] and Allen et al.^[19] a modified version of equation (9.8.1), including the effect of diffusion:

$$v(E_2) = v(E_1) + \frac{dv(E_1)}{dE_2} \int_{E_1}^{E_2} \frac{D(E_2)}{D(E)} dE \quad 9.9.1$$

Calculations of diffusion coefficient in indium phosphide have been

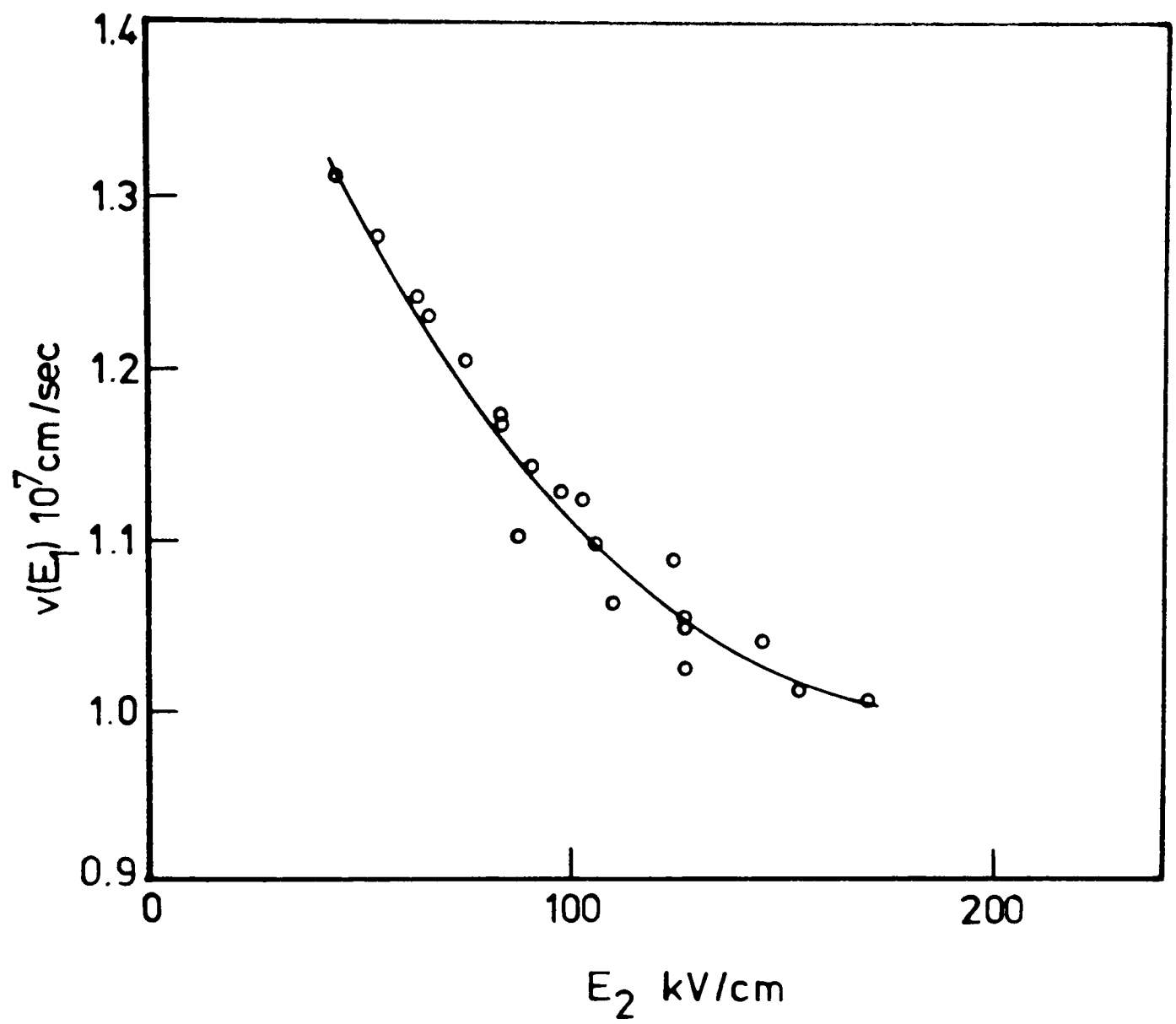


Fig. 9.9 Drift velocity outside domain plotted against domain peak field.

