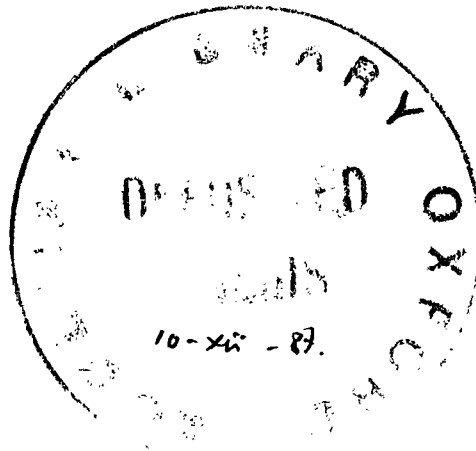


**SCANNING OPTICAL MICROSCOPY OF**  
**SEMICONDUCTOR DEVICES**

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A thesis submitted for the degree of Doctor of Philosophy  
at the University of Oxford

Department of Engineering Science,  
Parks Road,  
Oxford.

**To my mother and father**

## **FOREWORD..**

Grains of sand  
Melt and mould  
And carve a slice  
To mesh a mirror?  
No, not quite.  
Take up a mask  
Diffuse in life,  
Feed from a source  
Via Midas strings  
And watch  
The magic  
Happening...

And then to look  
From deep within  
A bar of light  
Is focused in.  
The magic carpet  
Surface hides  
Confidences  
To confide  
And light,  
Delight  
Clear sparkling eyes  
Which want  
To open wide and see  
The magic  
Of OBICuity.

## ACKNOWLEDGEMENTS

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## **ABSTRACT**

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July 1987

### **SCANNING OPTICAL MICROSCOPY OF SEMICONDUCTOR DEVICES**

This thesis explores the interaction of light and semiconductors using a scanning optical microscope. A key advantage to this approach is its non-destructiveness. This is a critical factor in the assurance of semiconductor device reliability. This research investigates novel ways in which the light beam of a scanning optical microscope may be used to detect defects in semiconductors. Attention is focused on the use of the optical beam induced current technique (OBIC). This method permits the imaging of defects in semiconductor devices which may affect the electrical performance of these devices.

For the first time a theory has been developed which forms the basis of an understanding of how excess minority carriers are distributed in a semiconductor when probed with a with a finely focused light beam. This theory is used to predict the resolution of device defects imaged using OBIC. This work is particularly important in that it may incorporate the exact light probe distribution in the semiconductor material which is calculated in this thesis.

A new method to display low contrast OBIC images has been used to highlight defects in semiconductor devices. In addition an exciting novel method to obtain spatial information on the distribution of defects at the silicon/silicon-dioxide interface in metal oxide semiconductor devices has been found. This method can examine many defects which cause serious problems for device manufacturers including the effect of radiation damage on device performance. Other non-destructive techniques which can complement OBIC imaging are explored including photoluminescence and infrared transmission imaging. Additional research is proposed for the future. This research in conjunction with the research in this thesis would allow a comprehensive and powerful examination approach of both static and dynamic conditions of semiconductor devices.

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# **CHAPTER 1**

## **INTRODUCTION**

### **1.1 INTRODUCTION**

While the computer industry continues to call for a lower cost per calculation the demand for a new level of reliability in semiconductor devices becomes increasingly important. Semiconductor device reliability is a critical factor in applications where computer downtime or circuit failure is not acceptable. These applications include the use of semiconductor devices in communications systems for transatlantic cables or space satellites where device replacement on failure is not possible or in terrestrial computing and control systems where the poor performance of devices may have serious consequences in terms of cost and safety. This quest for reliability has highlighted the importance of non-destructive techniques to examine semiconductor devices.

This thesis explores the interaction of light and semiconductors using a scanning optical microscope (SOM). It investigates several non-destructive techniques which this arrangement allows to examine semiconductors and semiconductor devices. The thesis focuses attention on the use of the optical beam induced current technique (OBIC) which permits the imaging of defects in semiconductor devices which may affect the electrical performance of these devices. The research involves the use of the SOM as a multi-purpose tool to yield important information on the position, nature and inhomogeneity of device defects. This information may be used in process control and in routine device inspection to ensure higher quality in device performance and reduced device cost.

## **1.2 SCANNING LIGHT MICROSCOPY-BACKGROUND**

In 1951 Roberts and Young<sup>1,1</sup> first introduced a new means of building up an image of an object by scanning. The light transmitted by each point of the object was detected by a photocell. This facilitated control of contrast. Roberts and Young defined the problem of resolution as the problem in separating the light passing through very close regions of the object. The conventional microscope in Fig. 1.1 does this by using refraction by lenses to separate the light from neighbouring regions. Roberts and Young suggested reversing the lens system to produce a minute spot of light. By making this spot scan the object, discrimination between neighbouring points is obtained by passing the light through them at different times. The resulting spot fell on a photocell allowing subsequent amplification as required. This method was based on the well-known flying-spot scanning technique using two cathode-ray tube rasters locked together. It was called a flying-spot microscope. This microscope provided all the advantages of conventional microscopy with the important additional advantages of contrast and brightness control and the possibility of quantitative analysis. The contrast control was made possible by varying the amplifier gain.

The flying-spot system had the advantage that the image was in the form of an electronic signal suited to image processing techniques. However, it had a disadvantage in that the light spot was not very bright. Thus a long period of time was necessary to build up a picture. The later invention of the laser and its incorporation as the light source in a scanning microscope overcame this problem and also increased the number of wavelengths at which the instrument could operate. Hence the observation of semiconductors in transmission became possible by imaging in the infrared <sup>1,2</sup>. In addition, many different modes of imaging have been developed for the scanning optical microscope (SOM) including conventional, confocal and extended focus imaging. The SOM has been developed at Oxford University

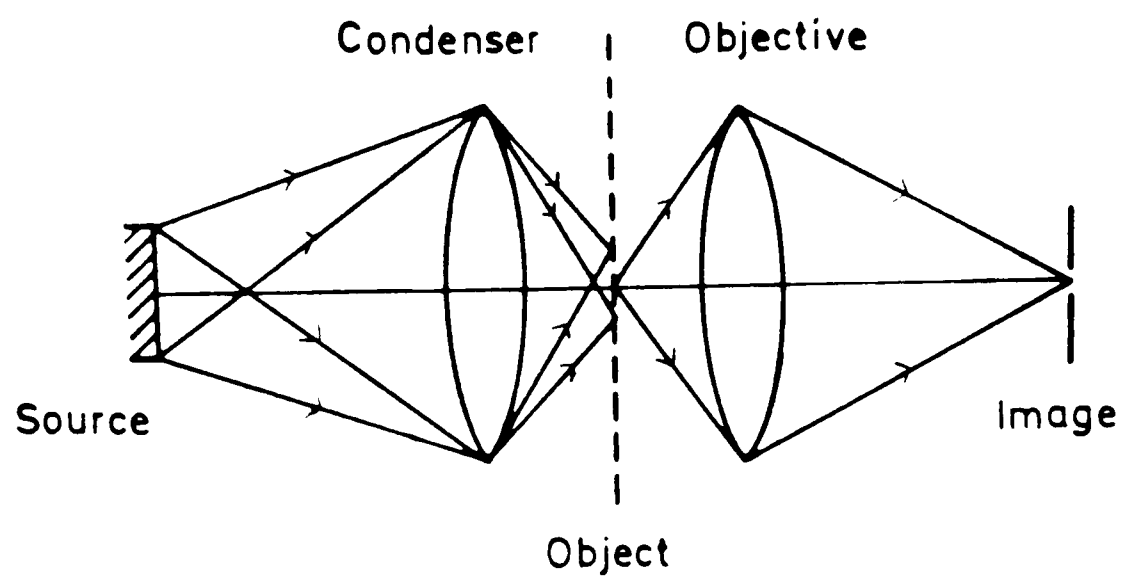


Fig.1.1.

The optical arrangement of a conventional optical microscope

into a high performance, easy-to-use and versatile instrument<sup>1,3</sup>. This versatility is evidenced by its sequential imaging system which allows images to be stored in a computer. In contrast to the parallel processing system of a conventional microscope, sequential imaging gives an image whose format is readily suited to electronic processing and to manipulation in various enhancement schemes.

The Oxford University SOM used in the experimental work in this thesis uses a scanning arrangement where the object is scanned and the light beam is stationary. Whereas a conventional microscope must image off-axis points this arrangement has the advantage that each point may be imaged on-axis. On-axis imaging means easier and less expensive lens design and fabrication. The resolution and contrast may be improved in the SOM compared to conventional microscopy by using the confocal imaging mode. Also in confocal imaging there is a unique optical sectioning property which allows imaging of thick objects, measurement of surface topography and extension of depth of focus.

### 1.3 SCANNING

Scanning could be achieved in principle by scanning a point detector across the image field in a conventional microscope (Fig.1.1). Here the object is illuminated with a patch of light from an extended incoherent source by a condenser lens. The object is imaged as shown, the final image being viewed through an eyepiece. This arrangement would not allow an important imaging mode for semiconductor devices to be used, called optical beam induced current imaging. This imaging mode is introduced later in this chapter. It may be shown by reciprocity<sup>1,4</sup> that the arrangement of Fig.1.2(b) using a point source and an incoherent detector has the same imaging properties as the microscope of Fig. 1.2(a) and the conventional microscope of Fig.1.1 if the roles of the two lenses are interchanged. This is the form of the Type 1 scanning microscope.

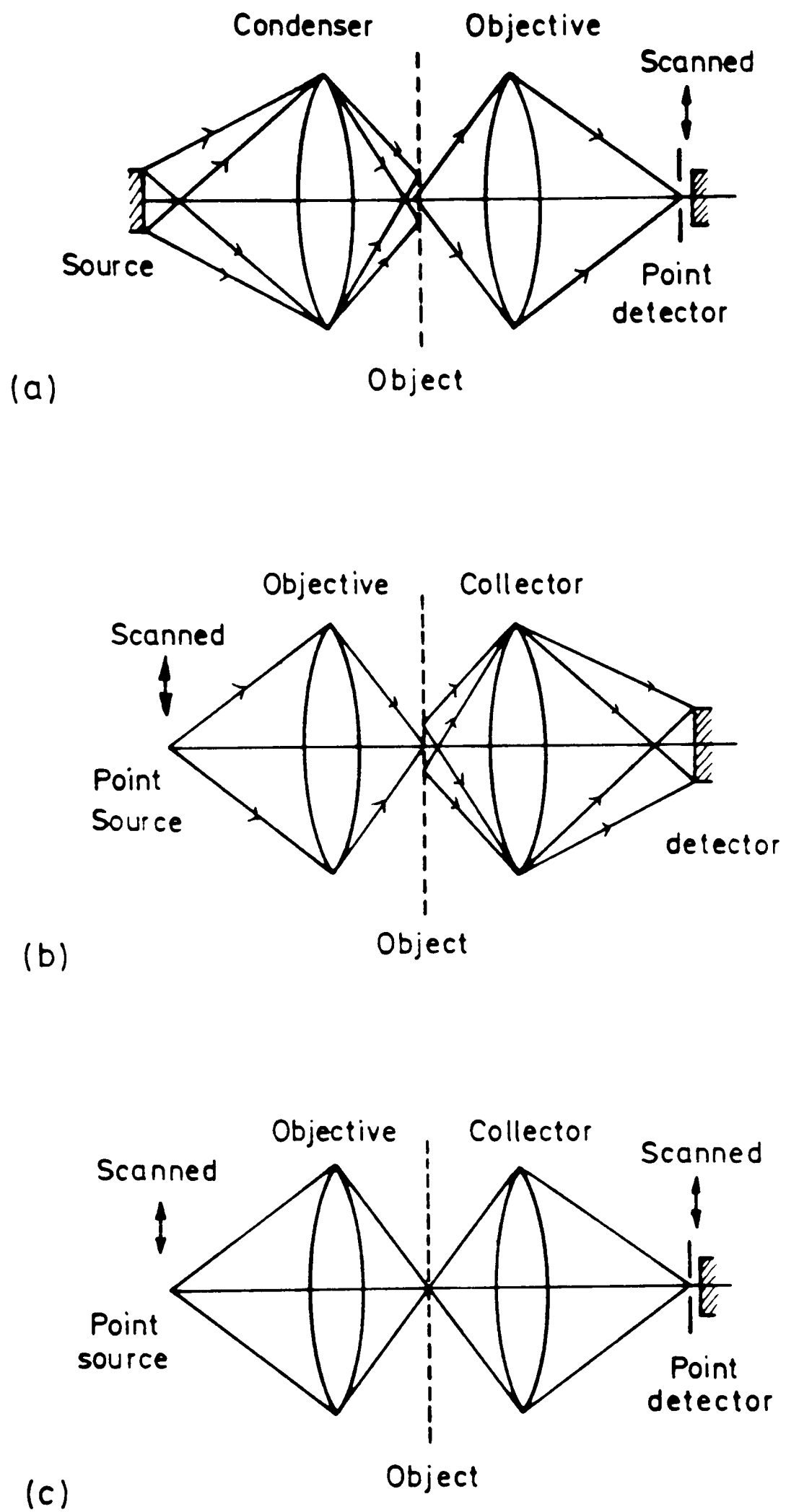


Fig.1.2.

(a) Type 1(a) scanning microscope

(b) Type 1(b) scanning microscope

(c) Type 2 or confocal scanning microscope

A number of scanning laser microscopes have been developed <sup>1.5–1.13</sup> over the years . The schematic layout of the scanning optical microscope used in work for this thesis is shown in Fig.1.3. Fig.1.4 shows one of the practical arrangements of this SOM. Only one point of the object is illuminated at a time as a focused laser is scanned relative to the object in a TV like raster. The required relative motion between the object and the diffraction limited spot of light may be achieved either by scanning the light beam across a stationary object or by mechanically moving the object relative to the stationary spot.

### **Mechanical scanning :**

Gannaway<sup>1.14</sup> adopted a mechanical scanning approach. The object is mechanically scanned with the advantage that the optical system remains stationary. This means that off-axis aberrations are unimportant allowing cheaper lenses to be used. The scanning arrangement adopted in this approach involves suspending the object between taut piano wires whose tension serves to keep the object in the same plane throughout the scanning cycle. Electro-mechanical vibrators attached to the wires provide the scanning. Thus there is a continuous magnification facility simply by altering the drive to the vibrators. Ichioka et al.<sup>1.9</sup> also use the object scanning approach. They determine precise sample position on a specimen by using an interference comparator.

### **Beam or lens scanning :**

Beam or lens scanning is more suited to examination of large specimens such as semiconductor wafers or in photoluminescence experiments which require a specimen to be cooled. However this method has the disadvantage that the light path through the objective is non-axial. Vignetting may also be the problem. Hence for ultimate resolution highly corrected microscope objectives would have to be used. Müller<sup>1.6</sup>

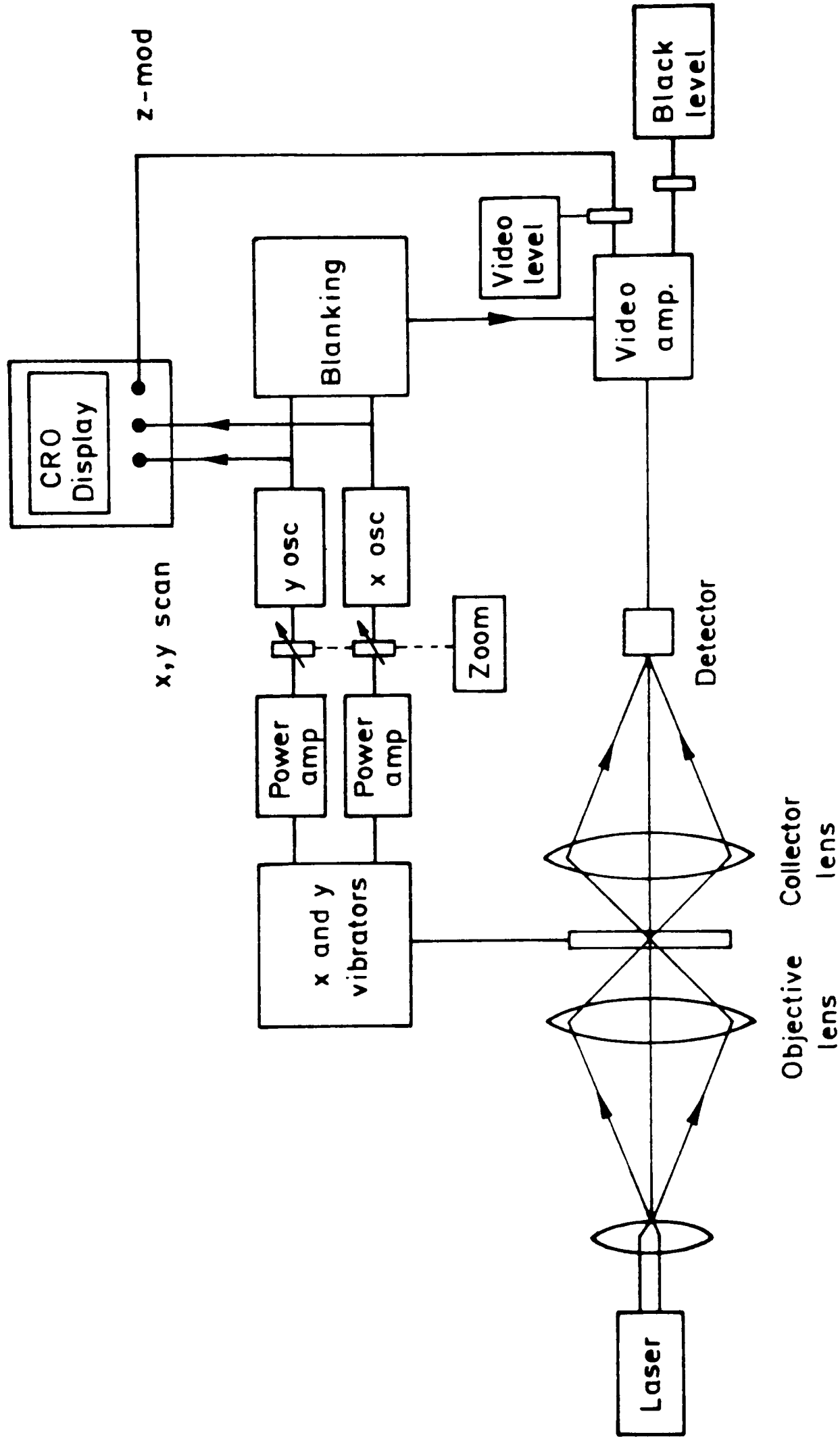


Fig.1.3

Schematic of the scanning optical microscope

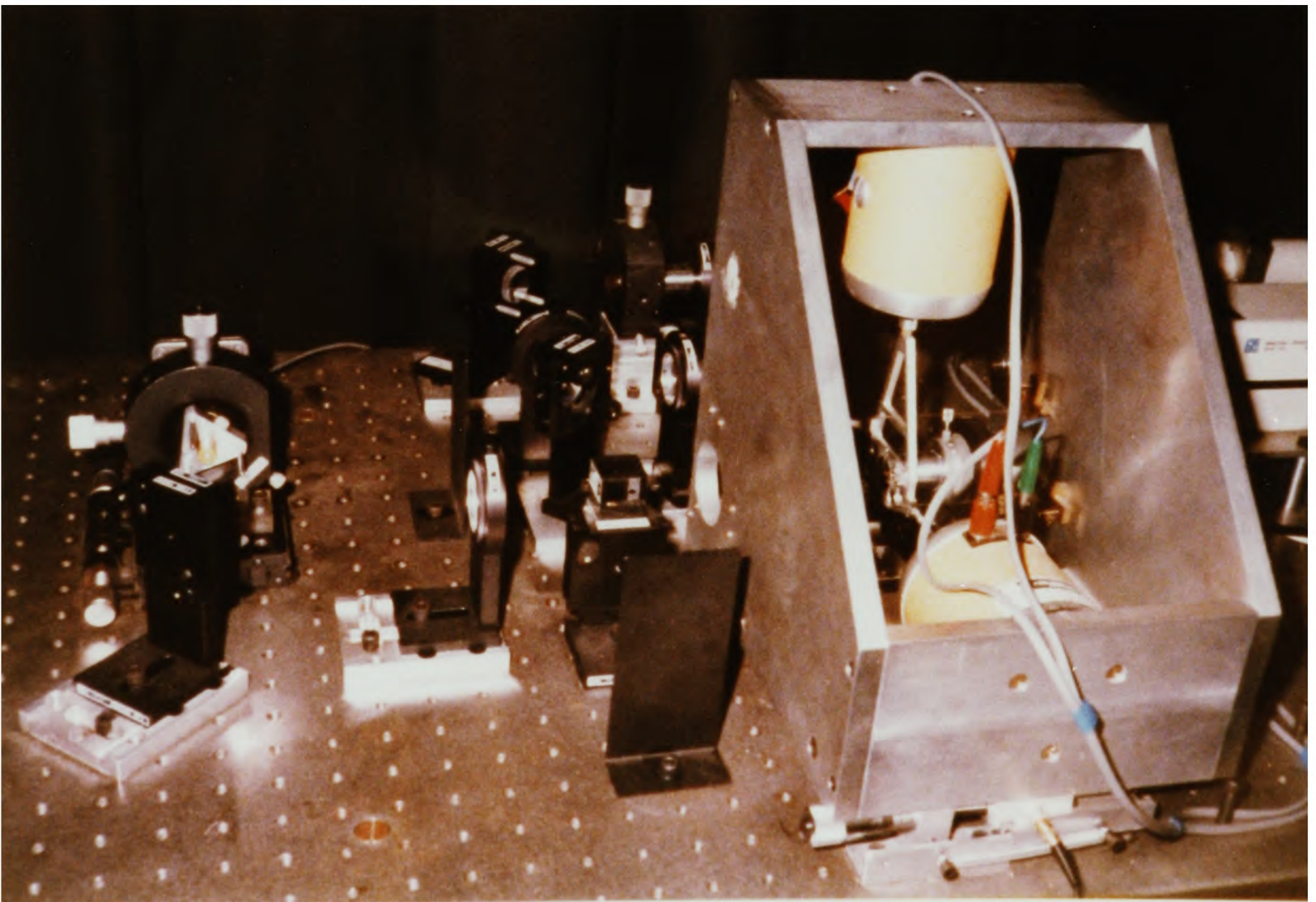
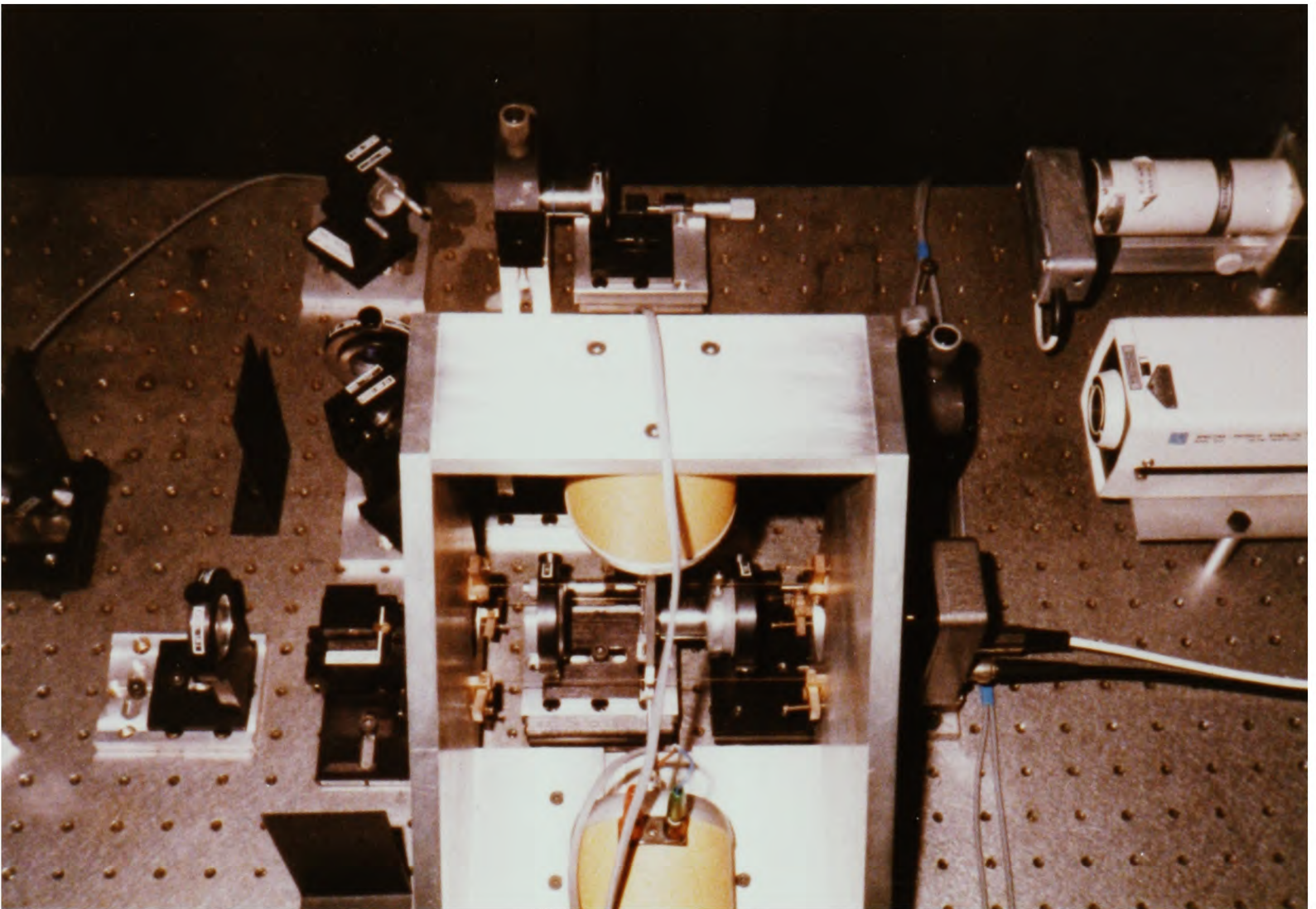


Fig.1.4 A practical arrangement of the scanning optical microscope

uses mirrors to scan the light beam. Jungerman et al.<sup>1.12</sup> use an acousto-optic beam deflector. It should be noted that the Bragg cell used in such beam deflection gives a beam intensity which is dependant on the angle through which the beam is scanned. Thus for small angles of scan this may not be important. For larger angles, however, this intensity dependance on scan position should be taken into account.