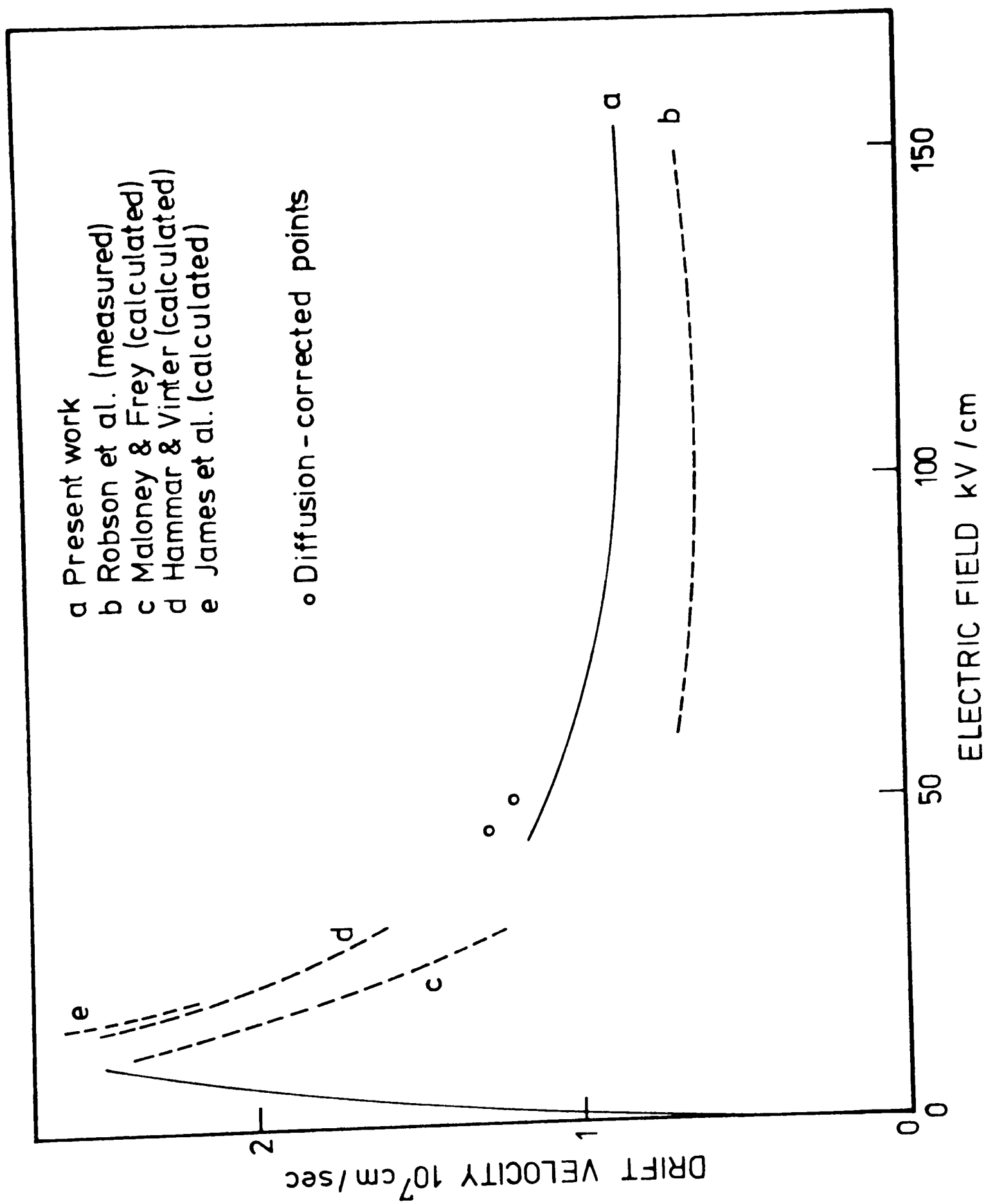


Fig. 9.10 Deduced high-field velocity-field characteristic compared with some calculated and other measured curves.

made by Hammar and Vinter^[91] for fields up to 25 kV/cm, by Fawcett and Hill^[48] and most recently Hill et al.^[92] for fields up to 50 kV/cm. The restricted field range of these means that a complete correction of the present results is not possible, most of the data being for peak domain fields greater than 50 kV/cm. Calculations were made, however, using (9.9.1) on the data for 45 kV/cm and 50 kV/cm, where it was found that the last term became respectively $0.28 (E_2 - E_1)$ and $0.35 (E_2 - E_1)$ (compared with $0.5 (E_2 - E_1)$ at 50 kV/cm calculated by Robson et al. from^[48]), giving the two points plotted in Fig. 9.10. As the D-E relation appears to be saturating for fields greater than 50 kV/cm, the corrections at such fields should be less, suggesting a valley velocity in the range $0.85 - 0.9 \times 10^7$ cm/sec, and hence giving a peak-to-valley ratio of 2.8. The total errors in the experiment were estimated at around 10%, making the predicted bounds of the valley velocity $0.76 - 0.99 \times 10^7$ cm/s.

9.10 Comparison with other results

Fig. 9.10 shows also the high-field velocity-field characteristics deduced by Robson et al.^[61]. The velocity measured in the present experiments is significantly higher, with a valley velocity of 0.9×10^7 cm/s at 130 kV/cm compared with 0.63×10^7 cm/s at 105 kV/cm. The shapes of the curves are seen to be similar. It is interesting that the difference in velocity is reflected in the domain velocity measurements, where the present measurements were again higher.

Whilst all these results have been deduced from material with a carrier density of $8.2 \times 10^{14} \text{ cm}^{-3}$, some current-voltage measurements were made, in early experiments, on a number of similar specimens with carrier densities of $1.5 \times 10^{15} \text{ cm}^{-3}$ and $2.4 \times 10^{15} \text{ cm}^{-3}$, as well as a few from other slices with lower densities. The values

to which the current dropped on formation of a domain gave values for $v(E_1)$ which were consistently in the same range as the values in the later experiments. Unfortunately, no domain measurements were made on these specimens, preventing the calculation of full $v - E$ characteristics, but, as the high field velocities had been found to be only 10% or so less than $v(E_1)$, these results may be taken as tending to confirm the deduced valley velocity.

None of the published calculated $v - E$ characteristics apart from that of Fawcett and Hill^[48] gives values for fields higher than 30 kV/cm, and so direct comparison with them is difficult (Fig. 2.4). Fawcett and Hill obtain a velocity below 1×10^7 cm/s at 50 kV/cm, and agree closely with the results of Robson et al. Fig. 9.10 includes the calculated curves of Hammar and Vinter^[41], of Maloney and Frey^[49] and of James et al.^[29], all for two-level models. The latter is of limited interest as the highest field point is at 20 kV/cm. The experimental results agree most closely with the trends of the other two curves, particularly that of Hammar and Vinter. Agreement with the three-level calculations, which predict a positive differential mobility in this field range, and with the characteristic measured by Prew^[27] is poor.