Lens scanning<sup>1.15</sup> is an alternative scan mode which allows the object to remain stationary thus giving the same imaging conditions for each scan point. However the beam scanning approach has the potential to be faster.

In conclusion a combination of the above scanning methods may provide the optimum raster scheme.

## **1.4 METHODS AVAILABLE TO EXAMINE SEMICONDUCTOR DEVICES**

This section gives a brief summary of instrumental methods used to examine semiconductor devices and to solve problems that arise in VSLI development efforts. The objectives of these methods fall into four general categories:

- (a) Morphology determination
- (b) Electrical mapping of device defects and failure
- (c) The determination of crystallographic structure and mechanical properties
- (d) Chemical analysis

The applications of these methods in the context of semiconductor device investigation are summarised in Table 1.1 Methods 1-7<sup>1.16-1.23</sup> in this table use a light beam as a non-destructive probe. These methods include the use of a surface photovoltage technique<sup>1.17</sup> to examine p-n junctions which is being used by Dr.C.Munakata at Hitachi's Central Research Laboratory in Tokyo and also by Dr.T.H.Di Stefano at

| Method                                                    | Acronym | Electrical Analysis | Morphology Determination | Crystallographic Structure | Chemical Analysis |
|-----------------------------------------------------------|---------|---------------------|--------------------------|----------------------------|-------------------|
| 1. Light Reflection                                       | OBIC    | *                   | *                        |                            |                   |
| 2. Optical beam Induced Current                           |         |                     |                          | *                          |                   |
| 3. Light transmission                                     |         |                     |                          | *                          |                   |
| 4. Photoluminescence                                      |         |                     |                          | *                          |                   |
| 5. Scanned and Surface Photovoltage <sup>1.16, 1.17</sup> |         | *                   |                          |                            |                   |
| 6. Nomarski Interference Contrast <sup>1.18</sup>         |         |                     | *                        |                            |                   |
| 7. Electro-optic Sampling <sup>1.19–1.23</sup>            |         | *                   |                          |                            |                   |
| 8. Secondary Electron Emission                            |         |                     | *                        |                            |                   |
| 9. Electron Beam Induced Contrast                         | EBIC    | *                   |                          | *                          |                   |
| 10. Transmission Electron Microscopy                      | TEM     | *                   |                          | *                          |                   |
| 11. Voltage Contrast                                      |         | *                   |                          |                            |                   |
| 12. Auger Electron Spectroscopy                           | AES     |                     |                          |                            | *                 |
| 13. Secondary Ion Mass Spectroscopy                       | SIMS    |                     |                          |                            | *                 |
| 14. X-Ray Diffraction                                     |         |                     |                          | *                          |                   |

Table 1.1

IBM Yorktown Heights. Another interesting method is being examined by Professor D.M.Bloom's group at Stanford University. This group is pursuing research in electro-optic sampling of gallium arsenide(GaAs) circuits<sup>1.19-1.23</sup>. Novel transistors fabricated using GaAs may have very short lifetimes of the order of 10ps. Sampling oscilloscopes can resolve lifetimes approaching 25ps. This points to the need for Professor Bloom's novel approach in sampling voltage waveforms of such circuits. For completeness additional methods are included. Methods 8-12 use an electron beam. Other methods use ion beams or X-rays to examine the devices. This thesis is concerned with the use of a light beam in methods 1-4 using the scanning optical microscope.

Reasons for using the optical probe of the scanning optical microscope instead of the electron beam of the scanning electron microscope(SEM) include the simplicity of the SOM and the fact that the SOM does not require a vacuum system. Also use of the SOM avoids the charging problems associated with the SEM in the examination of Metal Oxide Semiconductor devices, for example. The electron beam can deposit lines of contamination on the specimen surface caused by decomposition of organic vapours in the vacuum system. The SOM, however, does not cause device damage<sup>1.24,1.25</sup>.

## 1.5 IMAGING IN THE SCANNING OPTICAL MICROSCOPE

Methods of imaging frequently used in the scanning optical microscope include:

- (a) REFLECTION - Type 1 and Confocal
- (b) PHOTOCURRENT (OBIC)
- (c) PHOTOLUMINESCENCE
- (d) EMISSION
- (F) INTERFERENCE MICROSCOPY

This thesis is concerned principally with OBIC imaging of defects. An introduction to reflection imaging will be given as an illustration of the use of the SOM. Then OBIC imaging will be described briefly. Chapter 8 considers the use of emission imaging for a light emitting diode. Interference microscopy in the SOM is described elsewhere<sup>1,26</sup>.

### 1.5(a). LIGHT REFLECTION

Type 1 imaging in the SOM has already been described. This method allows surface features of a semiconductor device to be imaged. Use of the SOM in the confocal or Type 2 mode allows increased resolution in the focal plane. If a small pinhole is placed in front of the detector so that it behaves as a point detector a confocal microscope is formed which has different and superior imaging properties to the Type 1 arrangement<sup>1,26</sup>. A small region of the object is illuminated with a focused laser spot, and the point detector also detects light from this small region resulting in higher resolution. The confocal or Type 2 imaging arrangement is shown in Fig. 1.2(c). The image of a point object is about one third sharper in a confocal microscope.

The confocal arrangement results in a unique optical sectioning property. Light scattered by parts of the object away from the focal plane are defocused at the detector pinhole and hence detected weakly. Thus, unlike conventional microscopy in which the out-of-focus parts of the object appear blurred, in a confocal microscope they do not contribute to the image. By scanning the object in an axial direction, it is possible to build up a series of image slices. If these are summed a greatly extended depth of focus may be obtained giving what may be called an extended focus image.

### Depth discrimination :

The improvement in resolution obtained using confocal instead of Type 1 or conventional imaging may be explained by a principle described by Lukosz<sup>1.27</sup> which states that resolution may be improved at the expense of field of view. For many purposes it is preferable to use a microscope with a small depth of field. For such applications the depth discrimination property of the confocal scanning microscope is ideal.

Consider the intensity along the axis of a focused light beam which varies as

$$I(u) = \left( \frac{\sin u/4}{u/4} \right)^2 \quad (1.1)$$

where  $u$  represents the distance from the focal plane in optical units<sup>1.28</sup>. Consider the confocal optical case where light from outside the focal plane of the collector lens forms a defocused spot at the detector plane as in Fig. 1.5. Since an axial point detector is used, this results in a much weaker signal and therefore provides the required discrimination<sup>1.29</sup>.

This optical sectioning is clearly not present in the Type 1 scanning microscope or in the conventional instrument as the large area detector collects all the light from all sections of the object. Real time confocal images may be obtained<sup>1.30</sup> using a rotating Nipkow disc with a large number of pinholes etched in it. A large depth of focus with high resolution imaging is desirable when examining a micro-circuit. By moving a micro-circuit specimen axially using a confocal scanning microscope, a different portion of the object may be brought into focus at each axial position. At each focus position out of focus information will be rejected. Thus the image of a rough object may be obtained such that all areas appear in focus by scanning the object in the axial direction with an amplitude sufficiently large for every part of its surface to pass through its focal plane.

The confocal technique is potentially very powerful as it permits the depth of

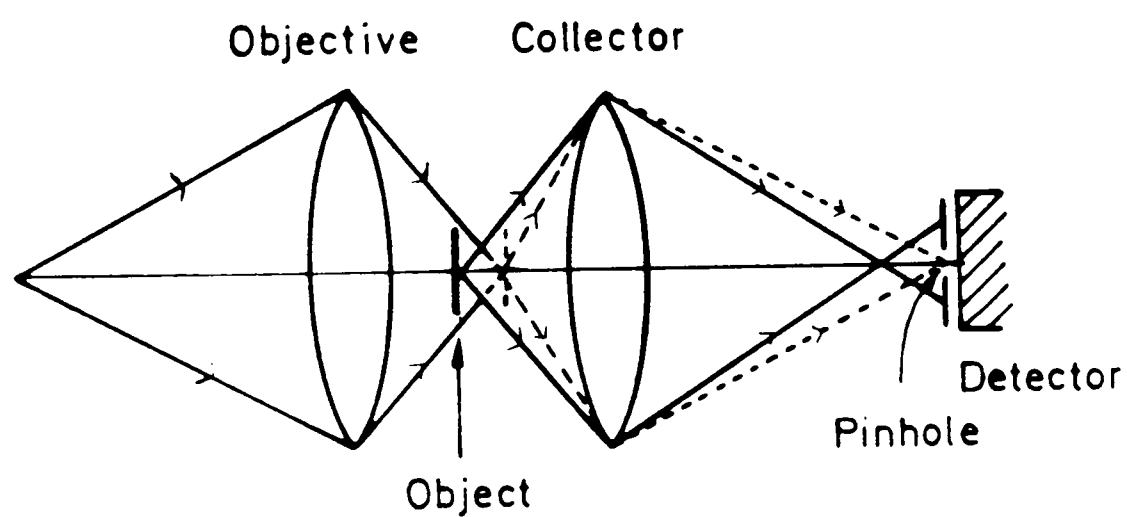


Fig. 1.5

Depth discrimination in a confocal microscope.

When the object is in the focal plane (dashed lines) the transmitted light is focused on the pinhole. When the object is out of the focal plane a defocused spot is formed at the pinhole and the detected intensity is much reduced.

field in optical microscopy to be extended in principle without limit, while still retaining high-resolution, diffraction-limited imaging.

### **Surface profiling with the confocal scanning microscope :**

The intensity  $I(u)$  in the image of a point object placed on the optic axis of a reflection confocal microscope at a normalised distance  $u$  from the focal plane of the lens is given by Eq. 1.1. As the object passes through focus the image intensity shows a sharp maximum. This result may be used to measure the surface profile of an object along a line scan. As the specimen is scanned in the axial direction, the position of the stage in each cycle of the scan where the intensity maximum occurs, will depend on the height of the object's surface. For a depression in the surface, the maximum occurs when the stage is nearer to the lens. Thus a measure of the stage position at the occurrence of the maximum in each cycle gives a measure of the surface profile of the specimen.

D.K. Hamilton et al.<sup>1,31</sup> describe a high resolution surface profiling technique. They use a feedback arrangement by moving the object axially to maintain a constant phase relationship between the signal and the reference beams of a confocal interference microscope.

### **Contrast Enhancement :**

Since the image in a scanning optical microscope is always in the form of an electronic signal contrast enhancement has always been possible. The image may be digitised with the advantage that many sophisticated contrast enhancement techniques may be employed. One technique, which is very useful in examination of areas of almost uniform brightness, consists of shifting a particular grey level to mid-grey and increasing the slope of the grey level mapping. The gain control in the SOM is used to vary the signal level relative to mid-grey in the display<sup>1,32</sup>. A d.c. offset is introduced before the gain control enabling the feature of interest to

be set to mid-grey after which increasing gain should simply increase its contrast. This technique is useful in observing detail in infrared transmission microscopy as well as in OBIC images.

### **1.5(b). OPTICAL BEAM INDUCED CURRENT IMAGING (OBIC)**

Photocurrent imaging allows inhomogeneities in minority carrier lifetime in a semiconductor device to be mapped out. This gives information on defects which may alter the electrical performance of the device. OBIC imaging can highlight defects below the surface of the device which would not be visible in the reflection image, grain boundaries buried beneath the surface of a polycrystalline cell, for example<sup>1,33</sup>

Consider the focused light beam of a SOM being scanned relative to the surface of the device under examination generating hole-electron pairs as it does so. A junction near the surface is used to collect a current which is displayed as a function of position, producing an image of the defects or inhomogeneities in the material. The structure of the image is due to fluctuations in the current produced by material inhomogeneities in the vicinity of the scanned beam. Defects act as sinks for the photo-excited carriers which would otherwise diffuse to a junction region and be collected as junction currents.

#### **Theoretical Background to the OBIC Method:**

The mechanism of carrier generation is such that illumination of the specimen with radiation of higher energy than the band gap causes the generation of excess carriers. It has been demonstrated<sup>1,26</sup> that it is possible to induce sufficient excess carriers into a semiconductor with a laser beam. In the absence of an external voltage source, the induced electron-hole pairs will flow externally if the specimen exhibits photo-voltaic effects to generate emfs in the specimen and so drive currents

around the circuit. This is the case for a p-n junction where a built-in voltage due to the space charged depletion region is present. Hence photo-induced currents may be collected from a p-n junction under no bias. The magnitude of the photo-current or the corresponding photo-voltage depends on the detection circuit.

Consider the energy band diagram of a p-n junction as shown in Fig. 1.6. The band bending arises from the requirement that the Fermi Level must be constant across the junction in equilibrium. Hence it is near the conduction band in n-type and near the valence band in p-type material. There is a space charge region of positive and negative charge layers on either side of the junction. This dipole layer produces a change in potential,  $qV_0$ , the 'diffusion voltage'. It is this change in potential which is manifested as energy band bending. The depletion region constitutes a high resistivity barrier.

When the specimen is probed by the laser the photo-induced holes and electrons are separated by the built-in field. This results in a flow of current generated in and near the junction. Light generated holes in the depletion region are swept to the p-side of the junction by the electric field at the junction. Similarly light generated electrons are swept to the n-side. These separated carriers produce a non-equilibrium potential difference,  $V$ , which unlike  $V_0$ , can lead to current flow in an external circuit. This is indicated in Fig. 1.7 and is the basis of the optical beam induced contrast (OBIC) method of semiconductor examination. As a result of laser beam excitation the Fermi levels are no longer equal in the p- and n-type material. External work can thus be done where the extra energy comes from the incident beam.

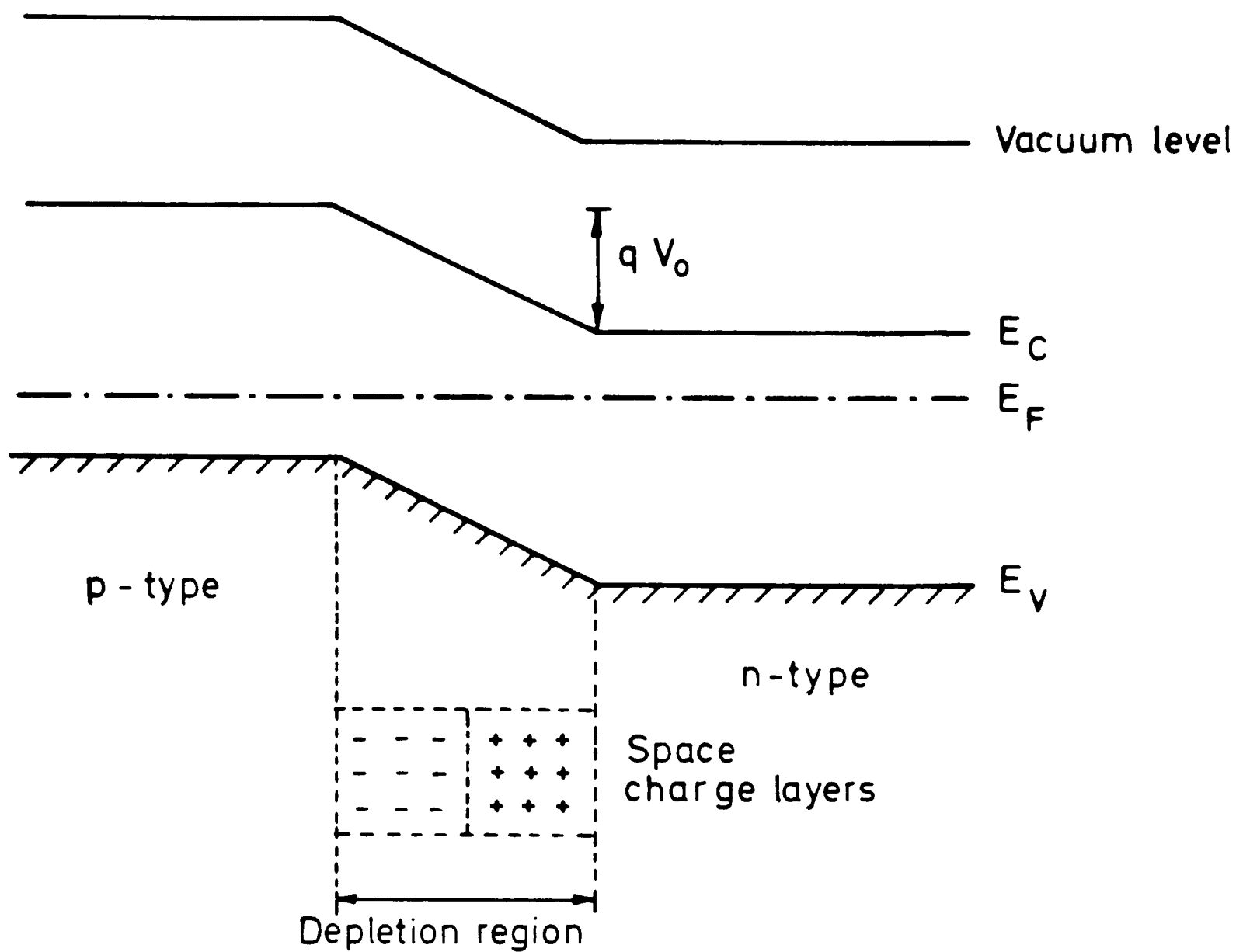


Fig.1.6

The energy band diagram of a p-n junction illustrating the presence of a depletion region at the junction

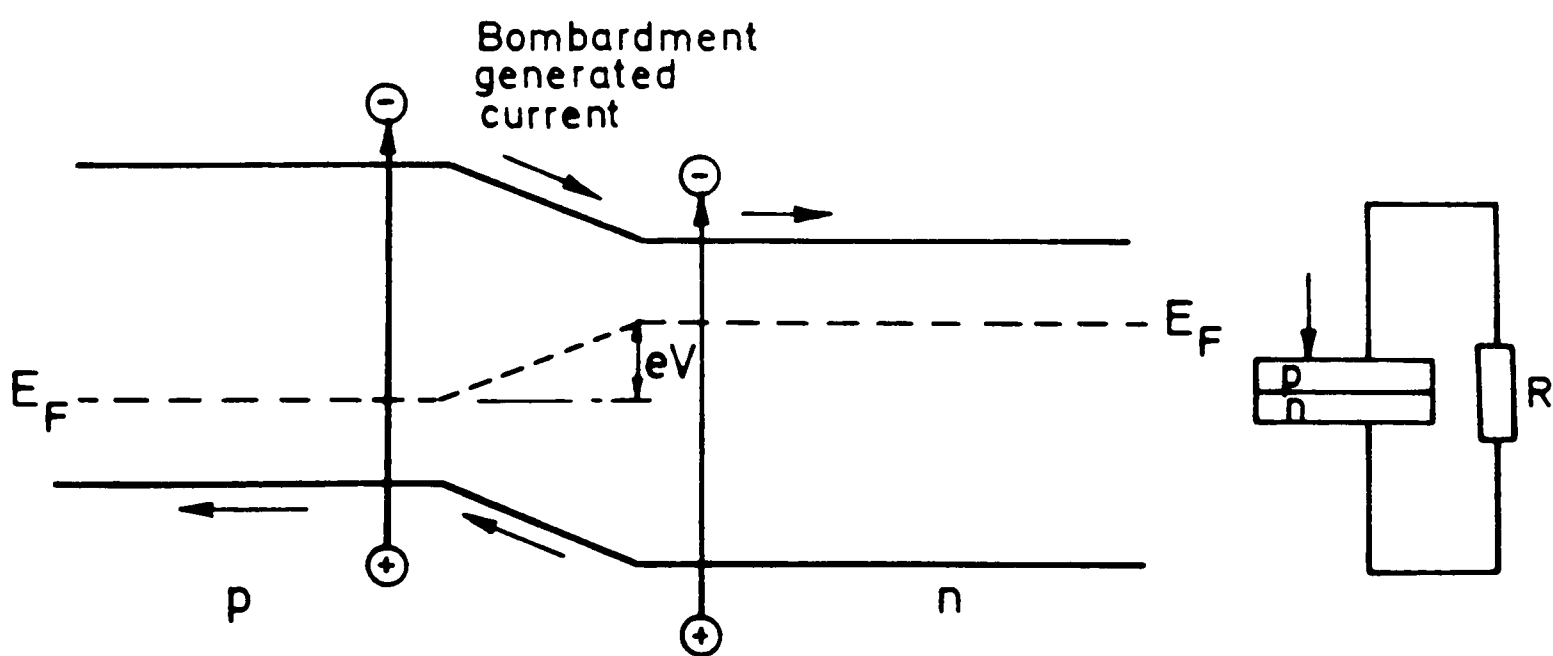


Fig.1.7

The energy band interpretation of the OBIC process

## **1.6 THE APPROACH ADOPTED IN THE SCANNING OPTICAL MICROSCOPY EXAMINATION OF SEMICONDUCTOR DEVICES**

This thesis examines the theory of using a laser probe to image electrical defects in semiconductors and semiconductor devices, where such defects may affect the electrical performance of the device. This is the first time this theory has been developed using a light beam as a probe. A Green's Function approach is used to solve for the excess minority carrier distribution in the material so that the optical beam induced current signal from the device may be obtained. The theoretical results are compared with defect images obtained experimentally.

The first step in the understanding of the way in which scanning optical microscopy may be used to examine semiconductor devices is understanding the effect of a convergent laser beam focused on a semiconductor material. Chapter 2 investigates the three dimensional intensity profile of a light beam incident on an absorbing material such as a semiconductor. This information forms the basis of an understanding of the interaction of laser light with a semiconductor giving rise to an OBIC current.

The next step is to obtain an OBIC image of a semiconductor device. In Chapter 3 OBIC is used to examine a bipolar transistor. There are dislocations in the transistor, but it is quite difficult and time-consuming to obtain the correct d.c. offset and contrast enhancement to display this clearly in the OBIC image. Hence a successful new technique is developed which displays the rectified, differentiated OBIC signal and makes the dislocations more easily discernable. The ease with which this method highlights dislocations points to the ready suitability of the method in device fault detection.

An essential ingredient in obtaining meaningful SOM images of defects in semiconductor devices is an understanding of the images the theory predicts for simple

defects considering simple devices initially. Chapters 4 and 5 use a Green's function approach to solve for the excess minority carrier distribution in Schottky barrier and planar junction devices respectively.

An estimate of the resolution of defects is made for both device types. A comparison of OBIC imaging and the analogue imaging technique using an electron beam, electron beam induced contrast (EBIC), is made in Chapter 6. This chapter points out the unsuitability of the electron beam to examine certain important device types including metal oxide semiconductor field effect transistors (MOSFETs).

Chapter 7 explores a novel method to examine the spatial inhomogeneity of defects at the silicon/silicon-dioxide interface in MOSFET devices. Defects at this interface can be detrimental to device performance and can seriously reduce reliability. This is a unique example of the superiority of OBIC over EBIC for this application because EBIC would cause charging problems and damage the specimen. This chapter also illustrates the spatial inhomogeneity and increase in number of defects found when a MOS device is heavily irradiated.

A further step in the non-destructive examination of semiconductors involves transmission and photoluminescence imaging. Chapter 8 considers the use of the scanning infra-red microscope to examine Gallium Arsenide. Defects in this material pose a serious drawback to the use of Gallium Arsenide in commercial devices. Chapter 8 also develops a theory to describe the imaging of defects using photoluminescence. This is an excellent non-destructive and non-contact technique to image defects in materials which are photoluminescent.

The final chapter in this thesis summarises the salient features of the research and proposes further research in the examination of semiconductor devices using an optical probe.

## CHAPTER 2

### THE INTENSITY DISTRIBUTION FOR A CONVERGENT LIGHT BEAM FOCUSED IN A SEMICONDUCTOR MATERIAL

#### 2.1 INTRODUCTION

There are many applications which involve a finely focused light beam being incident on an absorbing material <sup>1.5,1.25,1.26,2.1</sup>. The application with which this thesis is mainly concerned is the optical beam induced current (OBIC) mode of scanning optical microscopy. Another example might be the exposure of photoresist by a scanning beam. Here, the intensity distribution will be related to the etch profile. An analysis of the OBIC technique, and many others, involves calculating the intensity of the radiation within the material and finding how this depends, for example, on the focus position. This is important, as its use in the diffusion and continuity equations introduced in chapter 4 allows one to find the distribution of the generated carriers in the OBIC technique.

The first objective is to calculate the three dimensional intensity distribution in the focal region of a finely focused light beam in the presence of an absorbing medium. Reflection from the medium is neglected and the results are considered in terms of OBIC imaging although they are equally applicable in many other situations.

#### 2.2 THEORY

Consider the light intensity distribution in the focal region of a lens which focuses light at a distance  $h$  into the material. The amplitude absorption coefficient is  $k\beta$  where  $k$  is the wave number. Following Born and Wolf's method <sup>1.28</sup> and using Fig. 2.1 one may write, in the paraxial approximation, that the amplitude at P is given

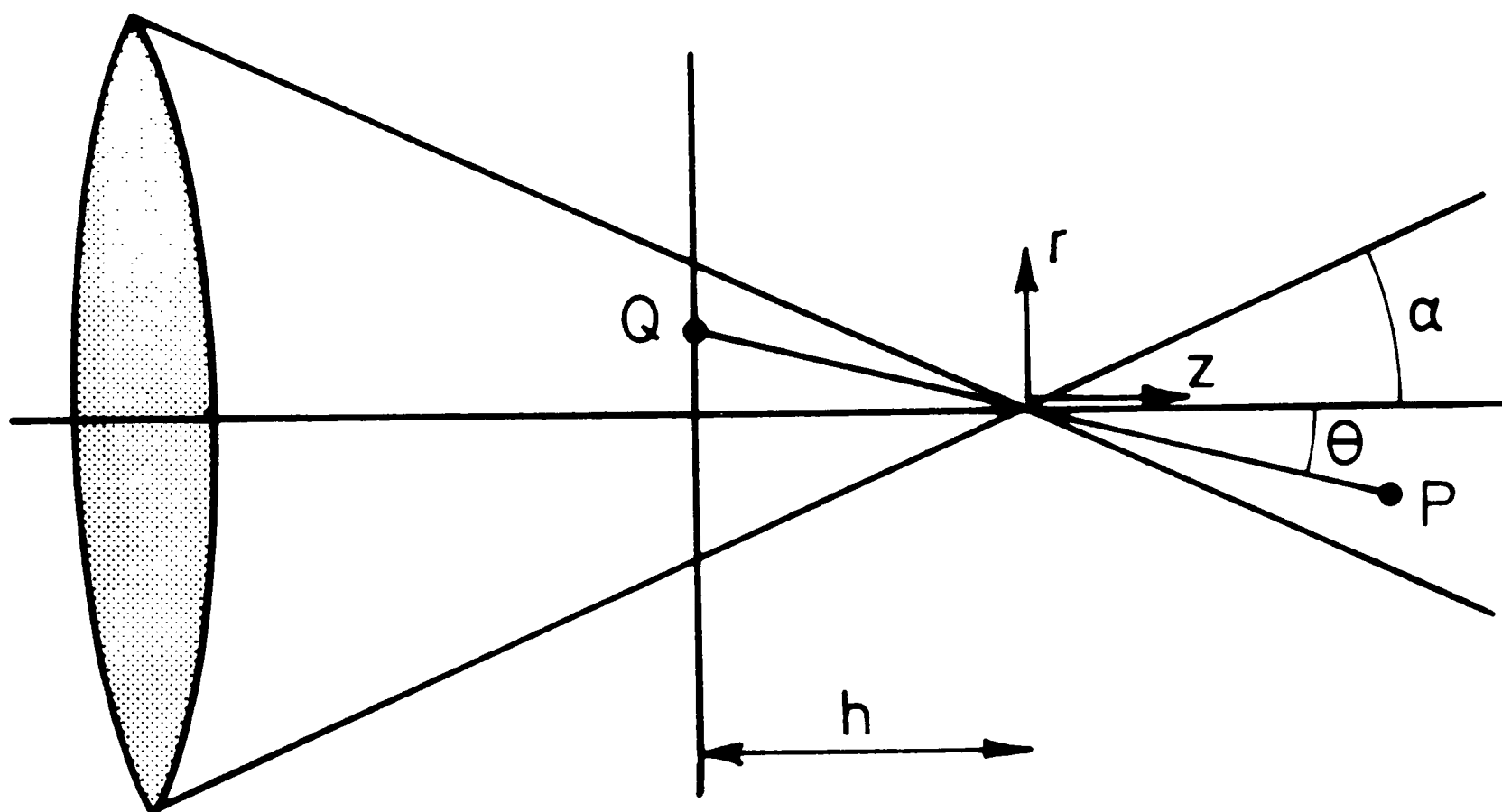


Fig.2.1

The geometry of focusing into the material

by

$$U(P) = -jA \exp(ju \sin^2 \alpha) \int_0^1 \exp -k\beta|PQ|J_0(v\rho) \exp(-0.5ju\rho^2) \cdot \rho d\rho \quad (2.1)$$

where  $A$  is a constant,  $\sin \alpha$  the numerical aperture and  $\rho$  is a normalised variable in the plane of the aperture. Optical co-ordinates in the focal region have been introduced. These are given by

$$u = kz \sin^2 \alpha \quad (2.2)$$

$$v = kr \sin \alpha$$

In order to evaluate Eq. 2.1 a suitable expression for  $|PQ|$  must be found. Clearly from Fig.2.1

$$|PQ| = (h + z) / \cos \theta \quad (2.3)$$

which using the small angle expansion for  $\cos \theta$  and the approximation that  $\theta \approx \rho \sin \alpha$  may be recast in the form

$$|PQ| = (h + z)(1 + 0.5\rho^2 \sin^2 \alpha) \quad (2.4)$$

Hence the intensity at  $P$  may be written

$$I(u, v) = A^2 \exp -2k\beta(h + z) \left| \int_0^1 J_0(v\rho) \exp -0.5ju\rho^2 \exp -0.5\beta(u + u_0)\rho^2 \cdot \rho d\rho \right|^2 \quad (2.5)$$

with  $u_0 = kh \sin^2 \alpha$

This is the main expression which shall be used to describe the generation of carriers within the semiconductor. Notice that in the case of no absorption ( $\beta = 0$ ), the expression reduces to the well-known form<sup>1,28</sup>. The effect of absorption is both to alter the form of the diffraction integrand and to pre-multiply the expression by an exponentially decaying term. The presence of an absorbing medium, of course, makes the diffraction integral no longer symmetrical in  $u$ .

## 2.3 THE LIGHT DISTRIBUTION WITHIN THE MATERIAL

An expression has now been derived for the three dimensional light distribution near the focus in the presence of absorption. Some general comments may now be made before considering results with specific application to semiconductor device inspection. Before producing contour plots of light distribution, it will be useful to consider the intensity variation in the focal plane and along the optic axis. In the focal plane Eq. 2.5 reduces to

$$I(0, v) = A^2 \exp -2k\beta h \left| \int_0^1 J_0(v\rho) \exp -0.5\beta u_0 \rho^2 \cdot \rho d\rho \right|^2 \quad (2.6)$$

which is plotted in Fig. 2.2 for  $\beta = 0.02$  which corresponds to the absorption of helium neon light (wavelength  $0.6328\mu\text{ m}$ ) in single crystal silicon<sup>2,2</sup>. The absorption essentially removes the side lobes in all cases apart from the case where light is focused on the semiconductor surface. The effect of focusing into the material is to reduce the central intensity although the full width half maximum, (FWHM), value of  $v$  is very insensitive to focus position for the value of  $\beta$  which was chosen. Hence the intensity distribution in the focal plane may be maintained for beams focused into the material.

The intensity variation along the optic axis is obtained by setting  $v = 0$  in Eq. 2.5 . In this case the integral may be performed analytically to yield

$$I(u, 0) = \frac{\exp -a\beta(u + u_0)}{(u/4)^2 + (\beta(u + u_0)/4)^2} \left[ \sin^2 u/4 + \sinh^2 \beta(u + u_0)/4 \right] \quad (2.7)$$

with

$$a = (4 + \sin^2 \alpha)/(2 \sin^2 \alpha) \quad (2.8)$$

where the intensity has been normalised such that  $I(0, 0) = 1$  when focused on the semiconductor surface. Notice that in the absence of attenuation  $I(u, 0)$  reduces to the usual  $\text{sinc}^2(u/4)$  expression<sup>1,28</sup>

In Fig. 2.3, the axial intensity variation is plotted for different values of  $u_0$  . Note that the curves all start at  $u = -u_0$  as this corresponds to the surface of the

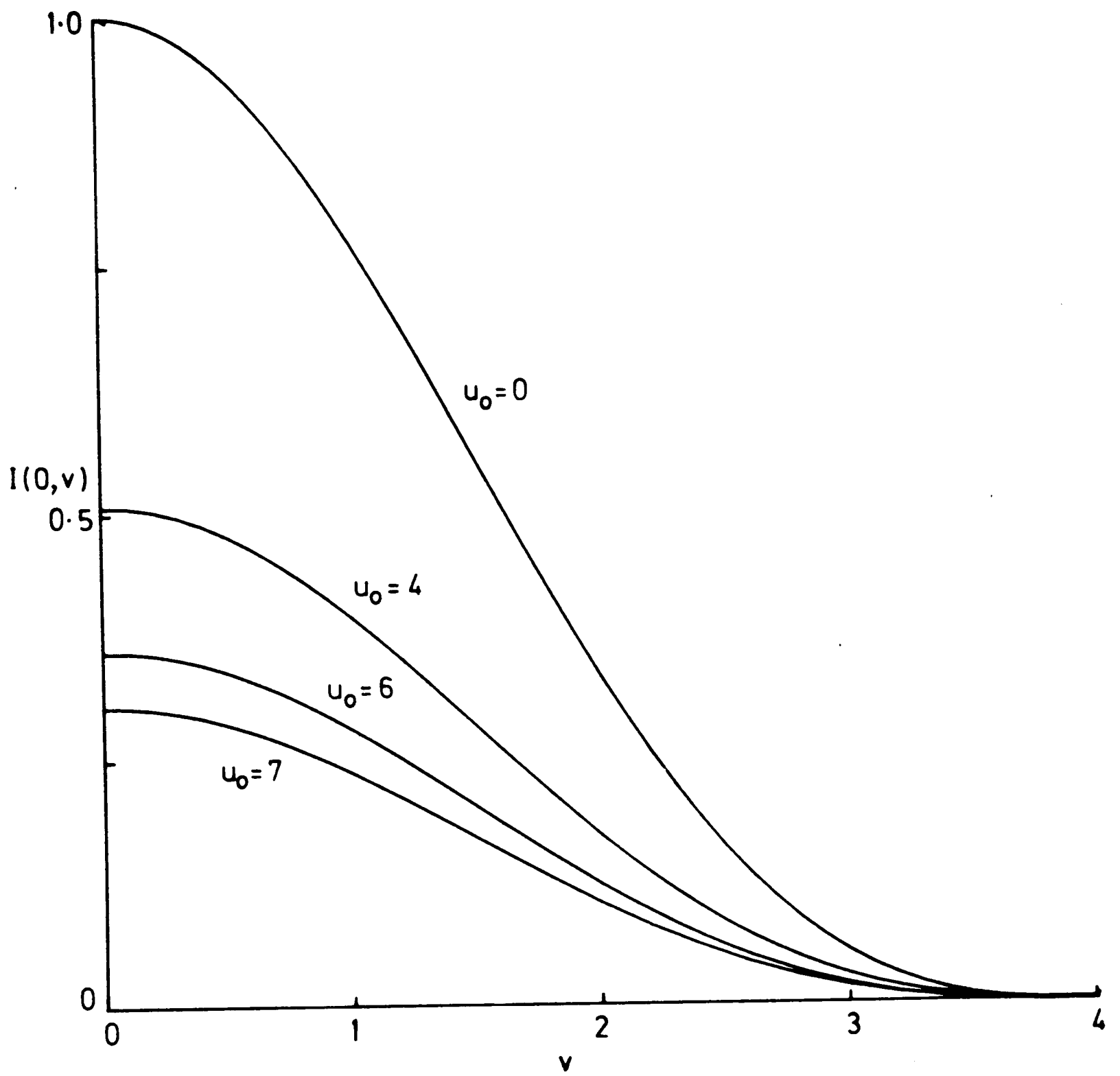


Fig.2.2

The intensity distribution in the focal plane

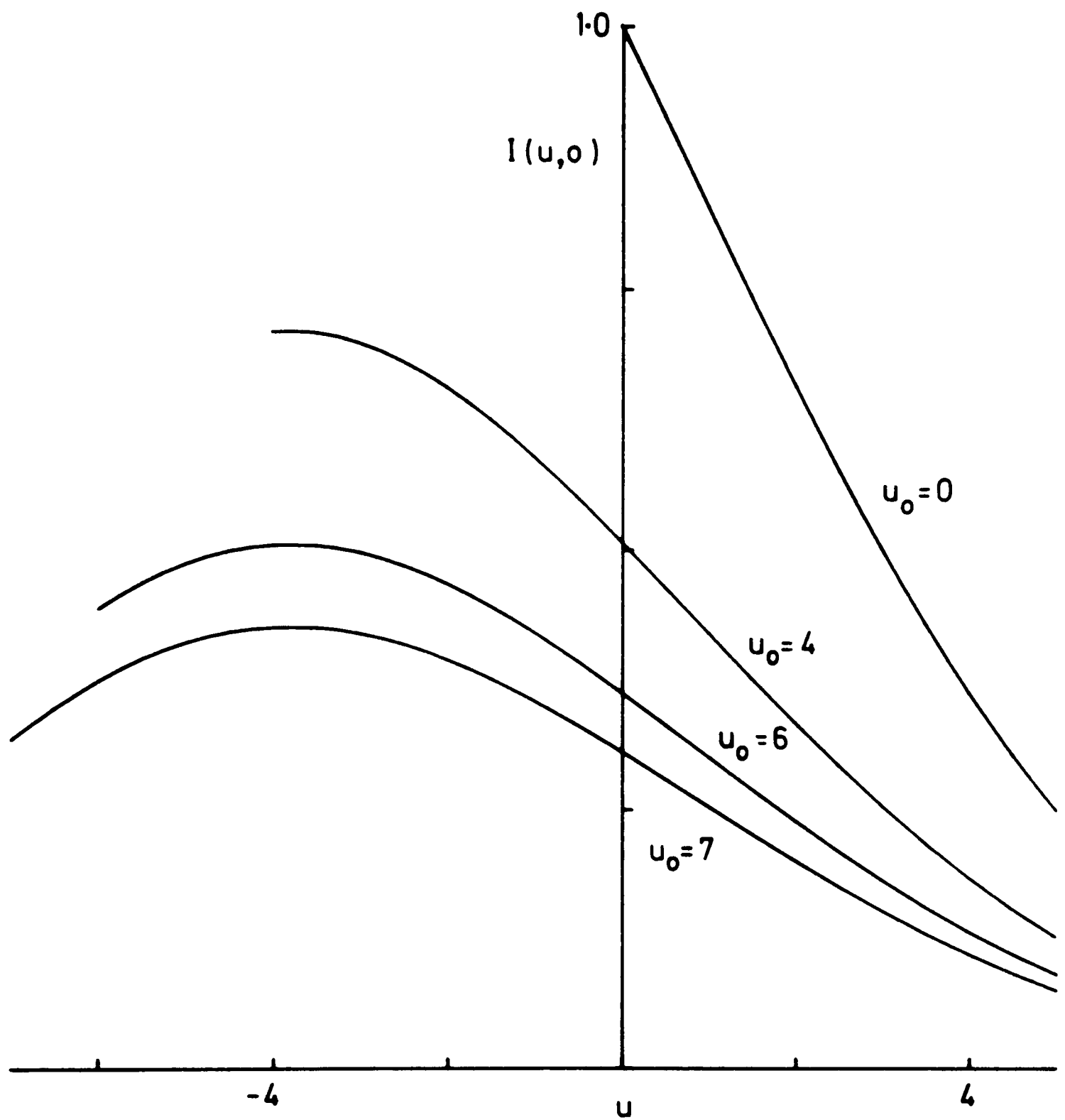


Fig.2.3

The intensity variation along the optic axis

semiconductor. In all cases it may be seen that the maximum in intensity does not occur at the surface except for  $u_0 = 0$ . Also the deeper one focuses into the material, (the greater  $u_0$ ), the further in the maximum intensity occurs, although, because of attenuation, it is of lower absolute value. The presence of attenuation has also removed the side lobes which would have been evident in the  $\text{sinc}^2 u/4$  expression for  $\beta = 0$ <sup>1.28</sup>.

Having developed a feeling for the intensity variation within the material, a contour map of the intensity in the focal region given by Eq. 2.5 may now be produced. The classical method of evaluating this integral in the absence of attenuation is to expand it in terms of Lommel functions. However, it is simpler to use a direct numerical integration technique in our case. Figs. 2.4 - 2.7 indicate the behaviour as one focuses further into the material. The contour spacing is as shown and the  $1/e$  contour is emphasised. For a beam focused on the surface, the intensity is a maximum at the focus and falls off with increasing distance into the semiconductor (Fig. 2.4). It should be mentioned that the program was checked by comparing the results for zero attenuation with those obtained by Born and Wolf (Ref.1.28, Fig. 8.41).

The absorption length for silicon is approximately 6.25 optical units when helium neon light is incident on the semiconductor. The contour plot of Fig. 2.6 and the axial profile of Fig. 2.3 corresponding to  $u_0 = 6$  illustrate that on focusing a distance approaching that of the absorption length into the material the intensity at the focus is close to  $1/e$ . Notice that on focusing further into the semiconductor that by  $u_0 = 7$  the  $1/e$  contour is contained wholly beneath the surface. Additional increase in  $u_0$  causes this contour to shrink until it has vanished by  $u_0 = 7.5$ .