The best agreement with other experimental results in the high field range is with those of Nielsen^[43] and of 'T Lam and Acket^[42], both using microwave methods. The latter measured a higher threshold velocity of 2.9×10^7 cm/s, however, whereas the value of the former (2.5×10^7 cm/s) agrees well with the present low-field measurements. The best overall agreement is probably, therefore, with the measurements of Nielsen.

CHAPTER X

CONCLUSIONS

10.1 Electron transfer mechanism in indium phosphide

The results presented here agree consistently with most of the published data based on strong coupling between the Γ valleys and a set of upper valleys in the conduction band, the two-level model. There are large discrepancies with the predictions from the three-level model where $\Gamma - L$ coupling is weak, as Fig. 5.20 shows.

10.1.1 Sub-threshold measurements

Precautions have been taken in these experiments to ensure a uniform, known field in part of the specimen, the field values being checked three ways at room temperature. This ensured that at 77 K when direct probing was impossible the field in the specimens was accurately deduced from an analogue. The room-temperature measurements gave a threshold field around the middle, and a threshold velocity a little below the middle of the several comparable published values.

The only calculated $v - E$ relation at 77 K is that of Maloney and Frey^[49], with which the present results compare well, the threshold velocity agreeing closely, although the measured threshold field is lower. No other measurements at 77 K exist, but comparisons with extrapolations of measured (Majerfeld et al.) and calculated (Fawcett and Hill) data show closer agreement (Figs. 5.24 and 5.25). This comparison gives credibility to the present results and suggests that Maloney and Frey overestimate E_T , a conclusion which is supported by the measurement of Parkes et al. at 110 K^[87].

Maloney and Frey took an intervalley coupling constant $D_{\Gamma L}$ of 2.5×10^9 eV/cm, compared with the values between 5.9×10^8 eV/cm and

8.3×10^8 eV/cm used by Fawcett and Hill, and a $\Gamma - L$ separation of 0.6 eV rather than 0.52 eV; both these differences could cause the difference in threshold field, although in comparison the former would dominate, the scattering rate being proportional to the square of the coupling constant. A further difference lies in the phonons assumed responsible for intervalley scattering, Fawcett and Hill considering separately optical and acoustic phonons with respective temperatures of 405 K and 103 K, whereas Maloney and Frey take a common phonon temperature of 320 K. As a change in the coupling constant would affect the threshold field at all temperatures, and as the threshold field predicted by Maloney and Frey at 300 K agrees well with other models and with experiment, this seems unlikely to be the reason for the discrepancy at 77 K, the different phonon mechanism being a more probable explanation.

Together with the results of Majerfeld et al., then, the present results indicate good agreement of E_T and v_{DT} with Fawcett and Hill's theory over a wide temperature range from 77 K to 450 K (Figs. 5.24 and 5.25). The coupling constant $D_{\Gamma L}$ here has been shown^[46] to be sufficiently large for the X valleys to play a negligible part in the conduction process.

10.1.2 Overall velocity-field characteristic

Comparison of the overall $v - E$ characteristic with calculations is not straightforward, as most of the calculated curves go to fields no higher than 30 kV/cm, meaning that the ranges covered by theory and experiment do not overlap; the curves can be compared only by estimating their trends between 30 and 50 kV/cm. Taking the room temperature results (Fig. 5.17 and Fig. 9.10), the closest overall agreement is with the theoretical work of Maloney and Frey^[49] and Hammar and Vinter^[41], (See Fig. 2.4). Both use two-level mechanisms, but rather differently. Maloney and Frey take

$D_{\Gamma L} = 2.5 \times 10^9$ eV/cm and m^*/m in the upper valleys = 0.4, whereas Hammar and Vinter postulate a two-level transfer mechanism between the Γ and X valleys, m^*/m in the X valleys = 0.4, and an intervalley phonon temperature of 430 K rather than 320 K, (this, and the wider separation of the Γ and X valleys should tend to give a larger threshold field); agreement with the latter is better for higher values of $D_{\Gamma X}$ (1×10^9 eV/cm and 2×10^9 eV/cm), there being very little difference between these two curves in the field range in question. The value of m^*/m used here for the X valleys, 0.4, is higher than the value which has been used elsewhere, 0.25; substituting this would raise the valley velocity, and enable agreement with experiment to be achieved with a lower coupling constant.

Because Hammar and Vinter give no curves for other temperatures and because of the discrepancy between the threshold fields measured and predicted by Maloney and Frey for 77 K, definite agreement with one or other theory cannot be claimed. The conclusion drawn is that the transfer mechanism behaves as a two-level one, either with all three levels present and strong $\Gamma - L$ coupling, or with the L levels playing no part and a perhaps less strong $\Gamma - X$ coupling.