Now consider physically the action of focussing the light beam into the semiconductor. If there were no absorption the intensity would increase on approaching the focus. Hence with absorption one would expect the intensity to increase initially

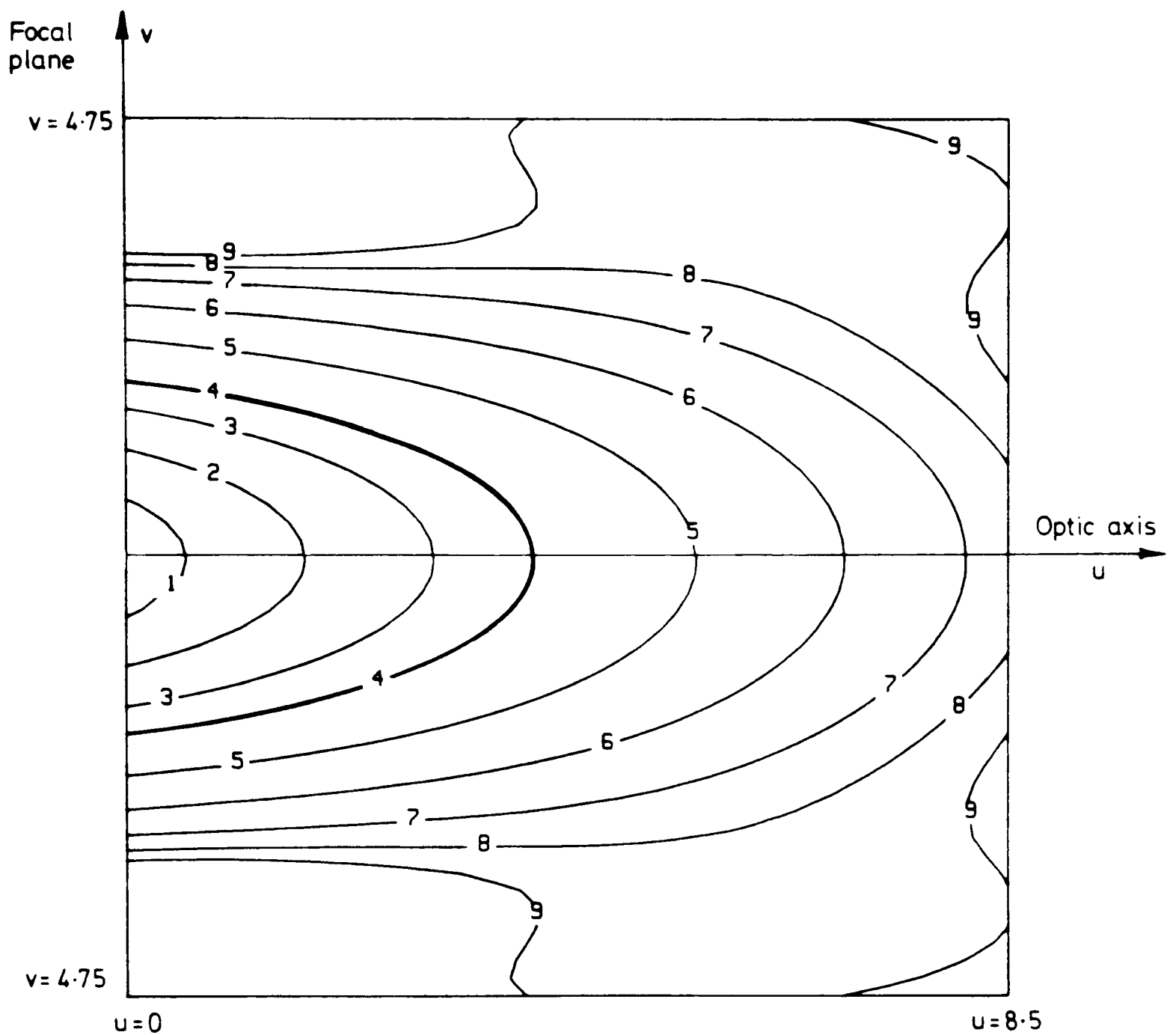


Fig.2.4

Equal intensity contours corresponding to  $u_0=0$

The  $1/e$  contour is emphasised.

The labelling contour for Figs.2.4-2.7 is

Contour 1  $\equiv 0.9$ ; Contour 2  $\equiv 0.7$ ;

Contour 3  $\equiv 0.5$ ; Contour 4  $\equiv 1/e$ ;

Contour 5  $\equiv 0.2$ ; Contour 6  $\equiv 0.1$ ;

Contour 7  $\equiv 0.05$ ; Contour 8  $\equiv 0.03$ ;

Contour 9  $\equiv 0.02$ ;

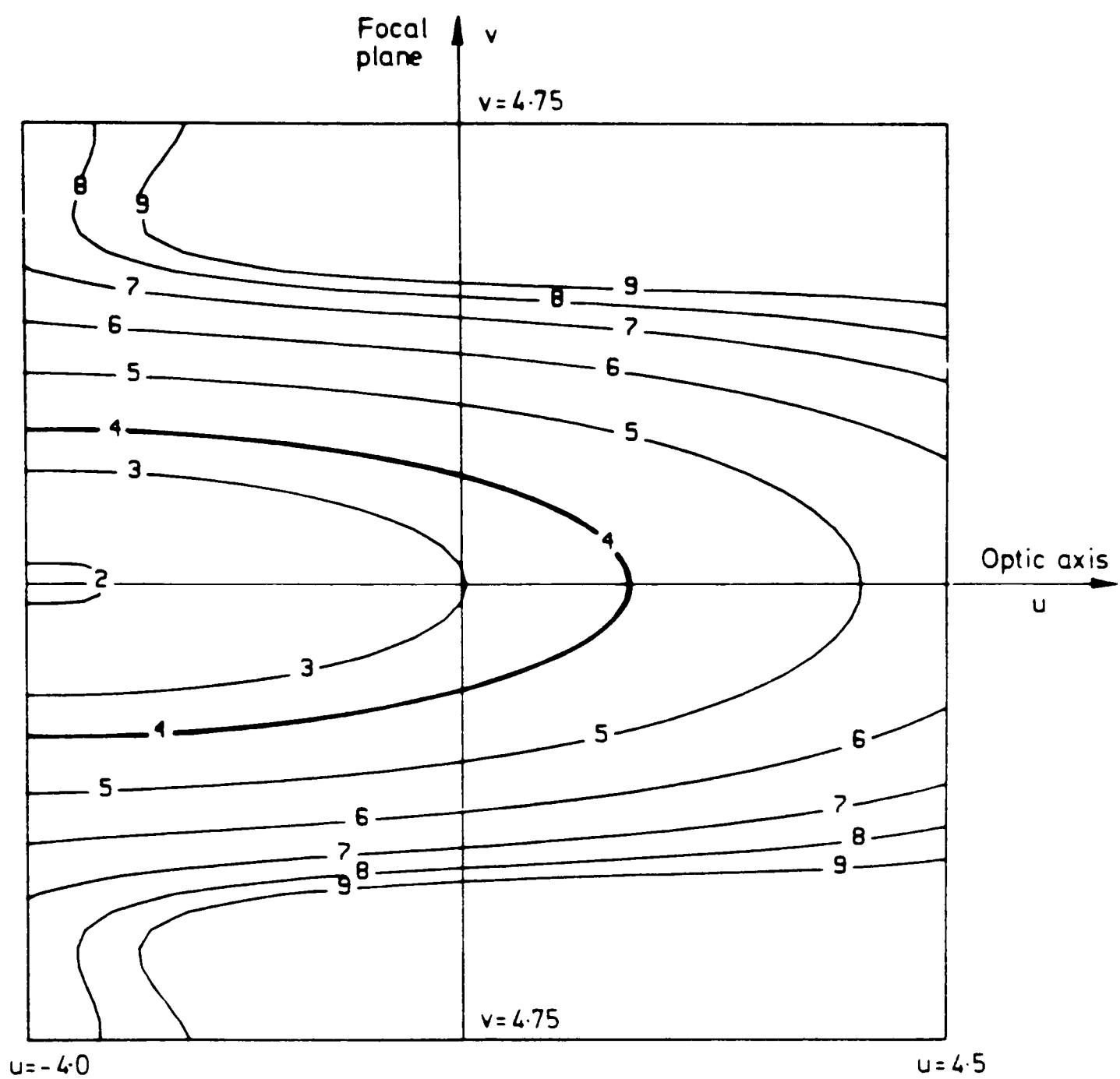


Fig.2.5

Equal intensity contours corresponding to  $u_0=4$

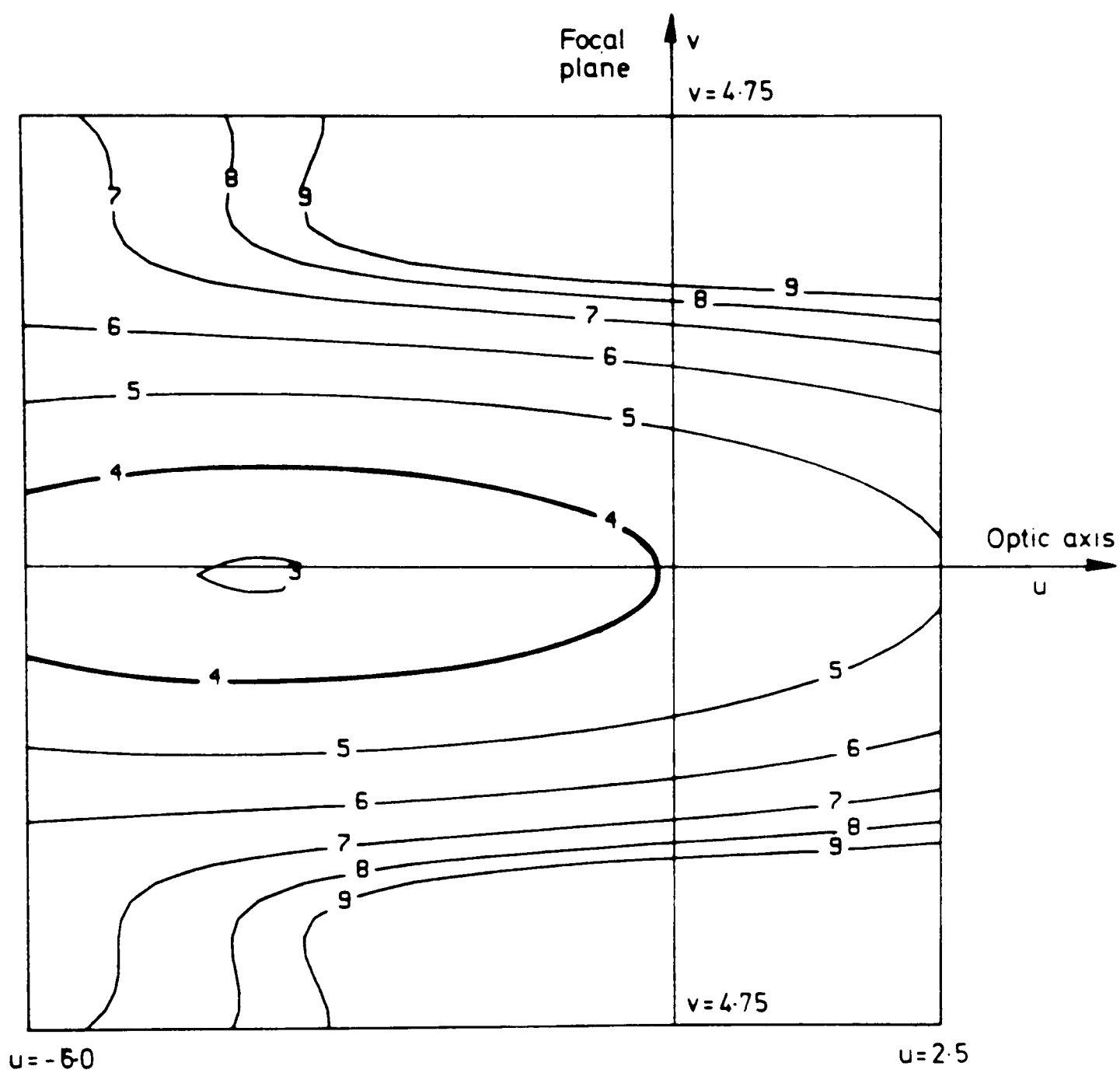


Fig 2.6

Equal intensity contours corresponding to  $u_0=6$

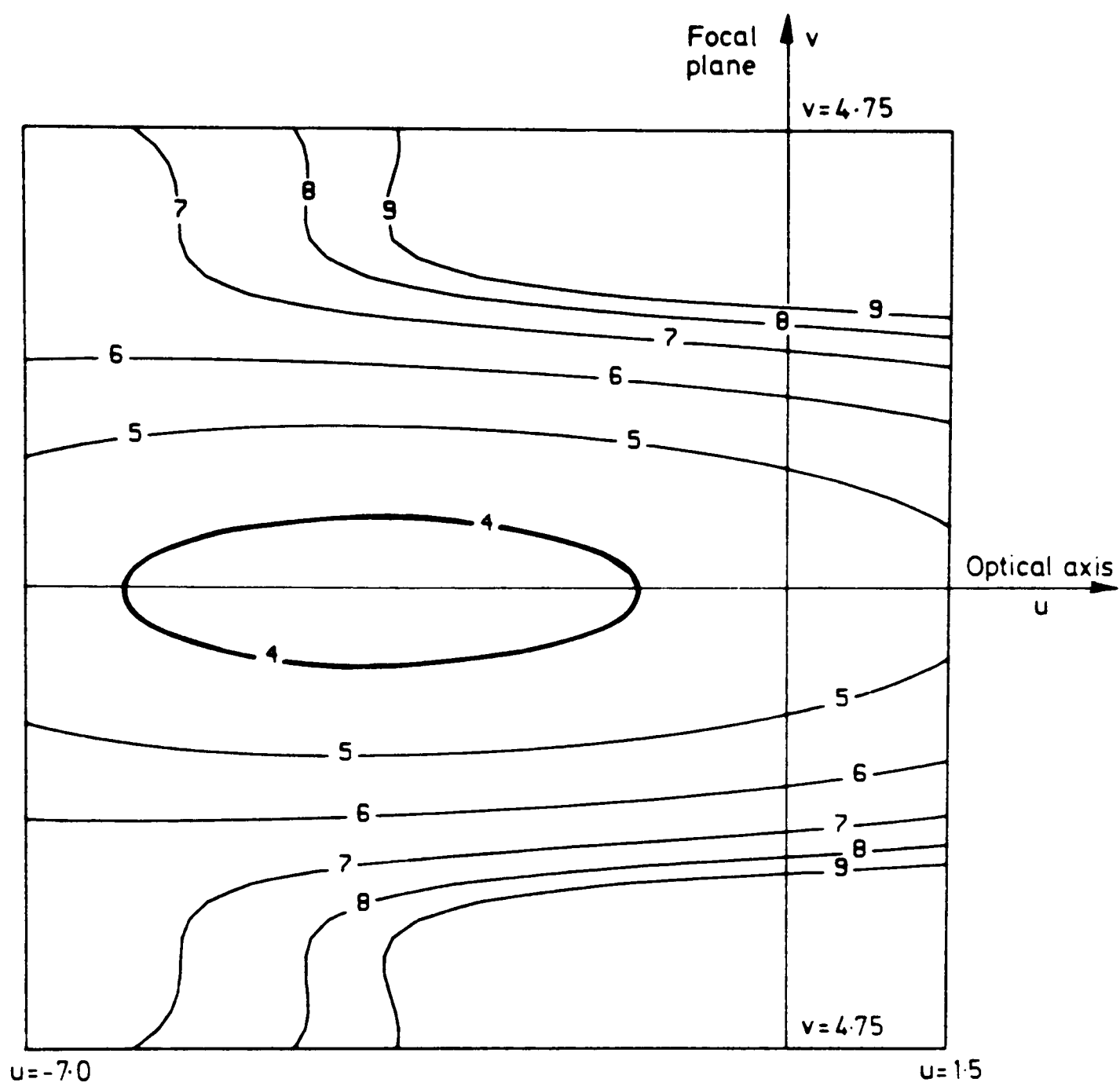


Fig.2.7

Equal intensity contours corresponding to  $u_0=7$

as the beam starts to converge, but to reach a maximum before the focus and to decrease thereafter. This is illustrated in Figs. 2.3 to 2.7.

A further important quantity to calculate is the integrated intensity. This represents the total radiation passing through a plane normal to the optic axis, and is given by

$$L(u) = \int_0^\infty I(u, v) v dv \quad (2.9)$$

Substitution of Eq. 2.5 into 2.9 together with the normalisation that  $L(-u_0) = 1$  gives after a little manipulation

$$L(u) = \exp -a\beta(u + u_0) \frac{\sinh \beta(u + u_0)/2}{\beta(u + u_0)/2} \quad (2.10)$$

where  $a$  is defined in Eq. 2.8. Since  $u_0$  defines the distance below the semiconductor surface at which the beam is focused, and  $u$  denotes the distance from this focal plane, then setting  $u = -u_0$  denotes the surface of the semiconductor. Thus the above normalisation gives the total energy incident on the surface of the semiconductor, which is, of course, independent of focus position, as unity.

The integrated intensity profile is plotted in Fig. 2.8 It is seen to be a function of  $(u + u_0)$  only. This is to be expected since  $(u + u_0)$  represents the distance from the surface and it is this, of course, which determines the absorption and not the position where the light beam is brought to a focus.

## 2.4 THE GENERATION VOLUME

The results are now considered in the context of the OBIC method of semiconductor device inspection. This method involves the optical excitation of carriers. The spatial intensity distribution is given by  $I(u, v)$  of Eq. 2.5 and by the contour plots of Figs. 2.4 - 2.7. One may define, somewhat arbitrarily, a generation volume within the  $1/e$  contour. This volume would describe the actual carrier distribution if the light were pulsed on for an instant before any diffusion could take place. This

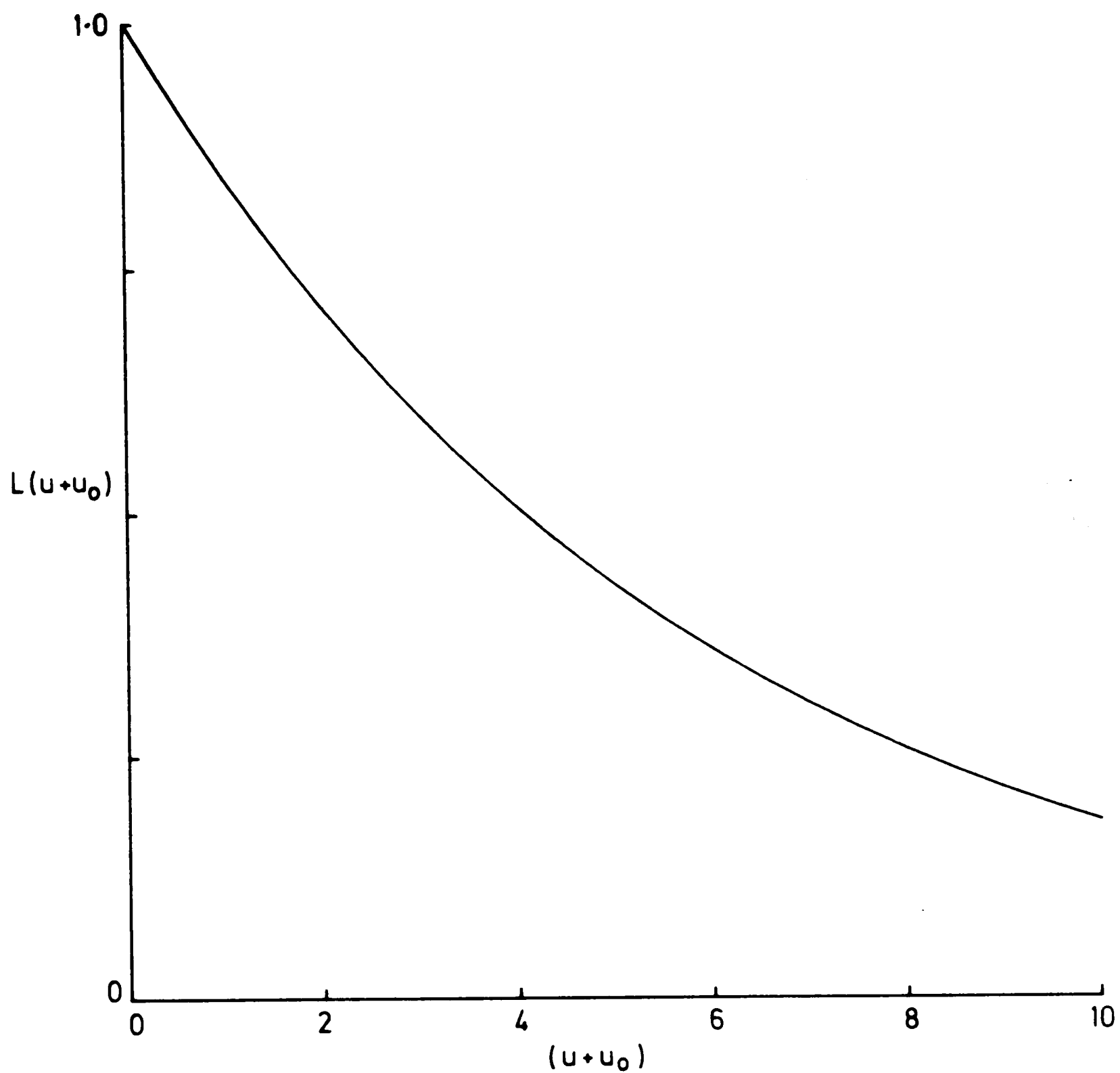


Fig.2.8

The variation of the integrated intensity  
with distance from the surface

variation of volume with focus position may be used to determine an optimum focus position in terms of maximum number of carriers generated in this way. Thus the generation volume is given by

$$V = \pi \int f^2(u) du \quad (2.11)$$

where  $f(u)$  represents the value of the radial optical coordinate,  $v$ , at which  $I(u, v) = 1/e$ .

This was calculated numerically and was plotted in Fig. 2.9 as a function of focus position,  $u_0$ , and it is found that the maximum generation volume does not occur when the light is focused on the semiconductor surface. For low values, of  $u_0$ , say 2.0 optical units, the  $1/e$  contour cuts the  $v$  axis at a slightly lower value of  $v$  than when  $u_0 = 0$ . However, the contour also extends much further in the  $u$  direction, thus resulting in a greater generation volume than when  $u_0 = 0$ . For much larger values of  $u_0$ , however, the contour becomes more elongated and narrower and results in a smaller generation volume. The effect is further demonstrated in Fig. 2.10 where a lower attenuation coefficient is used corresponding to Nd-Yag laser light in silicon. We also show the localisation of the probe in Fig. 2.11 where we have plotted the function  $V$ , of Eq. 2.11, but with the intensities now normalized to  $1/e$  relative to their peak at that focal depth.

## 2.5 CONCLUSIONS

The three dimensional light distribution in the focal region of a lens has been calculated in the presence of absorption. The results are directly applicable to the optical generation of carriers in a semiconductor. A generation volume for these carriers is introduced. It is found to depend on the focus position below the semiconductor surface in such a way that the optimum focus position in terms of the maximum number of carriers generated is not at the surface. This position lies a few

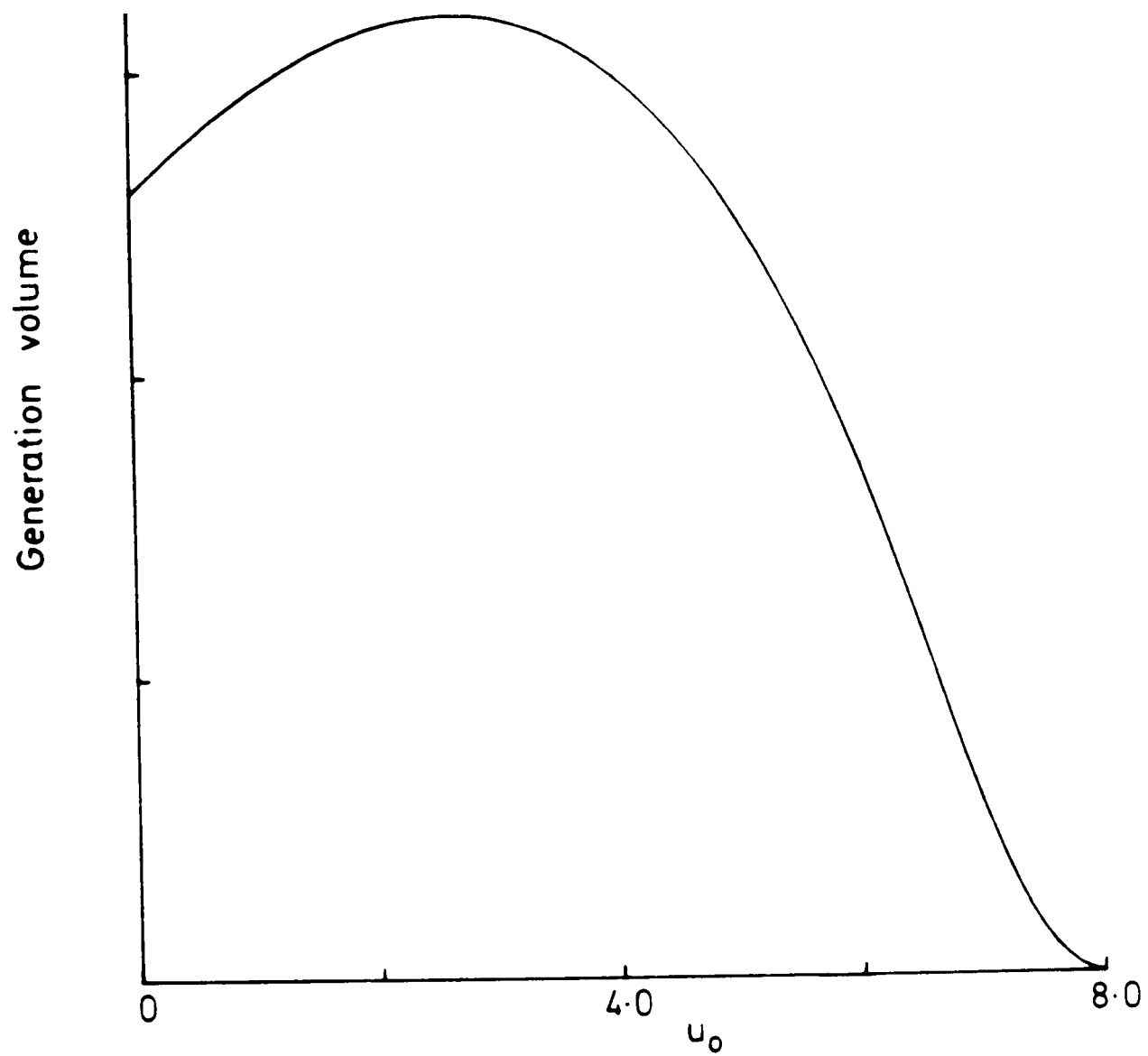


Fig2.9

The variation of the generation volume (in arbitrary units) with focus position for  $\beta = 0.02$

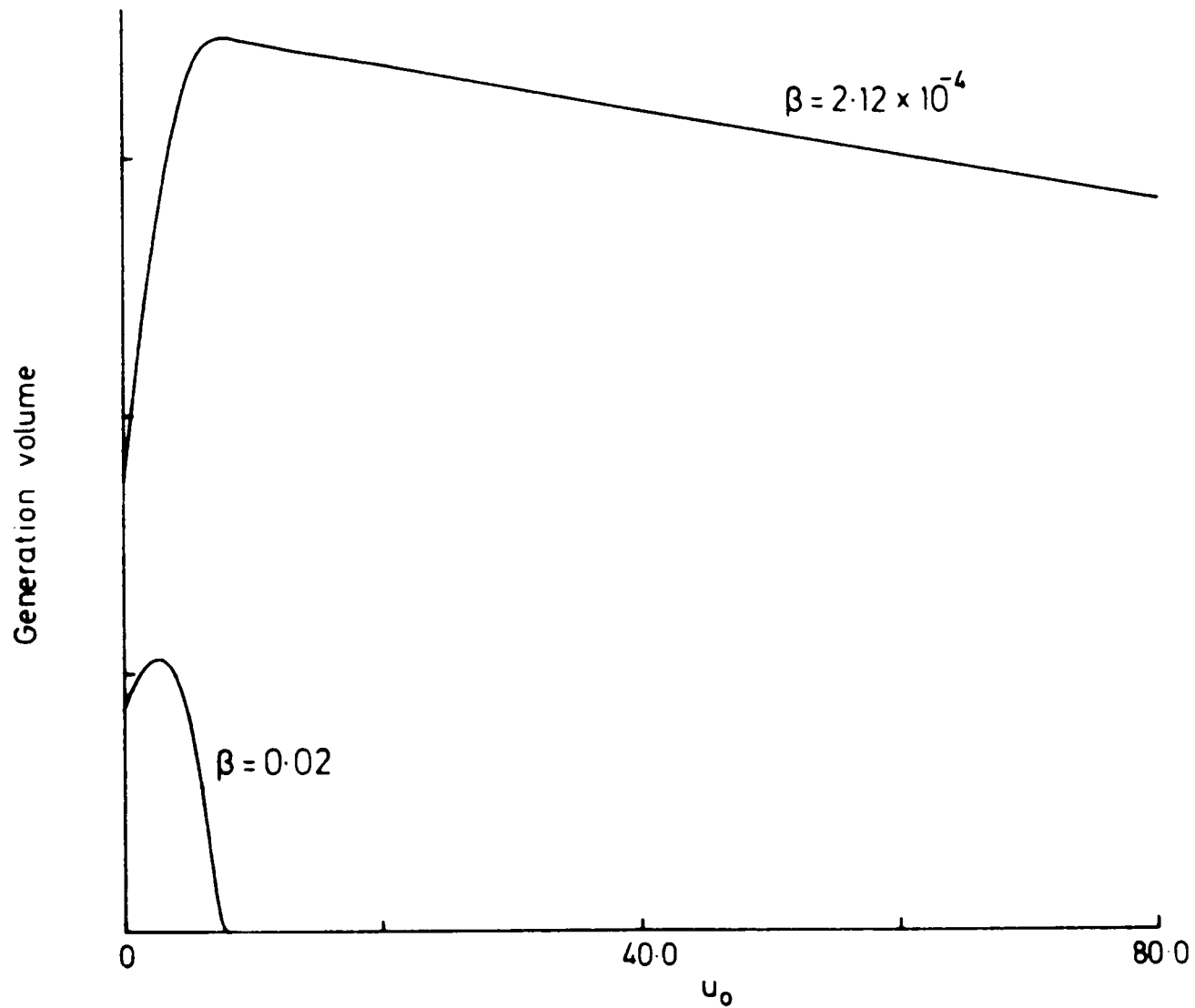


Fig2.10

The variation of the generation volume with focus position for  $\beta = 0.02$  and  $\beta = 2.12 \times 10^{-4}$

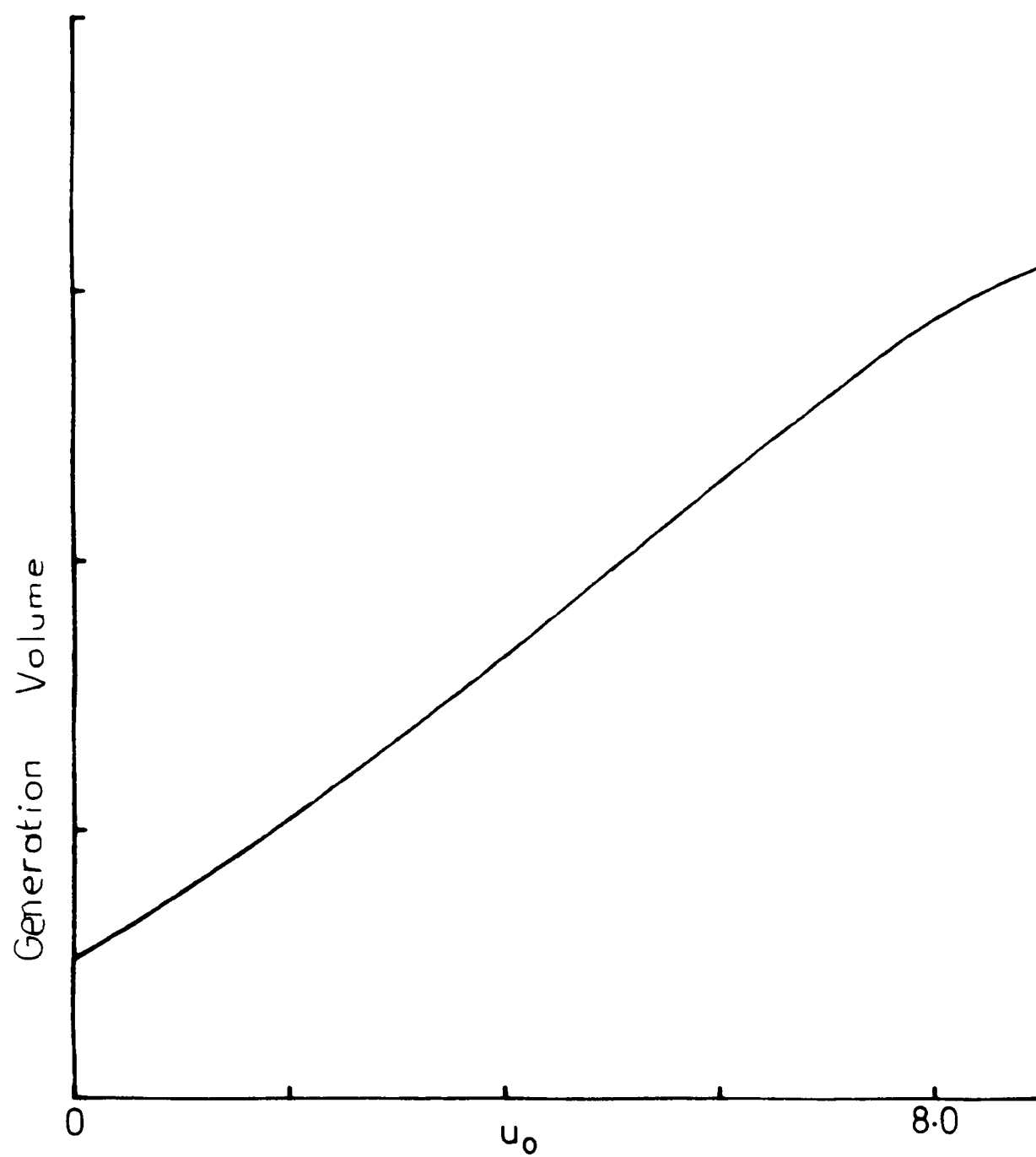


Fig.2.11

As Fig.2.9 and Eq.2.11 but redefined using  $1/e$  relative to the peak intensity at each point

optical units below the surface. The results are equally applicable to the exposure of photoresist by a scanning spot of light where the shape of the generation volume determines the line shape that may be obtained.

## **CHAPTER 3**

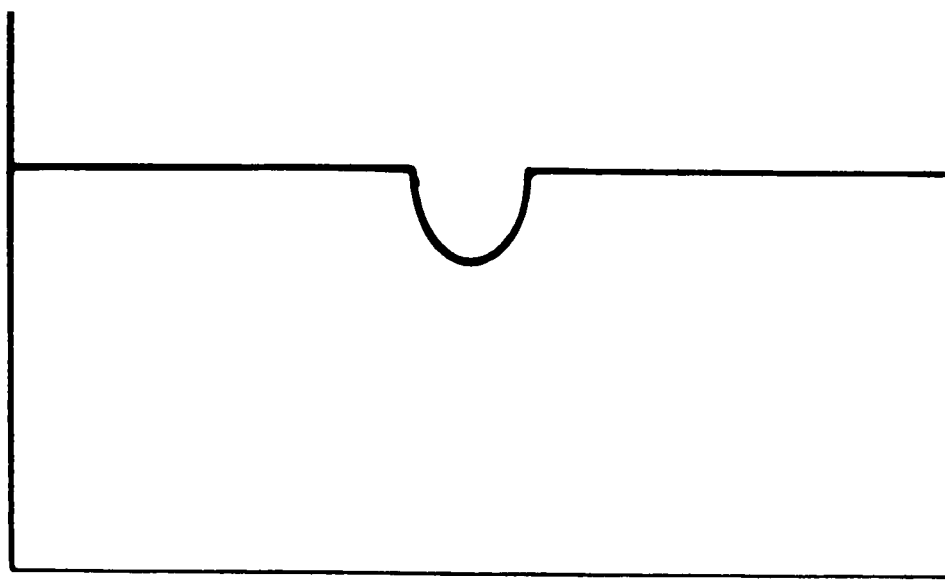
### **THE DISPLAY OF LOW-CONTRAST OBIC IMAGES**

#### **3.1 INTRODUCTION**

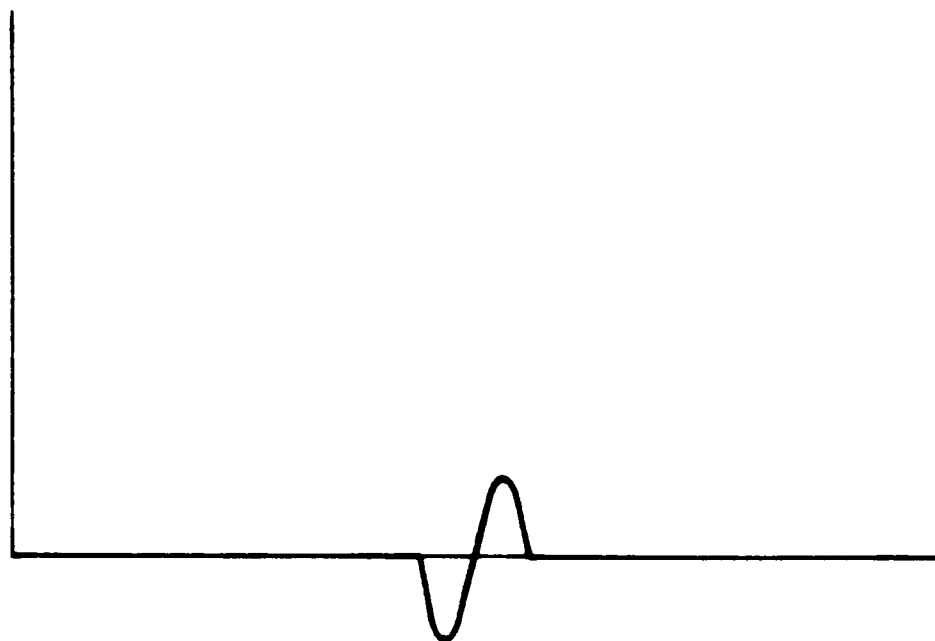
The OBIC technique can image defects such as dislocations and grain boundaries in semiconductor devices. The structure of the image is due to fluctuations in the OBIC signal as the laser beam scans over the surface of the device exciting carriers as it does so. A practical problem arises in displaying this OBIC signal on the TV screen as the interesting information is represented by a very small change (typically a few percent) in the total detected signal, Fig. 3.1(a). This low contrast can be made visible by introducing d.c. offset and using contrast enhancement. However, there are practical problems with this approach. This adjustment is very time consuming and demands skill and familiarity with OBIC imaging. In addition variations in background signal level means that it may be difficult to display defects over the entire specimen and over the entire field of view at the same time. This Chapter presents a new method of easily displaying OBIC images. The new technique which displays the rectified, differentiated OBIC signal is insensitive to variations in the background signal level.

#### **3.2 PROBLEM DEFINITION AND SOLUTION**

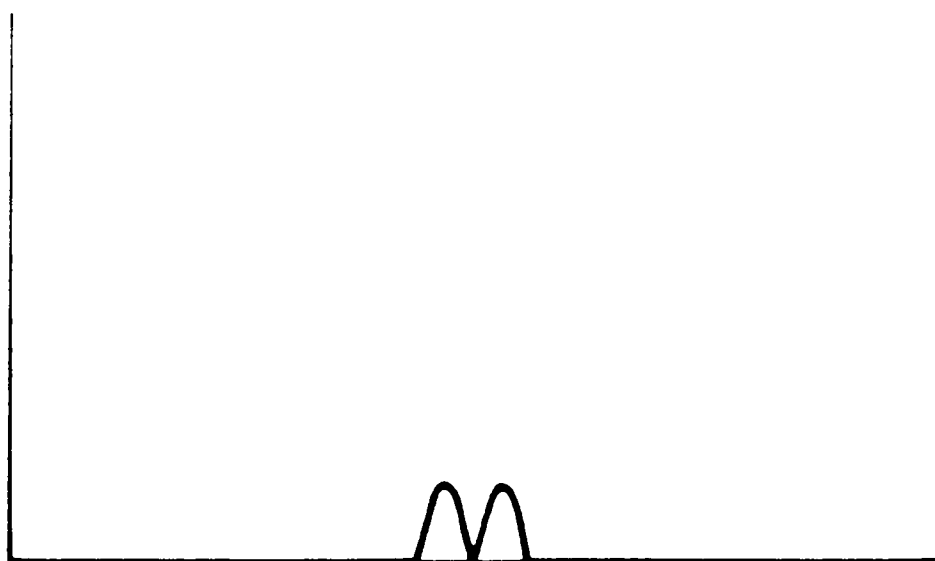
Given the problems associated with locating dislocations in semiconductor devices using OBIC imaging the need for a simple technique was identified which would make defects immediately evident. There are a number of approaches which could be employed to achieve this objective. The approach described in the introduction which involves electrically subtracting the dc background signal level and amplifying the perturbation before display on the TV screen is a tedious and difficult



(a)



(b)



(c)

Fig.3.1

Idealised line-scan profiles for

(a)Conventional OBIC

(b)Differentiated OBIC

(c)Rectified, differentiated OBIC

process when one is trying to see if any defects are present. This approach would also be difficult to automate. The degree of contrast enhancement required is often such that inevitable fluctuations in the laser output power cause an image either to disappear or saturate, requiring continual adjustment of the dc offset applied. This is because the contrast levels are basically of the same order as the laser stability. Another approach could involve the use of a computer to highlight the frequency component in the image corresponding to a defect. However this approach assumes that one already knows what kind of defect is present in the device.

An alternative approach to this problem would be to remove the dc level by differentiating, giving a line-scan signal such as in Fig. 3.1(b). Here the signal is bidirectional and so some dc offset must be introduced in order to display the image on a television screen. This extra complication may be overcome by rectifying the differentiated signal, Fig. 3.1(c). The rectified signal is always positive going and hence may be fed, via an amplifier, directly to the display screen without the need for any other conditioning electronics. The beauty of the approach is that any dislocations present anywhere in the object are immediately revealed. This is important because, in the absence of differentiating, slow variations in the dc level of the signal across a sample necessitate different degrees of contrast enhancement and so it is not possible to display defects in all parts of the sample on the same image. This restriction is completely removed by the present technique because low frequency variation in signal level undergoes relatively low amplification in the differentiator stage. In this way the crystallographic detail of interest appears more clearly in the differentiated image.

In order to demonstrate the method, a 0.6 numerical aperture objective was used in a scanning microscope with a helium neon laser (wavelength 632.8nm) to examine dislocations present in a silicon bipolar transistor by monitoring the emitter-base junction current. The detection electronics consisted of a transresistance amplifier

connected to a differentiator followed by a rectifier. Fig. 3.2 shows the steps involved in the manipulation of the OBIC signal to obtain the desired rectified, differentiated signal. A transresistance amplifier is used to amplify the OBIC signal before it enters the differentiator. The role of the transresistance amplifier is to convert the OBIC current to a voltage, to maximise the power transfer and hence maximise the signal fed to the differentiator stage. An additional gain element is introduced between the output of the differentiator and the input to the rectifier to ensure better operation of the rectifier stage.

Electrical differentiation is used instead of differentiating using the computer. This is because the latter approach would involve storing the background signal level as well as the small signal perturbation caused by the defect. This would pose the same problem as obtaining the normal undifferentiated OBIC image in that there may be a variation in background signal level perhaps due to a variation in the specimen reflectivity. An exciting feature of this technique is its potential suitability for automation. A suitable threshold difference between bright and dark lines could be set. Logic circuitry could be used to detect the bright-dark-bright pattern associated with dislocations. In a perfect device without dislocations a constant reference OBIC signal would be obtained when a laser beam is scanned over the device. On scanning the device under examination the OBIC signal recorded from the device could be compared with the reference signal. Any deviations in the values of these signals could allow pinpointing of dislocations in the device to be investigated.