10.2 Comparison with microwave measurements on similar material

The sub-threshold room temperature measurements have been compared with others made using a microwave heating method on specimens from the same slices, showing agreement of threshold field and velocity to within 10% on three slices out of four, a figure well within the combined experimental errors. Although no more material was available from these slices for domain measurements, the slice used (CJ 423) had properties similar enough to two of the others to allow a comparison. Comparison is also hampered because

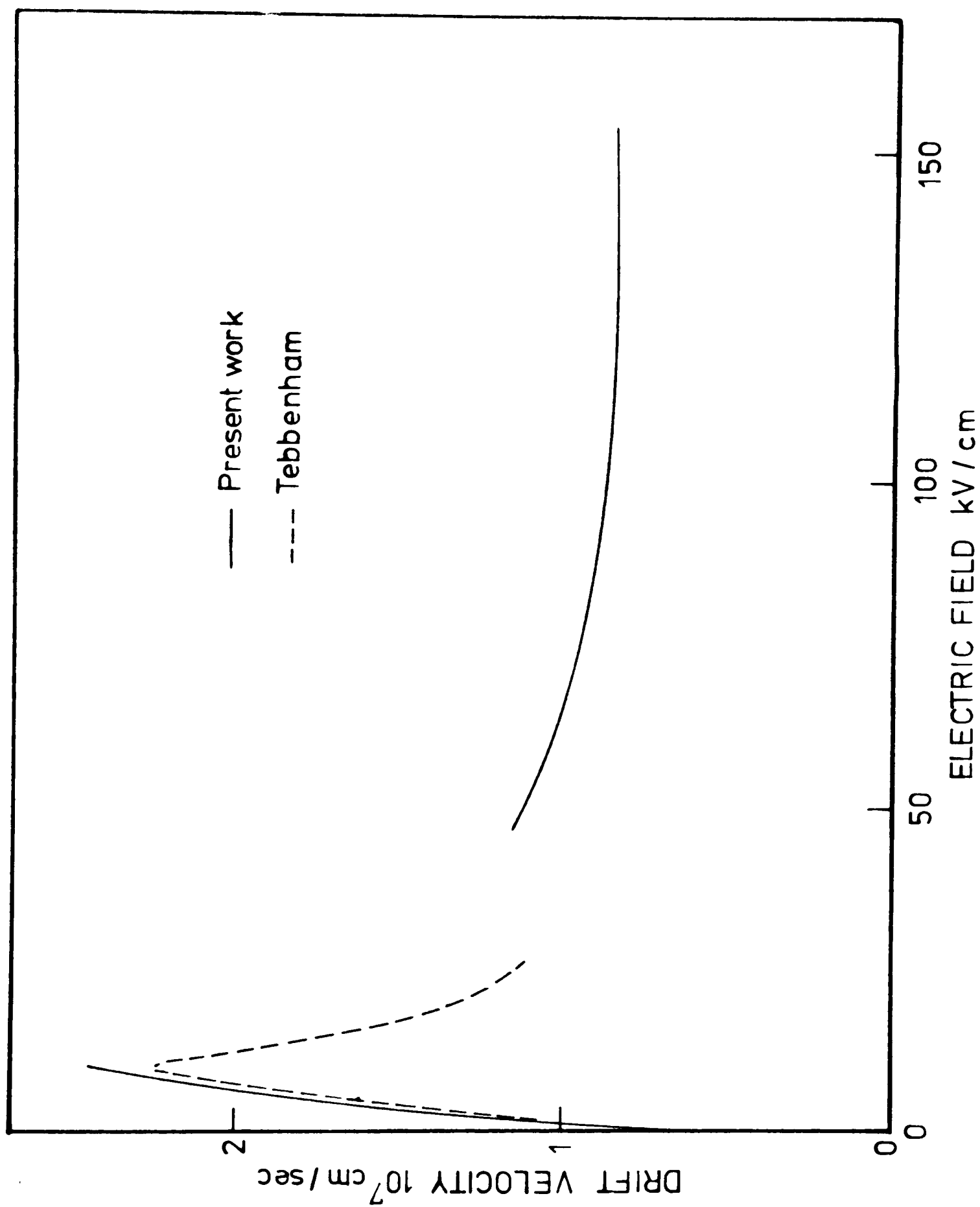


Fig. 10.1 Comparison of velocity-field characteristic deduced from the present work with that measured by Tebbenham.

of the limited field range in the microwave measurements, but extrapolation of the results suggests a valley velocity in the range $0.6 - 0.9 \times 10^7$ cm/s. This compares favourably with the present measurements, particularly when it is remembered that the specimen temperatures in the microwave measurements were about 40 K above ambient, which would tend to give a velocity lower than that at room temperature. Satisfactory overall agreement between the two sets of experiments can therefore be concluded (Fig. 10.1).

10.3 Point-contact probe design and measurements

The object of the probe experiments was to repeat the measurements made by Prew^[27] with a point-contact probe, which had given domain parameters and a velocity-field relationship different from other measured results: as far as is known, no other published results exist using a point-contact probe.

As it is important that the probe characteristics should be known to be suitable, and no detailed treatment of the point-contact probe exists in the literature, experiments have been carried out to find the optimum design, and a simple mathematical model made of this design. It was found that the probe and specimen had to be treated as a complete system, and that the optimum resistance for the probe depended on the resistivity of the semiconductor. Perhaps the most important result is that overshoot in the probe response cannot necessarily be equalised simply by adding distributed shunt capacitance from the resistor to earth; if the resistor is too large, it is impossible to obtain a flat frequency response in this way. The spreading resistance and contact resistance where the probe point touches the semiconductor are vital components in fixing the probe's response, and so it is necessary to ensure that they remain sensibly constant - in particular the point must be kept at the same diameter.

Despite these precautions the point-contact probe was still found very difficult to use, mainly, it is thought, because of variations in contact resistance between point and semiconductor. Biasing the probe in the manner of Thim and Barber^[31] gave no improvement in response, while increasing the unreliability of the probe, seemingly because of increased localised heating of the specimen immediately underneath the point. This may well be a fundamental limitation to the point-contact probe.

Using epitaxial semiconductor emphasised the problems, as any surface damage can be very significant. On specimens of bulk material, small amounts of surface damage may be tolerated, and the probe contact could perhaps be improved by applying more pressure to it. Avoidance of surface damage necessitated the rejection of tungsten in favour of nickel probe points for epitaxial material, but increased pressure would too easily deform nickel and tungsten could be substituted with advantage. The work functions of nickel and tungsten are respectively 5.01 eV and 4.49 eV, which makes the Schottky barrier height similar with the two metals, implying a similar probe performance.

Results obtained agreed broadly with other high-field domain measurements made with capacitive probes, and the deduced velocity field characteristic was markedly different from that obtained by Prew, tending to agree with measurements made by microwave methods. It has been shown that capacitive and point-contact probes do not give fundamentally different domain measurements, as long as the probe has been correctly designed and equalised. The implication of these experiments and calculations on the probe is that the broad, symmetrical, low-domain shape measured by Prew may have been due to a poorly designed probe system which was showing a slower response than expected.

10.4 The possibility of high-field measurements at low temperatures

It would be useful to be able to extend the high-field domain measurements to low temperatures to supplement the sub-threshold measurements there. However, with the probe in its present form this would be impracticable, unless it were re-designed to be in permanent contact with the specimen inside the low-temperature chamber. It would, too, be impracticable to move the probe to make domain velocity measurements; a possible solution might be to have two probes at points on the specimen a known distance apart. Their response would, of course, have to be equalised to suit the much lower resistivity of the material at these two temperatures.

A better solution, which might also be applicable to room temperature measurements, would be to use photo-lithography to deposit fine transverse lines of metal on the specimen. These could be only a few microns wide and would form the 'point-contact' probes. Small resistors could be attached close to the specimens and connected to the output lines. Experiment would obviously again be needed to optimise the response, but some of the contact problems may be overcome. With the specimen at a lower temperature, localised heating under the probe may be less of a problem. A capacitive probe might be made in a similar way, by depositing a thin insulating layer between the semiconductor and the metal.

APPENDIX 1

Temperature rise of specimens in low field measurements

a) Room temperature measurements

Fig. A.1 shows a model of an H-type specimen on the perspex mount, with idealised dimensions. The worst case which can occur is that of low resistivity material biased to a voltage giving just below threshold field in the central region. A typical specimen of this type passed 0.3 A with 600 V applied in the form of 25 ns pulses with a p.r.f. of 100 Hz, giving for the average power input

$$600 \times 0.3 \times 25 \times 10^{-9} \times 100 = 4.5 \times 10^{-4} \text{ W.}$$

From the approximate dimensions of the specimen, its volume is about 2.8 mm^3 , giving a mass of $2.8 \times 4.8 \times 10^{-6} \text{ Kg}$. Now if there were no heat loss, and the specific heat of indium phosphide is taken as $0.153 \times 10^3 \text{ J Kg}^{-1}\text{K}^{-1}$ [84], the rate of rise of temperature would be

$$\frac{4.5 \times 10^{-4}}{0.153 \times 10^3 \times 2.8 \times 4.8 \times 10^{-6}} = 0.22 \text{ Ks}^{-1}. \quad \text{A.1}$$

Considering heat loss by conduction through the perspex mount (clearly this ignores convection and radiation from the specimen), and regarding the copper plate as an infinite sink at room temperature, the rate of heat loss is given by

$$\frac{0.2 \times 10 \times 10^{-6}}{2 \times 10^{-3}} \theta = 10^{-3} \theta \quad \text{A.2}$$

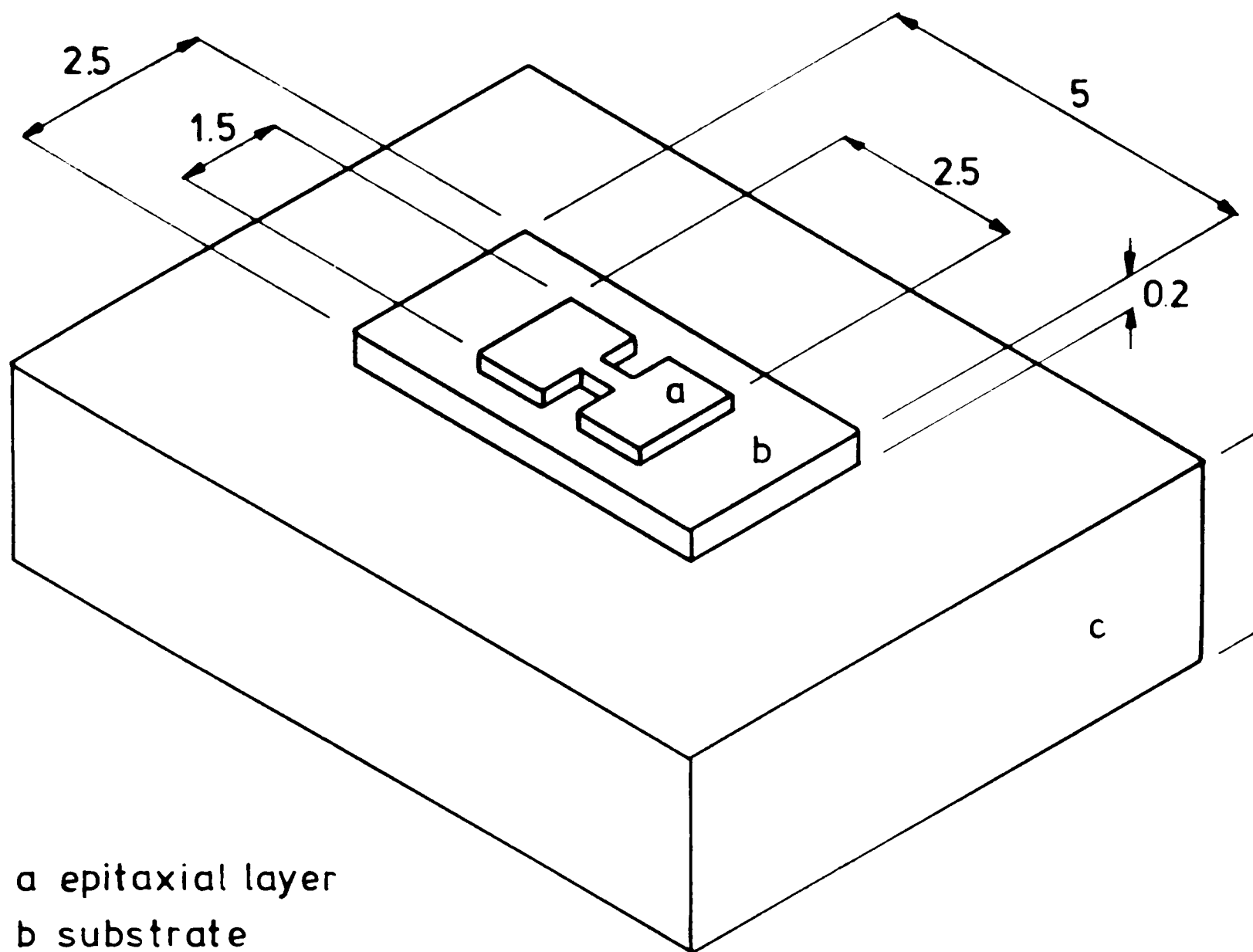
where θ is the excess temperature of the specimen, and the thermal conductivity of perspex has been taken as $0.2 \text{ Wm}^{-1}\text{K}^{-1}$. Equating A.1 and A.2 gives