### **3.2(a) : Differentiator Design**

Consider the differentiator design shown in Fig. 3.3. The transfer function for

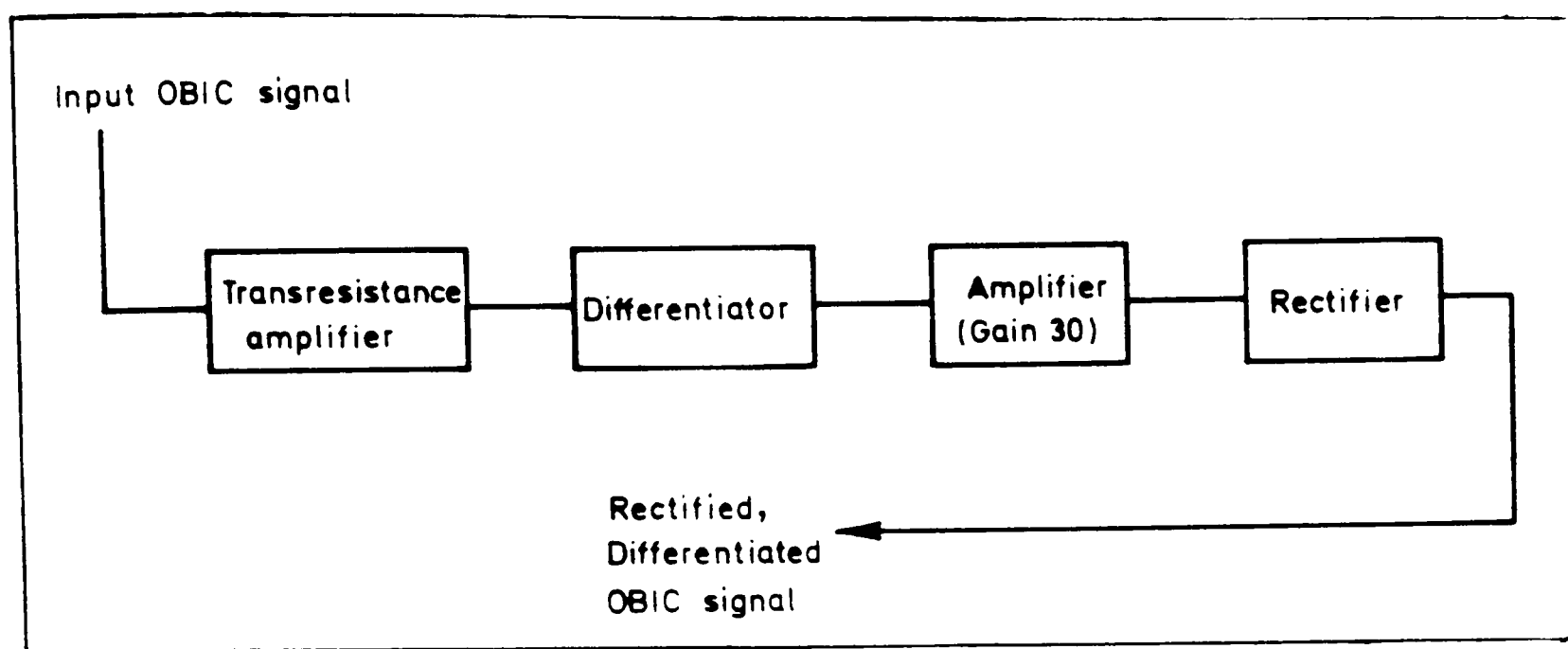


Fig.3.2

Block diagram of the steps involved in manipulating the OBIC signal to obtain the rectified, differentiated signal

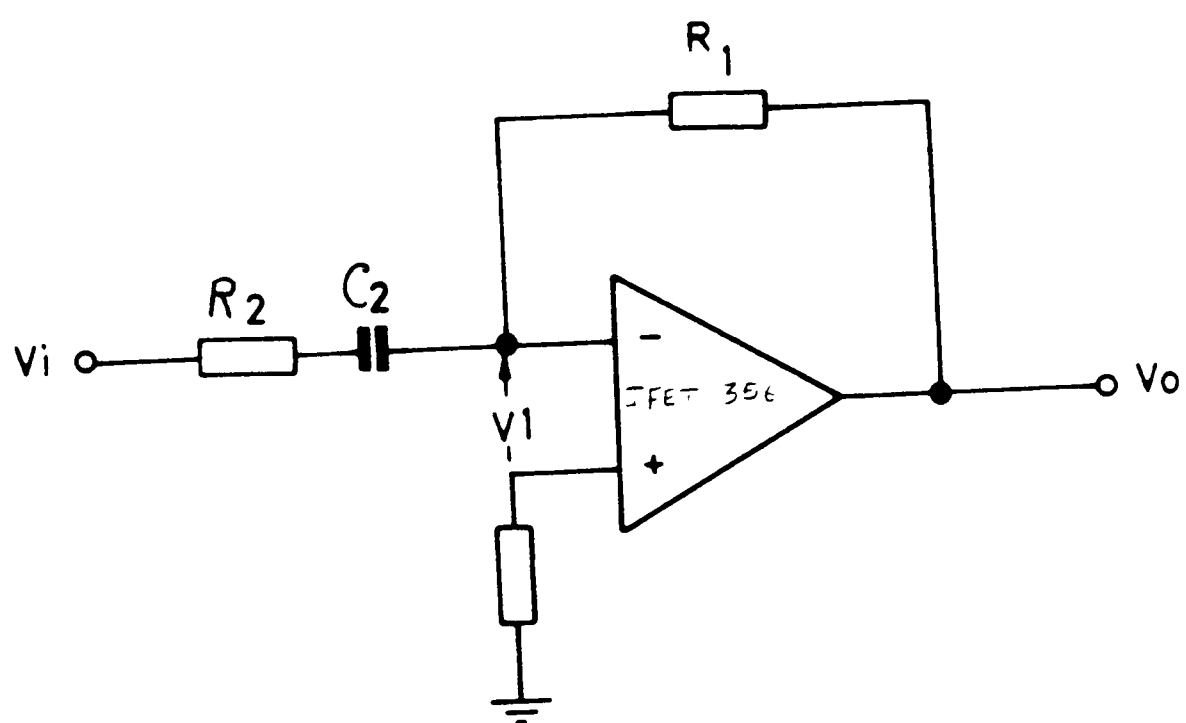


Fig.3.3

Outline design of the differentiator circuit

this circuit is

$$\frac{V_0}{V_i} = \frac{-sC_2R_1}{1 + s(C_2R_2 + 1/\omega_0) + s^2C_2(R_1 + R_2)/\omega_0} \quad (3.1)$$

using the operational amplifier's characteristic

$$\frac{V_0}{V_1} = \frac{-\omega_0}{s} \quad (3.2)$$

where  $s$  is the Laplace transform variable. This is a second order system with denominator of the form  $1 + 2\xi s/\omega_n + s^2/\omega_n^2$ . This gives

$$\omega_n^2 = \frac{\omega_0}{C_2(R_1 + R_2)} \quad (3.3)$$

where  $\omega_n (= 2\pi f_n)$  is the natural frequency of the second order system and  $\xi$  is the damping factor.  $\xi$  should be close to unity for suitable damping. Choosing such a value of  $\xi$  the transfer function of Eq.3.1 leads to a frequency response curve as in Fig. 3.4.

Differentiation occurs for  $f \ll f_1$  since for lower frequencies the transfer function described in Eq.3.1 has the form  $s$ . High frequency noise is attenuated for  $f \gg f_1$ . To choose a suitable value of  $f_n$  we must first consider the minimum bandwidth required for the SOM. The resolution we expect is approximately  $0.5\mu\text{m}$  using visible light. Thus working on low magnification, 100 X to the screen, and with a line scan frequency of approximately 80 Hz we scan approximately 320 000 picture points per second. Thus a minimum bandwidth of 160 KHz is required. Choice of  $f_n \approx 700$  kHz means that even for very low magnification the circuit will meet the minimum bandwidth requirements. Having chosen  $f_n$  and using a 357 operational amplifier with  $\omega_0 = 40.10^6$  rad/s suitable values of  $R_1$ ,  $R_2$  and  $C_2$  are:  $R_1 = 33 \text{ k}\Omega$  ;  $R_2 = 2\text{k}\Omega$  ;  $C_2 = 150 \text{ pF}$ . These component values give a suitable value of damping factor,  $\xi = 0.75$ .

To build a practical circuit which reduces the effect of high frequency noise Fig. 3.3 is modified by placing a capacitor,  $C_1$ , in parallel with  $R_1$ , where  $R_1C_1 = R_2C_2$ . This gives  $C_1 = 10 \text{ pF}$ .

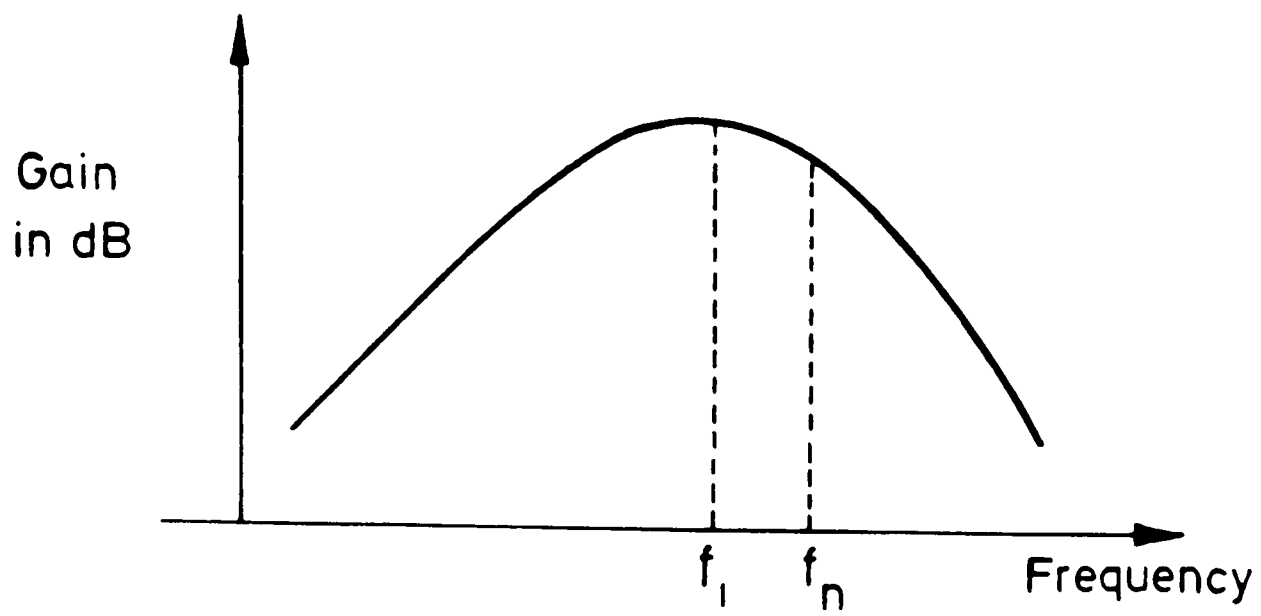


Fig.3.4

Frequency response for the circuit of Fig. 3.3

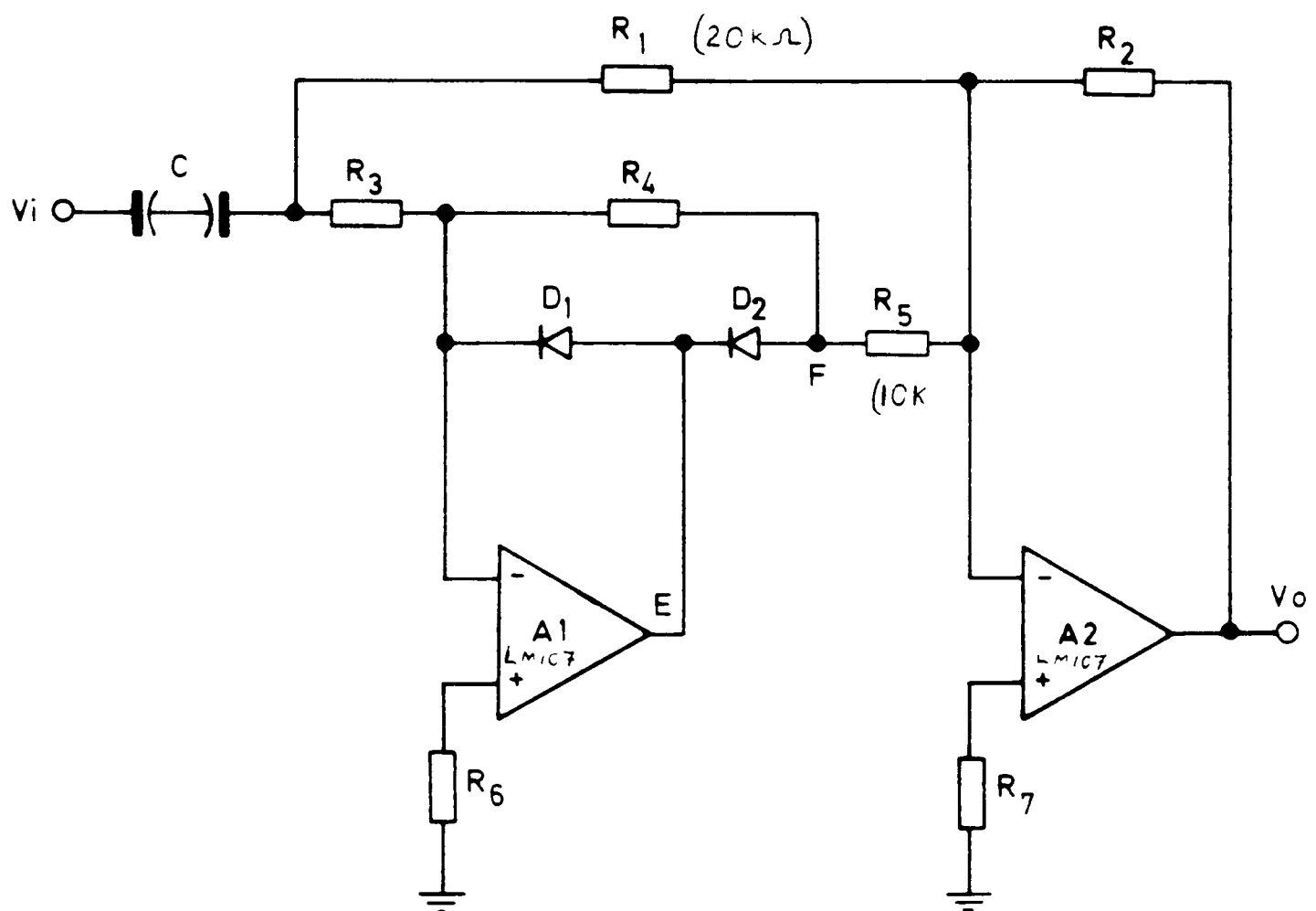


Fig.3.5

The rectifier circuit

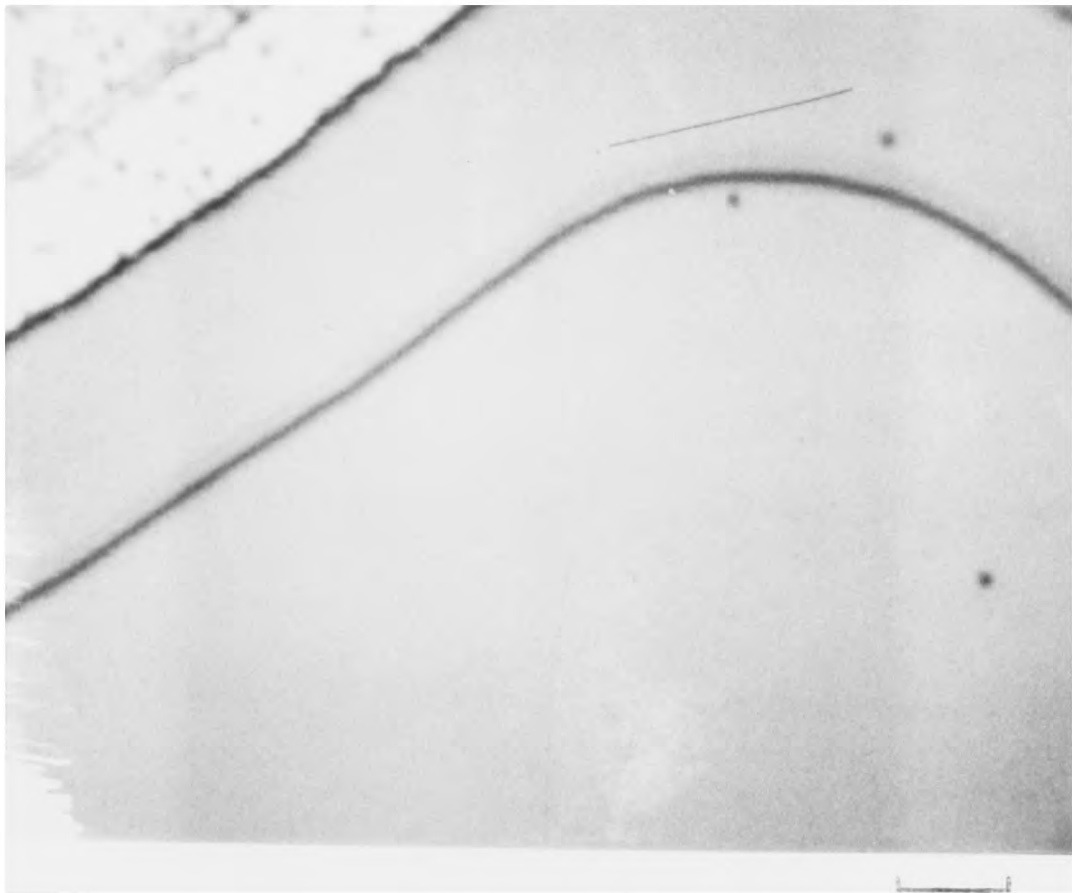
### **3.2(b) : Rectifier Design**

The circuit design of the rectifier used in this experiment is shown in Fig. 3.5. The differentiated OBIC signal is fed into the input of the rectifier circuit. Since  $R_1 = R_2 = 2R_5$  the circuit of Fig. 3.5 clearly acts as a full wave rectifier.

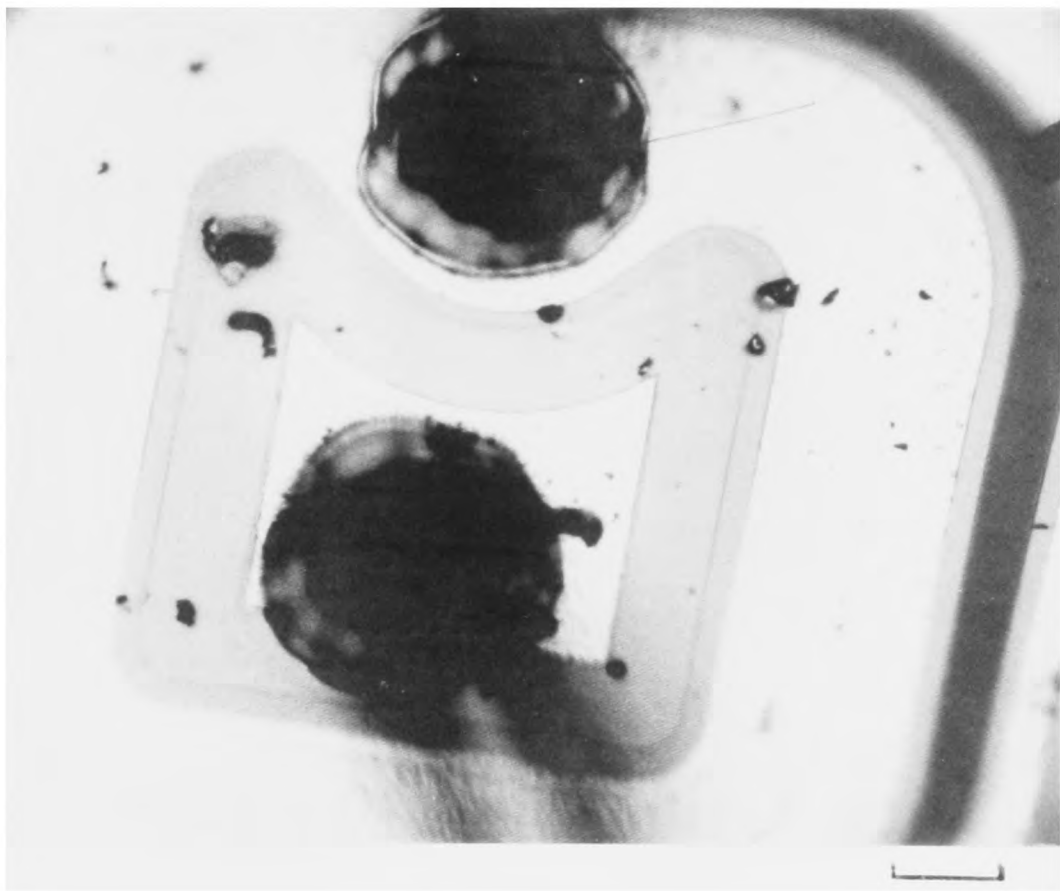
To determine a suitable value of capacitor,  $C$ , in Fig. 3.5 such that it blocks d.c. but provides negligible reactance to the frequencies encountered in the differentiated signal it is desirable to have the circuit input time constant of the order of 0.01 s. Thus a suitable value of  $C$  may be chosen.  $C = 2.35 \mu F$  is used in this circuit.

### **3.3 RESULTS**

Fig. 3.6(a) shows the Type 1 reflected light image of a bipolar BFY51 transistor while Fig. 3.6(b) shows the device in reflection on a much lower magnification. It was possible to form images corresponding to the OBIC images of Fig. 3.1 and they are shown in Fig. 3.7. The dislocation contrast in Fig. 3.7(a) was measured to be 3% and the OBIC resolution is seen to be approximately  $1\mu m$ . The electrical differentiation is performed only horizontally and hence the technique is not so sensitive to horizontal detail but nevertheless the contrast obtained in Fig. 3.7(c) is considerably greater and more stable than that in Fig. 3.7(a). Fig. 3.8 shows linetraces across a dislocation in the OBIC image of Fig. 3.7. The upper trace corresponds to the rectified signal whereas the lower trace shows the original OBIC signal, one large division representing  $1\mu m$  of scan. This demonstrates the high-resolution nature of the technique.

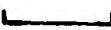


(a)

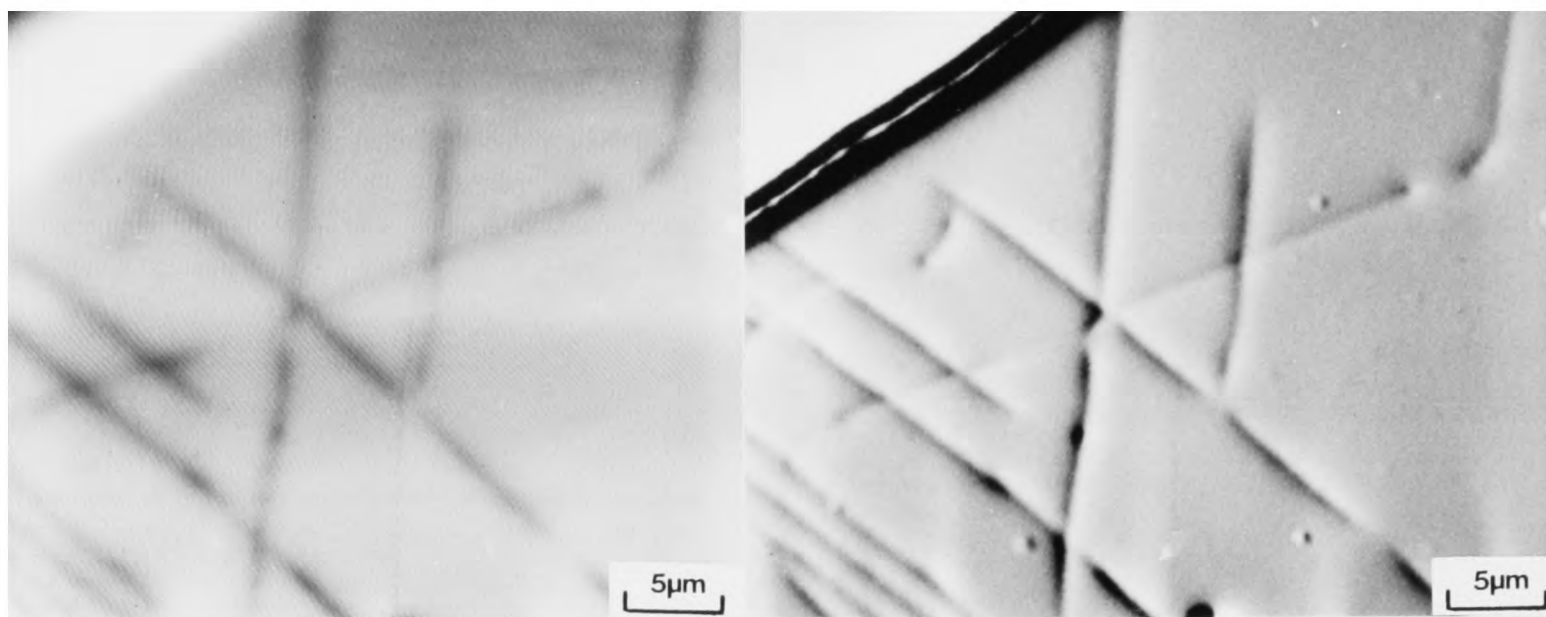


(b)

Fig. 3.6 Type 1 Reflected Light Images of the BFY51 Transistor

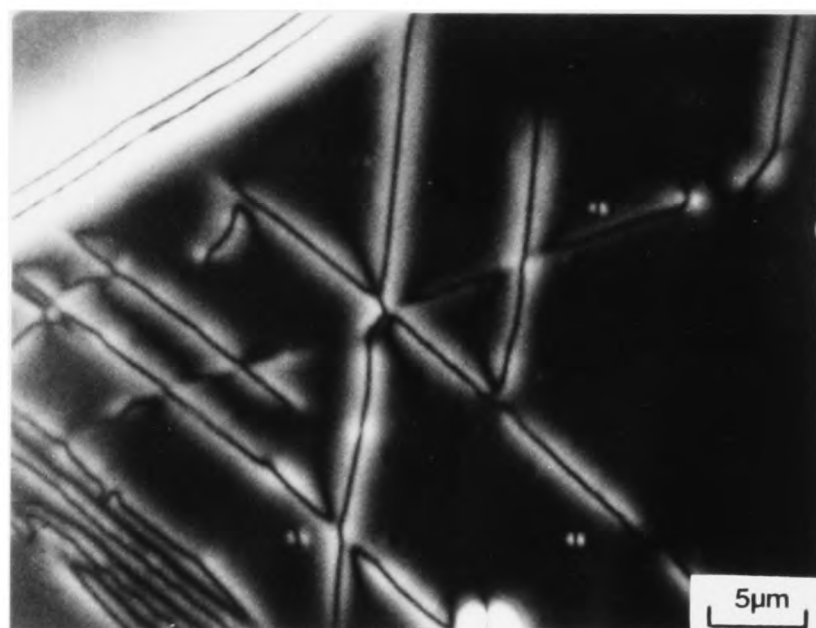
(a)  = 5 $\mu$ m

(b)  = 50 $\mu$ m



(a)

(b)



(c)

Fig. 3.7 Defects in a Silicon Bipolar Transistor imaged by displaying

(a)Conventional OBIC Image

(b)Differentiated OBIC Image

(c)Rectified,differentiated OBIC Image

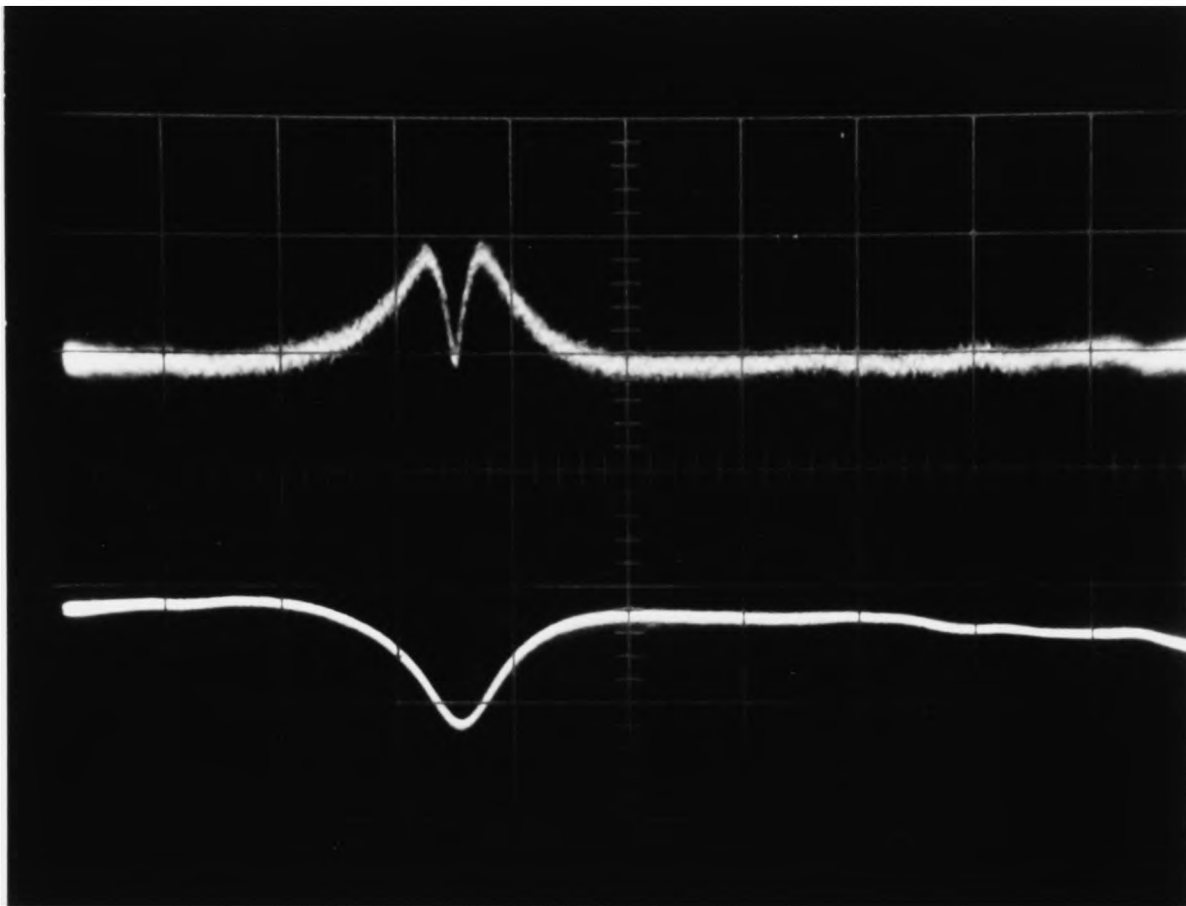


Fig.3.8 High resolution line scan profiles across a single line defect in the same transistor. The lower trace shows the conventional OBIC image (with zero suppressed); the upper trace corresponds to the rectified, differentiated OBIC signal. The horizontal scale is such that one large division is equivalent to  $1\mu\text{m}$ .

### **3.4 CONCLUSIONS**

A new method of displaying OBIC images has been presented. This method is equally suitable to display EBIC images. The method is insensitive to laser fluctuations or other effects such as surface reflectivity variations which change the background signal level. The technique removes the necessity for a d.c. offset to be applied to the signal and is very simple to use.

## **CHAPTER 4**

### **OBIC IMAGING OF DEFECTS IN SCHOTTKY BARRIER AND SHALLOW JUNCTION DEVICES**

#### **4.1 INTRODUCTION**

Dislocations which occur within a few microns of the surface of a semiconductor device may be detrimental to the performance of the device. The presence of such dislocations may be imaged via their influence on the short circuit photocurrent as the laser beam of a SOM scans over the surface of the device. This Chapter examines the theory of OBIC imaging of defects in Schottky and shallow junction devices and predicts the resolution which would be obtained for such devices. The theory is developed for an arbitrary defect before applying the theory to the specific cases of point and line defects. The consideration of such a basic device as a Schottky diode is important because the simplicity of such devices allows the initial steps of the theory to be developed. The theory may then be extended to more complicated devices.

Consider a device, for example, with many semiconductor layers and with a junction at the interface of each layer. To predict the resolution of a defect looking at the OBIC signal from contacts to one of these junctions we need to first consider each layer as an absorbing or transmitting medium, to specify the boundary conditions at each interface and hence calculate the carrier distribution within each layer. Using this approach the theory of defect imaging for complicated devices may be developed.

Schottky barriers may also be used as solar cell devices where they may exhibit certain advantages over the more commonly used p - n junction solar cell<sup>4.1</sup>. These advantages include simplicity and economy of fabrication. In addition Schottky diodes are important in their use to improve the speed performance of integrated

injection logic <sup>4.2</sup> circuits . It is therefore important to develop a theory of the OBIC image formation in Schottky barrier devices such that OBIC images of defects in such devices may be understood. This chapter considers Schottky barriers whose depletion width is negligible. The effect of finite depletion width is discussed in Chapter 5 where biasing is considered.

## 4.2 BASIC THEORY

We now develop theoretical expressions for the OBIC signal due to scanning a laser beam over the surface of a shallow junction device containing a defect , Figure 4.1. Several assumptions are made to simplify the analysis. We assume low injection conditions, linear recombination and that the semiconductor is much thicker than the minority carrier diffusion length. Steady state conditions are also assumed. A further simplification is that charge collection takes place at the depletion edge of a shallow p-n junction or Schottky barrier diode.

To derive the equation governing the minority carrier (hole) concentration in an n-type semiconductor under illumination, several assumptions are made. Consider a uniformly illuminated semiconductor slice where carriers are generated in the material at a rate  $G_L$  per unit volume per unit time. Noting that the rate of increase of minority carrier concentration,  $dp_n/dt$ , equals the total generation rate of minority carriers minus the net recombination rate,  $U$ , or

$$\frac{dp_n}{dt} = G_L - U \quad (4.1)$$

where the net rate of recombination equals the total rate of recombination minus the rate of generation in the dark. From Eq.4.1 it is clear that the net rate of recombination,  $U$ , equals zero in the steady state if there is no light injection.

The assumption of linear recombination means that we assume that  $U$  is pro-

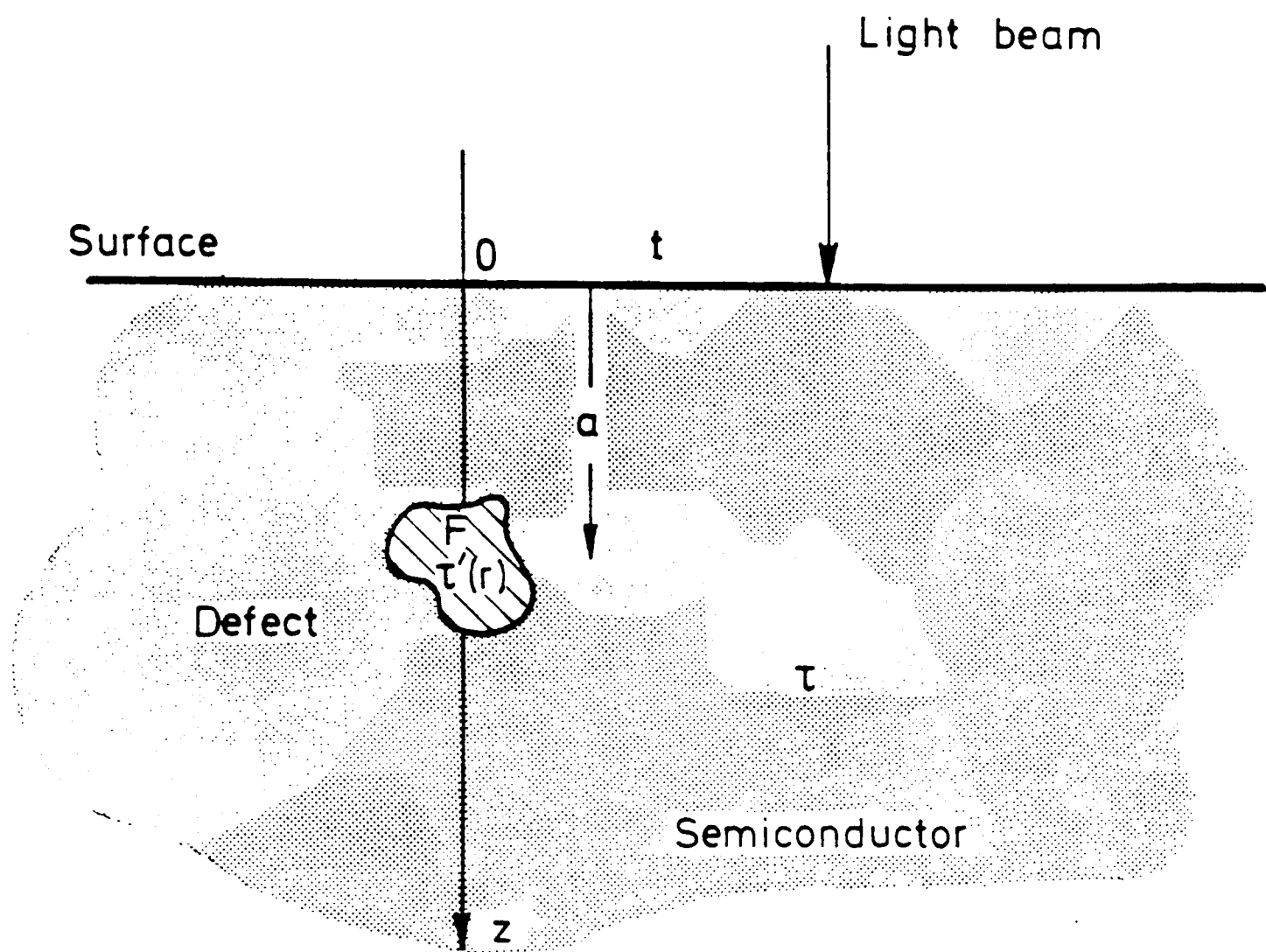


Fig. 4.1

Schematic of the model used to derive the OBIC image of a localised defect

portional to the excess minority concentration,  $p$ , or

$$U = \frac{p_n - p_0}{\tau_p} = \frac{p}{\tau_p}$$

where  $p_0$  denotes the minority carrier concentration in equilibrium and  $\tau_p$  is the lifetime of the excess holes. This assumption has the correct feature that  $U = 0$  in equilibrium.

Now let us make the further assumption that there is an enhanced rate of recombination of excess minority carriers at the surface of the infinitely deep semiconductor where the surface occurs at  $z = 0$ . Thus the concentration of holes at the surface is lower than that in the main body of the semiconductor. Hence both minority and majority carriers will flow to this surface and recombine there. The flux of holes,  $F_p$ , equals the flux of electrons with the result that no net current flows. Now minority and majority carrier concentrations vary spatially. The hole distribution is described by the transport equation<sup>4.3</sup>

$$\frac{\partial p_n}{\partial t} = -\frac{\partial F_p}{\partial z} + G_L - U \quad (4.2)$$

The flux of holes is given by<sup>4.3</sup>

$$F_p = -D_p \frac{\partial p_n}{\partial z} + \mu_p E p_n \quad (4.3)$$

where  $D_p$  and  $\mu_p$  are the diffusion coefficient and mobility of holes respectively and  $E$  is the electric field. Similarly for electrons we obtain

$$F_n = -D_n \frac{\partial n_n}{\partial z} - \mu_n E n_n \quad (4.4)$$

From the equality of the two fluxes  $F_p = F_n$  and from the requirement of space charge neutrality due to which  $\partial p_n / \partial z = \partial n_n / \partial z$  we obtain an expression for the electric field

$$E = -\frac{(D_n - D_p) \partial p_n / \partial z}{\mu_p p_n + \mu_n n_n} \quad (4.5)$$

The drift term in Eq.4.3 is given by

$$\mu_p E p_n = D_p \frac{\partial p_n}{\partial z} \left( 1 - \frac{D_n}{D_p} \right) \frac{\mu_p}{\mu_n + \mu_p (p_n/n_n)} \frac{p_n}{n_n} \quad (4.6)$$

In the case of low level injection,  $p_n \ll n_n$ , this drift term is clearly negligible in comparison to the diffusion term of Eq.4.3. The transport equation of Eq.4.2 now becomes

$$\frac{\partial p_n}{\partial t} = D_p \frac{\partial^2 p_n}{\partial z^2} + G_L - \frac{p_n - p_0}{\tau_p} \quad (4.7)$$

Now applying our assumption of steady state conditions we obtain the equation

$$\frac{\partial^2 p}{\partial z^2} - \frac{p}{L^2} = -\frac{1}{D} G_L \quad (4.8)$$

where  $p$  is the excess minority carrier distribution,  $L$  is the minority carrier diffusion length and subscripts have been dropped for convenience.

The above situation considered uniform illumination. Now consider the more general situation where a laser beam is focused on the surface generating carriers at rate  $g(\mathbf{r})$  per unit volume which, of course, replaces the  $G_L$  term. Following Donolato <sup>4.4</sup> we consider a localised defect under the surface represented by a region  $F$  where the minority carrier lifetime ( $\tau'(\mathbf{r})$ ) is lower than the lifetime,  $\tau$ , in the surrounding n-type semiconductor. Under these circumstances we may include the spatial nature of the generation function and the effect of the defect in the modification of Eq.4.8 to obtain an equation giving the excess hole concentration  $p(\mathbf{r})$  in the presence of a defect given by

$$\nabla^2 p(\mathbf{r}) - \frac{1}{L^2} p(\mathbf{r}) = -\frac{1}{D} g(\mathbf{r}) + \gamma(\mathbf{r}) u(\mathbf{r}) p(\mathbf{r}) \quad (4.9)$$

where  $D$  and  $L$  are the minority carrier diffusion coefficient and diffusion length respectively and  $u(\mathbf{r})$  is a function which is unity within the defect region  $F$  and zero outside.  $\gamma(\mathbf{r})$  has been called the strength of the defect and is given by

$$\gamma(\mathbf{r}) = \frac{1}{D} \left\{ \frac{1}{\tau'(\mathbf{r})} - \frac{1}{\tau} \right\} = \frac{1}{L'^2(\mathbf{r})} - \frac{1}{L^2} \quad (4.10)$$

This function is always positive and if  $L'(\mathbf{r}) \ll L$  then the strength of the defect is essentially independent of the bulk diffusion length,  $L$ , of the semiconductor.

We may solve Eq.4.9 most easily by a Green's function approach <sup>4,5</sup> to give

$$p(\mathbf{r}) = \frac{1}{D} \int_V g(\mathbf{r}') G(\mathbf{r}|\mathbf{r}') d\mathbf{r}' - \int_F \gamma(\mathbf{r}') p(\mathbf{r}') G(\mathbf{r}|\mathbf{r}') d\mathbf{r}' \quad (4.11)$$

where  $V$  is the half space,  $z \geq 0$ .  $p(\mathbf{r})$  satisfies the boundary conditions

$$p(\mathbf{r})|_{z=0} = 0 \quad \text{and} \quad p(\mathbf{r})|_{z \rightarrow \infty} = 0 \quad (4.12)$$

where the first condition is due to the infinite surface recombination velocity and the second condition states that there are very few excess minority carriers deep in the semiconductor.  $G(\mathbf{r}|\mathbf{r}')$  is the Green's function for the semi-infinite region  $z \geq 0$  for the equation

$$\nabla^2 p(\mathbf{r}) - \frac{1}{L^2} p(\mathbf{r}) = 0 \quad (4.13)$$

The zeroth approximation to the solution of Eq.4.11 is given by

$$p_0(\mathbf{r}) = \frac{1}{D} \int_V g(\mathbf{r}') G(\mathbf{r}|\mathbf{r}') d\mathbf{r}' \quad (4.14)$$

which represents the minority carrier distribution in a defect-free homogeneous semiconductor. The first approximation is obtained by setting  $p(\mathbf{r}) = p_0(\mathbf{r})$  in the second integral equation of Eq.4.11. This yields the first Born approximation

$$p_1(\mathbf{r}) = p_0(\mathbf{r}) - \int_F \gamma(\mathbf{r}') p_0(\mathbf{r}') G(\mathbf{r}|\mathbf{r}') d\mathbf{r}' \quad (4.15)$$

where the second term represents the change in hole concentration brought about by the defect. It is expected on physical grounds that the Born approximation is a good one when the perturbation introduced by the defect in the distribution of minority carriers and hence on the total current is small. We know that this is the case in OBIC imaging<sup>1,25</sup>. The current collected at the surface may be calculated as

$$I = qD \int \int \left. \frac{\partial p_1}{\partial z} \right|_{z=0} dx dy \quad (4.16)$$

where  $q$  is the electron charge. We need to know the Green's function,  $G(\mathbf{r}|\mathbf{r}')$ , to evaluate this current.

The Green's function for point excitation <sup>4,6</sup> at  $(x'y'z')$  is given by

$$G(\mathbf{r}|\mathbf{r}') = G(x, y, z|x', y', z') = \frac{1}{4\pi} \left\{ \frac{\exp -\rho_1/L}{\rho_1} - \frac{\exp -\rho_2/L}{\rho_2} \right\} \quad (4.17)$$

with

$$\rho_1 = [(x - x')^2 + (y - y')^2 + (z - z')^2]^{\frac{1}{2}} \quad (4.18)$$

and

$$\rho_2 = [(x - x')^2 + (y - y')^2 + (z + z')^2]^{\frac{1}{2}}$$

Substitution of this expression for  $G$  into Eq.4.16 allows the current  $I$  to be written as

$$I(\xi) = I_0 - qD \int_F \gamma(x, y, z) p_0(x - \xi, y, z) \exp -\frac{z}{L} dx dy dz \quad (4.19)$$

ie.

$$I(\xi) = I_0 - I_d(\xi)$$

where  $\xi$  is the scan coordinate,

$$I_0 = q \int \int \int_V g(x, y, z) \exp -\frac{z}{L} dx dy dz \quad (4.20)$$

and  $I_d$  is the current reduction due to the defect. Eq. 4.19 may be written alternatively as

$$I = I_0 - \gamma \otimes h \quad (4.21)$$

where  $\otimes$  denotes the convolution operation and  $h$  represents, in imaging theory terminology, the point spread function of the system. It is given by

$$h = qD p_0(x, y, z) \exp -\frac{z}{L} \quad (4.22)$$

This is clearly a very important function as it is this function which determines the form of the OBIC image of a defect distribution,  $\gamma(x, y, z, )$ .

### 4.3 THE GENERATION TERM, $g(\mathbf{r})$

In order to estimate the resolution of the OBIC technique and to understand the various factors which affect it we must first determine the form of the generation term  $g(\mathbf{r})$ . Eq.4.11 may not be solved easily analytically. Its numerical solution is greatly simplified by using an approximate expression for the complicated generation function given in Chapter 2. Appendix 1 gives this approximate expression as

$$g(r, z) = \frac{g_0 \alpha}{\pi c^2} \exp - \frac{r^2}{c^2} \exp - \alpha z \quad (4.23)$$

where  $r$  is a radial variable,  $g_0$  is a constant which takes into account the surface reflectivity and quantum efficiency,  $\alpha$  is the intensity attenuation coefficient and  $c$  is the half width of the probe beam. An advantage of this approximation is that our simplified analysis neglects the converging nature of a highly focused light beam and thus allows sub-surface effects to be explained free from any possible confusion due to the converging nature of the illumination. Also the gaussian term in this expression may reflect the gaussian nature of the light emerging from a real laser source.

An alternative form of  $g$  has been used by several authors to analyse specific problems such as the measurement of grain boundary recombination velocity<sup>4,7</sup>. This involves considering  $g$  to be an exponentially decaying array of point sources. It is a special case of Eq. 4.23 with  $c = 0$ . For our purposes Eq. 4.23 is favoured because it allows us to consider the effects of beam size on the OBIC images.

#### 4.4 THE DISTRIBUTION OF EXCESS MINORITY CARRIERS, $p_0$

The next step in the imaging calculation is to consider the form of the point spread function,  $h(\mathbf{r})$  of Eq.4.22, and initially the form of  $p_0(x, y, z)$  as we notice that for large diffusion lengths these functions become identical in shape. Before we calculate these functions we can make the general statement that both  $p_0(\mathbf{r})$  and the point spread function  $h(\mathbf{r})$  will peak beneath the surface. This is because we model the surface as having an infinite recombination velocity. In fact, this statement is true for any non-zero surface recombination velocity. It is important to note that this behaviour is caused by the surface boundary conditions and applies equally well to illumination with either a converging or parallel beam of light.