$$\theta = 0.45^\circ \text{ K}$$

This is obviously negligibly small, and, as the calculation has taken the worst case of all the parameters, shows that the specimens may be assumed to be at room temperature.

b) 77 K measurements

For the specimens used for these measurements, the power input was about the same as that already calculated. In the low-temperature apparatus the specimens were mounted directly on the copper heat sink, kept cool by liquid nitrogen. Taking the latent heat of vaporisation of nitrogen as 5.59 KJ mol^{-1} , a power of $4.5 \times 10^{-4} \text{ W}$ corresponds to a rate of evaporation of nitrogen of 0.0022 gm s^{-1} [85], which is very small, and could easily be supplied by the reservoir in the apparatus. Other heat supplied to the nitrogen would be responsible for most of the evaporation.



a epitaxial layer

b substrate

c perspex

(all dimensions in millimetres)

Fig. A.1. Model used for estimating specimen temperature rise.

APPENDIX 2

A2.1 The simulated domain function

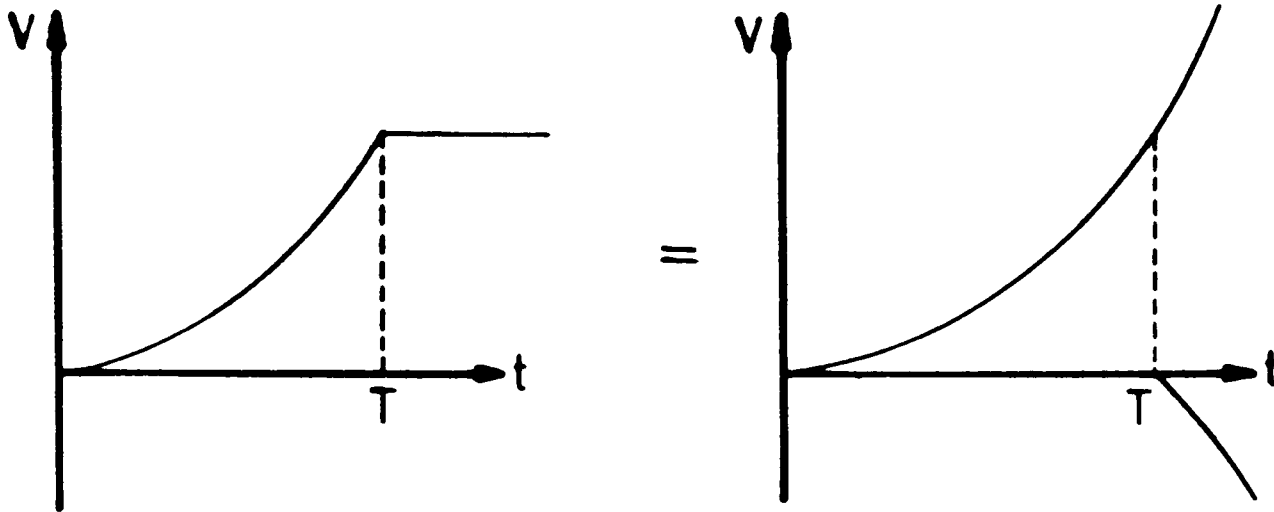


Fig. A2.1

The simulated domain function $f(t)$ may be split up and represented as the sum of two functions, as shown in Fig. A .1.

$$f(t) = t^2 - u(T) (t'^2 + 2t'T) \quad \text{A2.1.1}$$

where $u(T)$ is a unit step function at time t , and

$$t' = t - T.$$

Taking the Laplace transform of A1.1 term by term, and using the Laplace transform shifting theorem to transform the second term gives

$$F(s) = \frac{2}{s^3} - e^{-sT} \left(\frac{2}{s^3} + \frac{2T}{s^2} \right) \quad \text{A2.1.2}$$

A2.2 Step response and response to domain simulation

Applying a unit step function (Laplace Transform $\frac{1}{s}$) as an input to (8.4.1) gives for $I(s)$

$$\frac{(1 + Zs)^3}{s(as^3 + bs^2 + cs + d)} = \frac{D}{s} + \frac{E}{s + A} + \frac{F}{s + B} + \frac{G}{s + C} \quad \text{A2.2.1}$$

where $-A, -B, -C, -D$ are the roots of $as^3 + bs^2 + cs + d = 0$ and $D, E,$

F, G are constants and functions of a, b, c, d, Z. Inverting A2.1 gives

$$i(t) = D + Ee^{-At} + Fe^{-Bt} + Ge^{-Ct} \quad \text{A2.2.2}$$

Applying (8.5.2) as an input to (8.5.1) gives for the transform of the output

$$\frac{2(1 + Zs)^3}{s^3(s + A)(s + B)(s + C)} \frac{\omega^4}{(s + \omega)^4}$$

$$- e^{-sT} \left[\frac{2(1 + Zs)^3}{s^3(s + A)(s + B)(s + C)} \frac{\omega^4}{(s + \omega)^4} + \frac{2T(1 + Zs)^3}{s^2(s + A)(s + B)(s + C)} \frac{\omega^4}{(s + \omega)^4} \right]$$

Splitting this into partial fractions by the standard method and inverting gives the output domain voltage. For $t < T$,

$$v_1(t) = dt^2 + ft + g + he^{-At} + je^{-Bt} + ke^{-Ct}$$

$$+ e^{-wt}(lt^3 + mt^2 + nt + p)$$

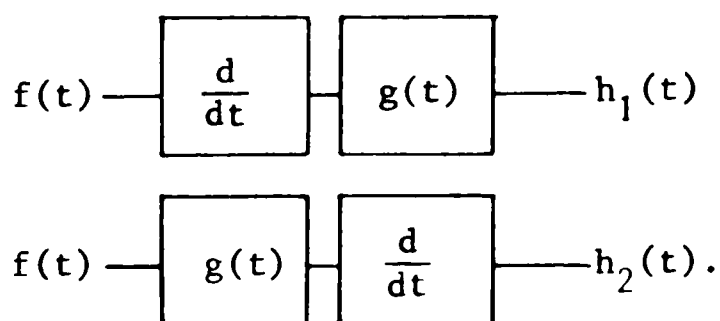
and for $t > T$,

$$v_2(t) = v_1(t) - v_1(t') - 2T[qt' + r + se^{-At'} + ve^{-Bt'}$$

$$+ xe^{-Ct'} + e^{-wt'}(\alpha t'^3 + \beta t'^2 + \gamma t' + \delta)]$$

where d, f, g, h, j, k, l, m, n, p, q, r, s, v, x, α , β , γ , δ are all constants and functions of A, B, C, Z and w.

A2.3 Treatment of differentiation in system transfer function



When a signal $f(t)$ passes through a system with impulse response $g(t)$, the output is given by

$$\int_{-\infty}^{\infty} f(t - \tau)g(\tau)d\tau.$$

which immediately gives

$$h_1(t) = \int_{-\infty}^{\infty} f'(t - \tau)g(\tau)d\tau.$$

Now,

$$\begin{aligned} h_2(t) &= \frac{d}{dt} \int_{-\infty}^{\infty} f(t - \tau)g(\tau)d\tau \\ &= \int_{-\infty}^{\infty} f'(t - \tau)g(\tau)d\tau \\ &= h_1(t) \end{aligned}$$

showing that the position of the differentiation is immaterial.

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Subthreshold velocity-field characteristic of *n*-type indium phosphide at 77 K

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Measurements of the subthreshold velocity-field characteristic at 77 K using a direct technique show reasonable agreement with theoretical predictions, but show a lower threshold field. Comparisons of threshold values of field and velocity with extrapolations from other measured and theoretical data are favorable.

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Maloney and Frey¹ have recently calculated a velocity-field characteristic for indium phosphide at 77 K based on a two-valley conduction-band structure. This letter describes the results of subthreshold measurements on epitaxial *n*-type indium phosphide at this temperature.

The technique used was similar to that described by Majerfeld *et al.*,² where an H-shaped specimen was used to produce an active region of uniform field remote from the contacts. The material used was on a semi-insulating substrate, and the required geometry was formed as a mesa structure by photolithography. The contacts were a tin-silver alloy. The specimens were included in a 50-Ω circuit, so that specimen voltage and current in response to applied 25-ns voltage pulses could be measured on a sampling oscilloscope, and were mounted in direct contact with a copper block cooled by liquid nitrogen, the whole assembly being contained in an evacuated chamber. The temperature of the specimen block close to the specimen was monitored by a thermocouple.

The voltage across the central region of the specimens, and hence the field there, was deduced using measurements on a resistance-paper analogue which, at room temperature, gave excellent agreement with direct measurements using a point-contact probe. The low-field Hall mobility was known, and this enabled the current-voltage characteristic to be converted to a drift velocity-field characteristic, a Hall scattering factor of

1.05 at this temperature being taken from measurements by Potter³ on similar material.

Results from four specimens are shown in Fig. 1, along with the calculated curves of Maloney and Frey for impurity densities N_D of 0 and 10^{17} cm⁻³. The specimen data is summarized in Table I.

The results from specimens 1–3 are seen to agree quite closely in shape with the theoretical curve for $N_D = 0$, which is clearly the more appropriate to material with these values of n and μ_H at 77 K. There is, however, some discrepancy between the measured and calculated values of threshold field. The results for specimen 4 are seen to tend towards the curve for $N_D = 10^{17}$; again this is in agreement with expectations, as the low value of mobility of this material suggests a larger amount of impurity scattering.

The mean threshold field of the four specimens is 6.9 kV/cm, and the mean threshold drift velocity of specimens 1–3 (neglecting the low-mobility specimen 4) is 3.9×10^7 cm/s. It is interesting to compare these results with other low-temperature data: Majerfeld *et al.*⁴ measured the subthreshold velocity field characteristic over the temperature range 446–118 K, and this was shown by Fawcett and Hill⁵ to agree well, particularly in the case of the threshold field, with a calculation based on unscreened electron-phonon interactions. These data are shown in Figs. 2 and 3 where they are extrapolated to lower temperatures, showing reasonable agreement with the present results.

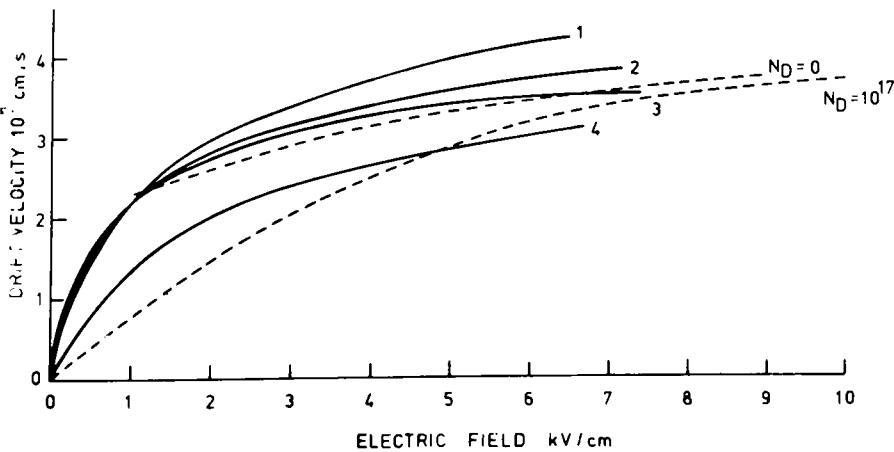


FIG. 1. Velocity-field characteristics of InP at 77 K, (—): present results; (---): Maloney and Frey (theory).

TABLE I. Specimen data.

Specimen	μ_H (300 K) (cm ² V ⁻¹ s ⁻¹)	μ_H (77 K) (cm ² V ⁻¹ s ⁻¹)	n (77 K) (cm ⁻³)
1	4600	48 000	1.4×10^{15}
2	4740	55 400	7.1×10^{15}
3	4740	55 400	7.1×10^{15}
4	4140	17 100	5.5×10^{15}

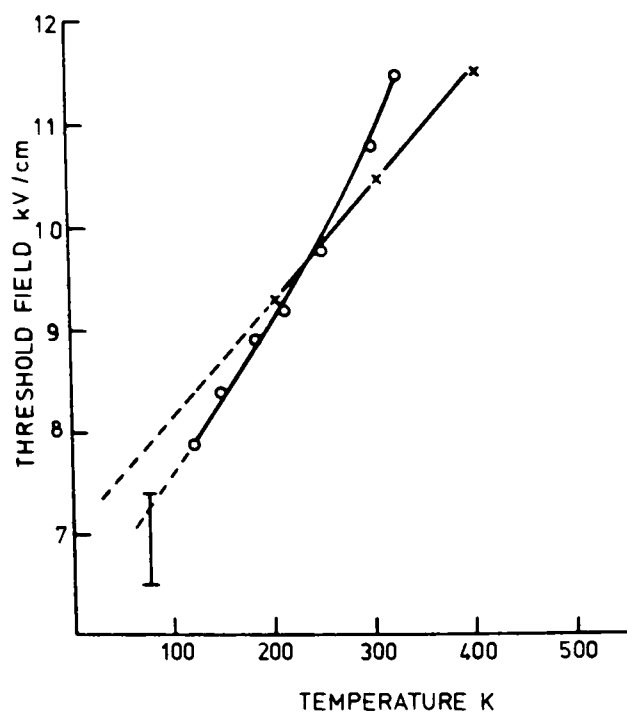


FIG. 2. Threshold field plotted against temperature. $\times$: Fawcett and Hill (theory); $\circ$: Majerfeld *et al.* (measured); I : present results.

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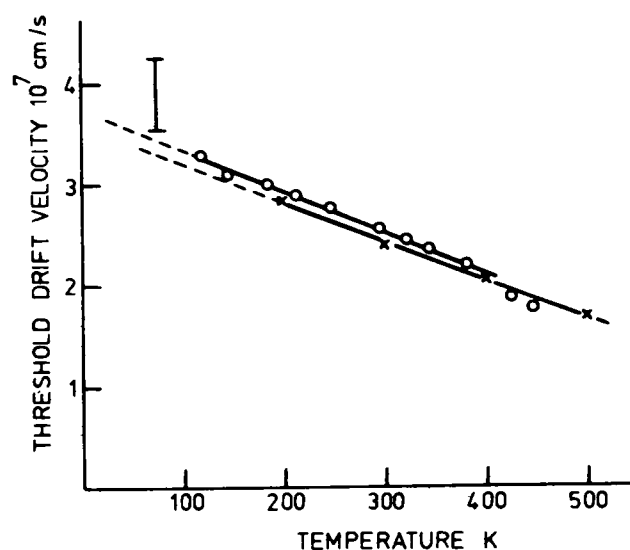


FIG. 3. Threshold velocity plotted against temperature. $\times$: Fawcett and Hill (theory); $\circ$: Majerfeld *et al.* (measured); I : present results.

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