To find  $p_0(x, y, z)$  we must solve

$$\nabla^2 p_0(x, y, z) - \frac{1}{L^2} p_0(x, y, z) = -\frac{1}{D} g(x, y, z) \quad (4.24)$$

subject to the boundary conditions of Eq.4.12 and using the generation term of Eq.4.23. We could use the general expression for  $p_0$  of Eq.4.14. However since the problem has cylindrical symmetry and the boundary conditions only involve  $z$  this suggests an alternative approach in taking the Fourier-Bessel transform of Eq.4.24 and using a Green's function technique to solve the resulting equation for the Fourier-Bessel transform of  $p_0$ ,  $\bar{p}_0$ . Using

$$\bar{p}_0(\nu, z) = \int_0^\infty p_0(\mathbf{r}, z) J_0(\nu \mathbf{r}) \mathbf{r} d\mathbf{r} \quad (4.25)$$

and

$$\bar{g}(\nu, z) = \int_0^\infty g(\mathbf{r}, z) J_0(\nu \mathbf{r}) \mathbf{r} d\mathbf{r} \quad (4.26)$$

we get the Fourier-Bessel transform of Eq.4.24 as

$$\frac{\partial^2 \bar{p}_0(\nu, z)}{\partial^2 z} - \beta^2 \bar{p}_0(\nu, z) = -\frac{1}{D} \bar{g}(\nu, z) \quad (4.27)$$

with  $\beta^2 = \nu^2 + 1/L^2$ . To find the Green's function for Eq.4.27 replace  $\bar{p}_0$  by  $G$  in this equation and replace the right hand side of the equation by a delta function.

Now solve the resulting equation for  $G$  using the appropriate boundary conditions. Having found  $G$  then the solution,  $\bar{p}_0$ , to Eq.4.27 may be found by performing the following integral

$$\bar{p}_0(\nu, z) = \frac{1}{D} \int_0^\infty \bar{g}(\nu, z') G(\nu, z|z') dz' \quad (4.28)$$

An expression for  $p_0(r, z)$  is then conveniently obtained by taking the inverse Fourier-Bessel transform of  $\bar{p}_0$ . The analysis <sup>4.5,4.8</sup> gives

$$p_0(r, z) = \frac{g_0 \alpha}{2\pi D} \int_0^\infty \left[ \exp(-\alpha z) - \exp(-\beta z) \right] \frac{\exp(-\nu^2 c^2/4)}{\beta^2 - \alpha^2} J_0(\nu r) \nu d\nu \quad (4.29)$$

where  $\beta^2 = \nu^2 + 1/L^2$  and  $J_0$  is a zero order Bessel function of the first kind. It is now a routine matter to substitute this expression into Eq.4.19 for any given defect distribution. A full discussion of the solution of Eq. 4.29 has already been given<sup>4.8</sup>.

The reason that the Fourier-Bessel approach has been adopted in the evaluation of the carrier distribution in the absence of a defect is because of the cylindrical symmetry of the problem. This approach was not used in the previous section to obtain an expression for defect current (Eq.4.19) since in this case we considered an arbitrary defect. Hence the same symmetry conditions need not apply.

We plot, in Fig. 4.2 the distribution of excess carriers  $\Delta p(0, z) = p_0(0, 0, z)$  along the axis beneath the exciting light spot. We choose an attenuation coefficient  $\alpha = 0.4\mu m^{-1}$  which corresponds to helium neon light being absorbed in silicon. The value of  $c = 0.5\mu m$  corresponds to a  $1\mu m$  spot of light or a numerical aperture of about 0.4 (Appendix 1). The curves all show the predicted peak and also indicate that for diffusion lengths greater than about  $10\mu m$  the infinite diffusion length approximation may be used.

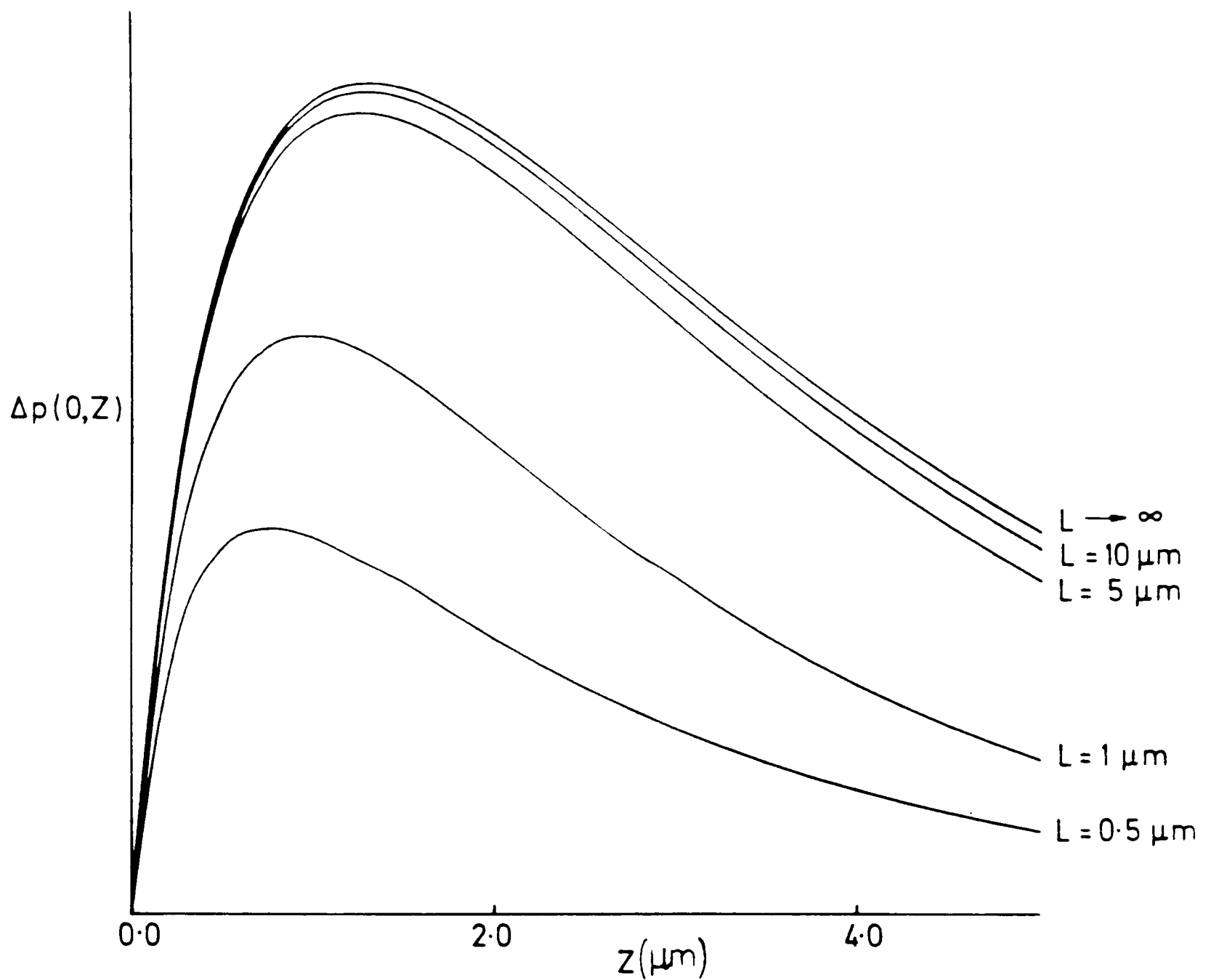


Fig. 4.2

The distribution of excess carriers along the axis for various diffusion lengths. The curves correspond to  $\alpha = 0.4 \mu \text{ m}^{-1}$  and  $c = 0.5 \mu \text{ m}$ . The axial distance  $z$  is also measured in microns.

Typical forms of the solution of Eq.4.24 are shown in the isometric plots of  $p_0(r, z)$  in Figs. 4.3 and 4.4 where the two diffusion lengths  $10\mu m$  and  $1\mu m$  respectively are considered. Fig. 4.5 gives the form of the point spread function in the infinite diffusion length limit. It is this function which must be convolved with the specific defect distribution in order to obtain the OBIC image. The next step in the theory is to consider two important types of defect distribution, point and line defects.

#### 4.5 THE IMAGING of POINT DEFECTS

Consider the image of a point defect at a depth,  $a$ , in the semiconductor. Thus

$$\gamma(x, y, z) = \bar{\gamma}\delta(x)\delta(y)\delta(z - a) \quad (4.30)$$

where  $\bar{\gamma}$  represents the strength of the defect. Substituting this defect distribution into Eq.4.19 the OBIC signal reduction due to the defect,  $I_d$ , may be written as

$$I_d(\xi) = qD\bar{\gamma}p_0(\xi, 0, a)\exp(-a/L) \quad (4.31)$$

$p_0(\xi, 0, a)$  may be obtained directly from Eq.4.29.

We may now introduce contrast,  $C(\xi)$  as

$$C(\xi) = \frac{I_d(\xi)}{I_0} \quad (4.32)$$

which is given by

$$C(\xi) = qD\bar{\gamma}\left\{\frac{p_0(\xi, 0, a)\exp(-a/L)}{I_0}\right\} \quad (4.33)$$

This contrast,  $C$ , describes how the presence of the defect causes the detected current to fall.

$I_0$ , given by Eq. 4.20, gives the background current which would be obtained in the case of a defect-free material. Using the generation expression of Eq.4.23 this background current is given by

$$I_0 = qg_0\frac{\alpha L}{1 + \alpha L} \quad (4.34)$$

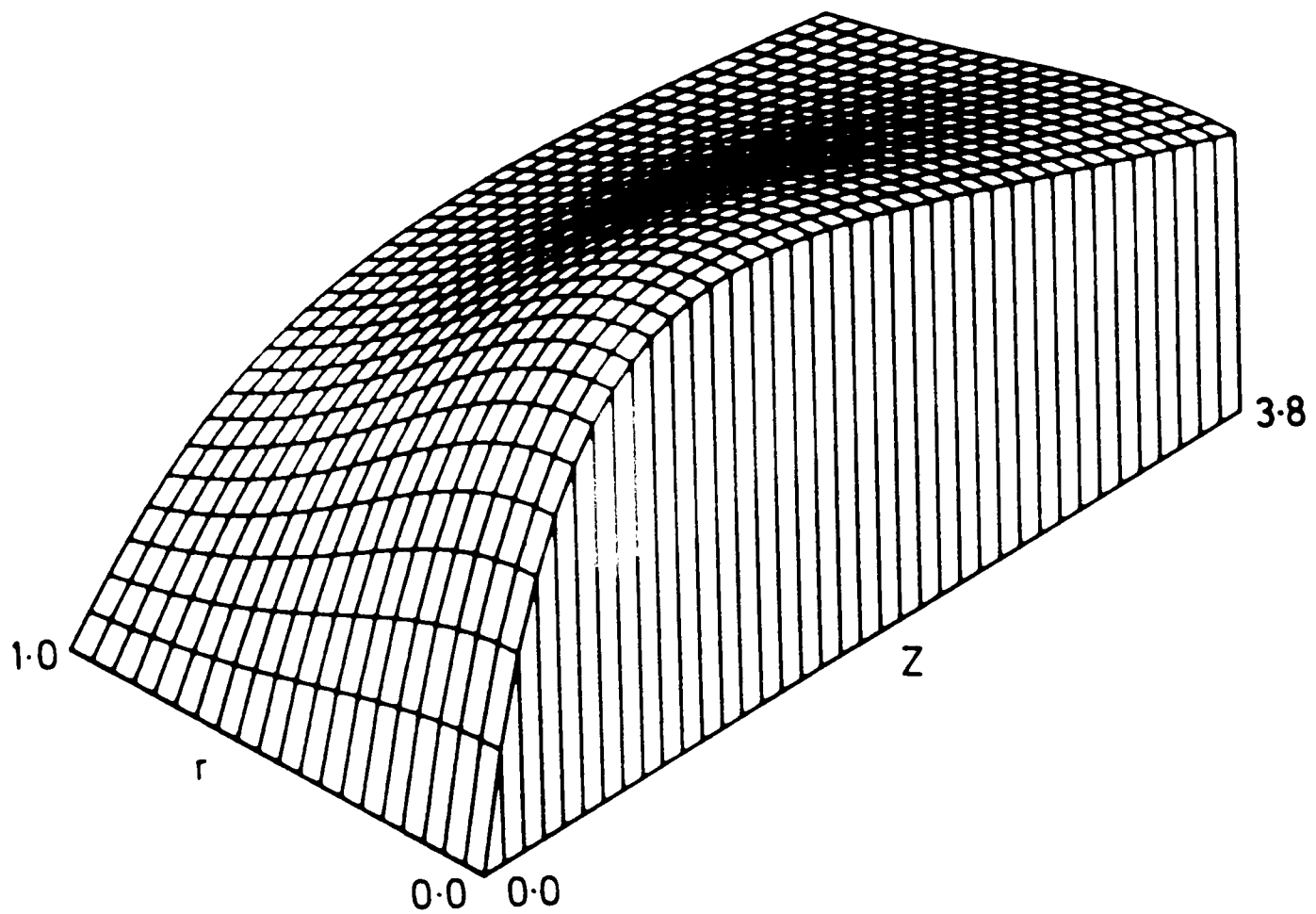


Fig. 4.3

Isometric projection of  $p(r, z)$  for  $10 \mu\text{m}$  diffusion length,

$\alpha = 0.4 \mu\text{m}^{-1}$  and  $c = 0.5 \mu\text{m}$ . All distances are measured in microns.

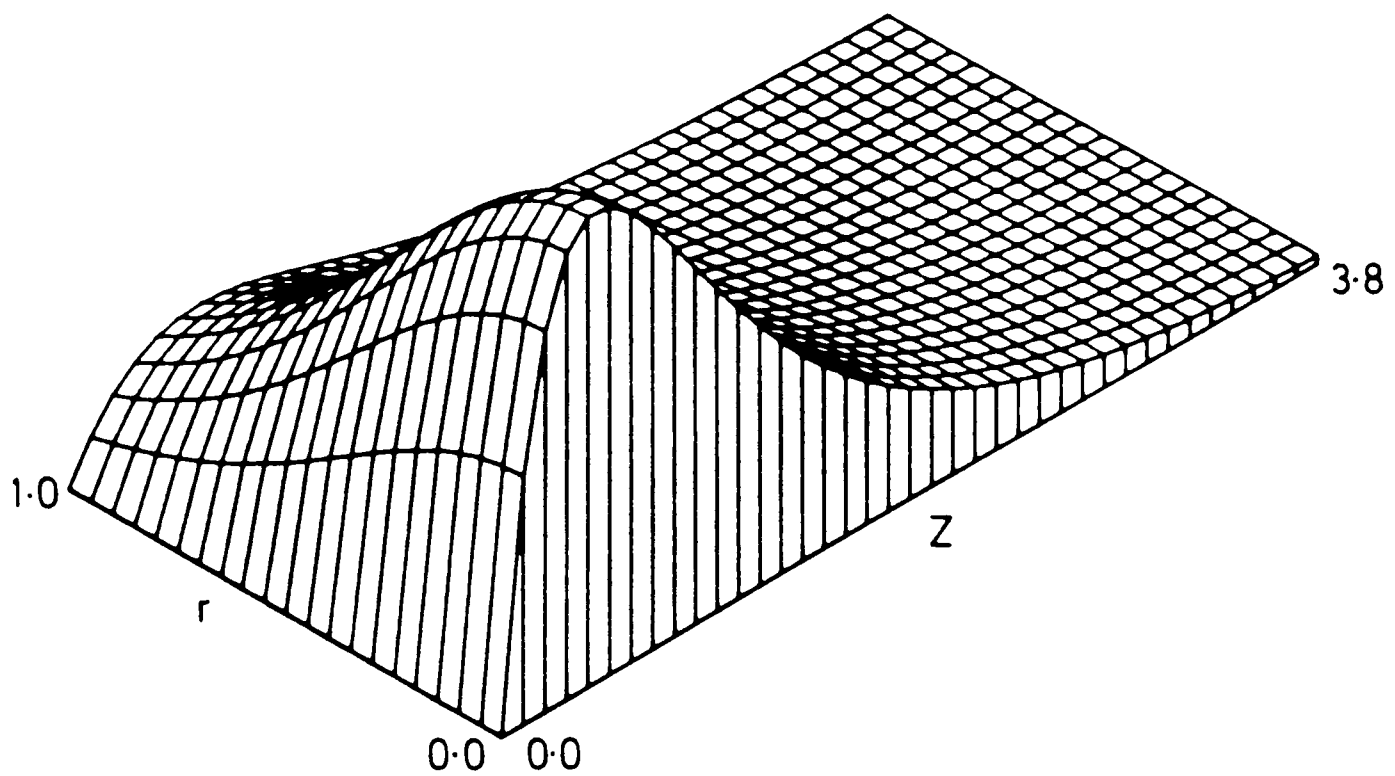


Fig. 4.4

Isometric projection of  $p(r, z)$  for  $1 \mu\text{m}$  diffusion length,

$\alpha = 0.4 \mu\text{m}^{-1}$  and  $c = 0.5 \mu\text{m}$ . All distances are measured in microns.

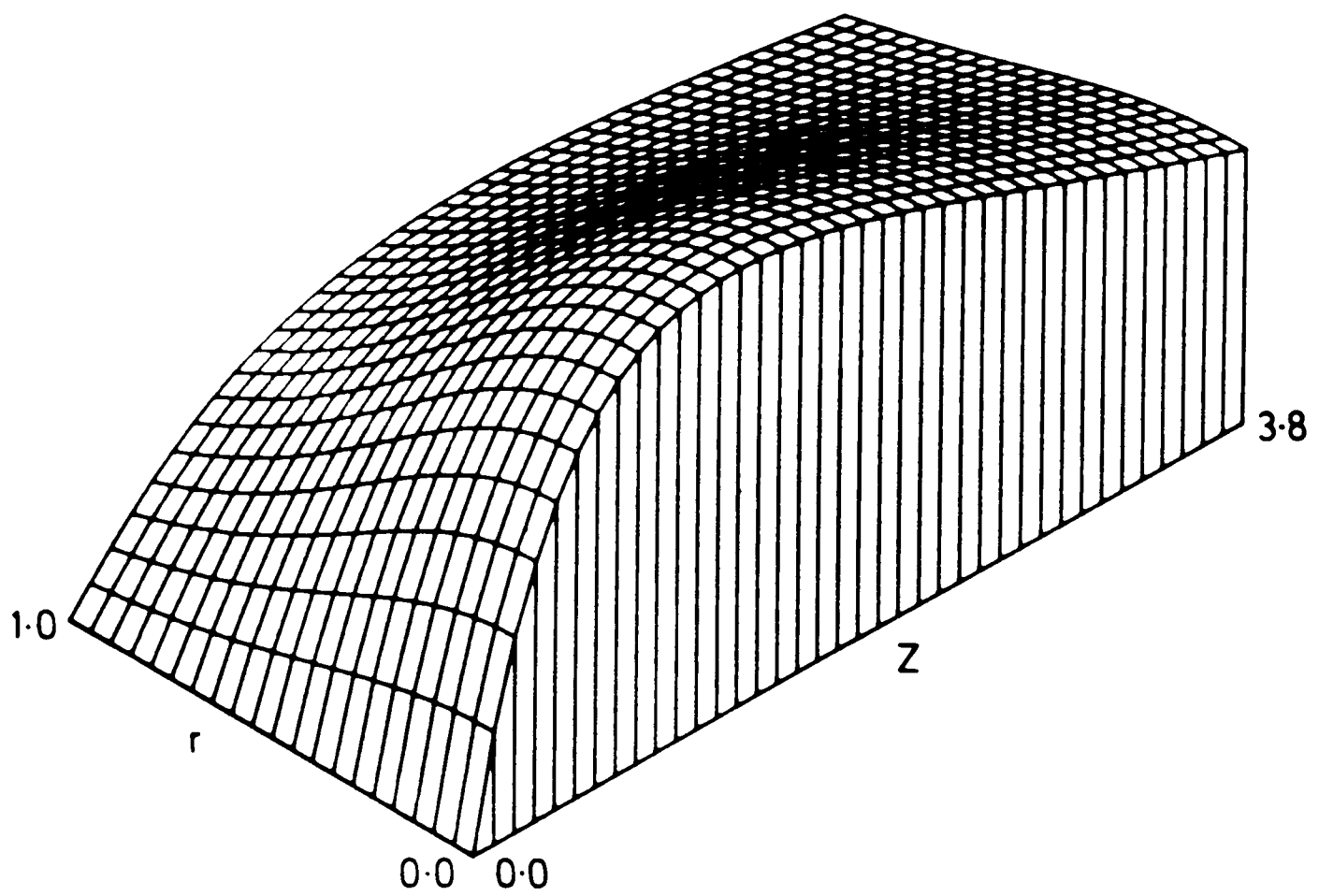


Fig4.5

Isometric projection of the impulse response function  $h(r, z)$  in the infinite diffusion length limit. Again,  $\alpha = 0.4\mu\text{m}^{-1}$ ,  $c = 0.5\mu\text{ m}$  and all distances are measured in microns.

Fig. 4.6 shows typical contrast curves for a variety of diffusion lengths for a defect  $2\mu m$  below the surface. We see that the curves all have submicron half widths. Such resolution values are in agreement with experimental observation<sup>1,25</sup>.

It is also clear that the value of the diffusion length is not critical in determining the width of these curves, that is, the resolution of the OBIC images. This is further emphasised in Fig. 4.7 where the full width half maximum of the contrast curves is plotted as a function of diffusion length. Finally Fig. 4.8 shows the effect of varying the depth of the defect for different diffusion lengths. We see, as we might expect, that the contrast on the axis is highest for shallow defects in materials of low diffusion length.

The insensitivity of resolution to changes in diffusion length may be understood as follows. We consider a relatively shallow defect at depth,  $a = 2\mu m$ . For diffusion lengths, say  $L = 10\mu m$  and  $L = 1\mu m$  the isometric plots of  $p_0(r, z)$  given in Figs. 4.3 and 4.4 are not dramatically different in the radial direction in the region of the defect around  $z = 2\mu m$ . From Eq.4.33 it is clear that differences in resolution due to varying diffusion length may be explained in essence by differences in the radial distribution of  $p_0(r, z)$  at the chosen defect depth. Thus we do not expect the resolution to be critically dependent on diffusion length.

This observation means that for a Schottky barrier the OBIC resolution of point defects is fairly independent of the shape of the excess minority carrier distribution. This in turn means that this resolution is fairly independent of the input beam generation function,  $g$ . Thus the approximating expression for  $g$  given by Eq. 4.23 is quite acceptable for this analysis. The advantage of using this expression over the case of an exponentially decaying array of point sources is that it allows us to examine the dependence of resolution on the beam width parameter,  $c$ , later in this chapter.

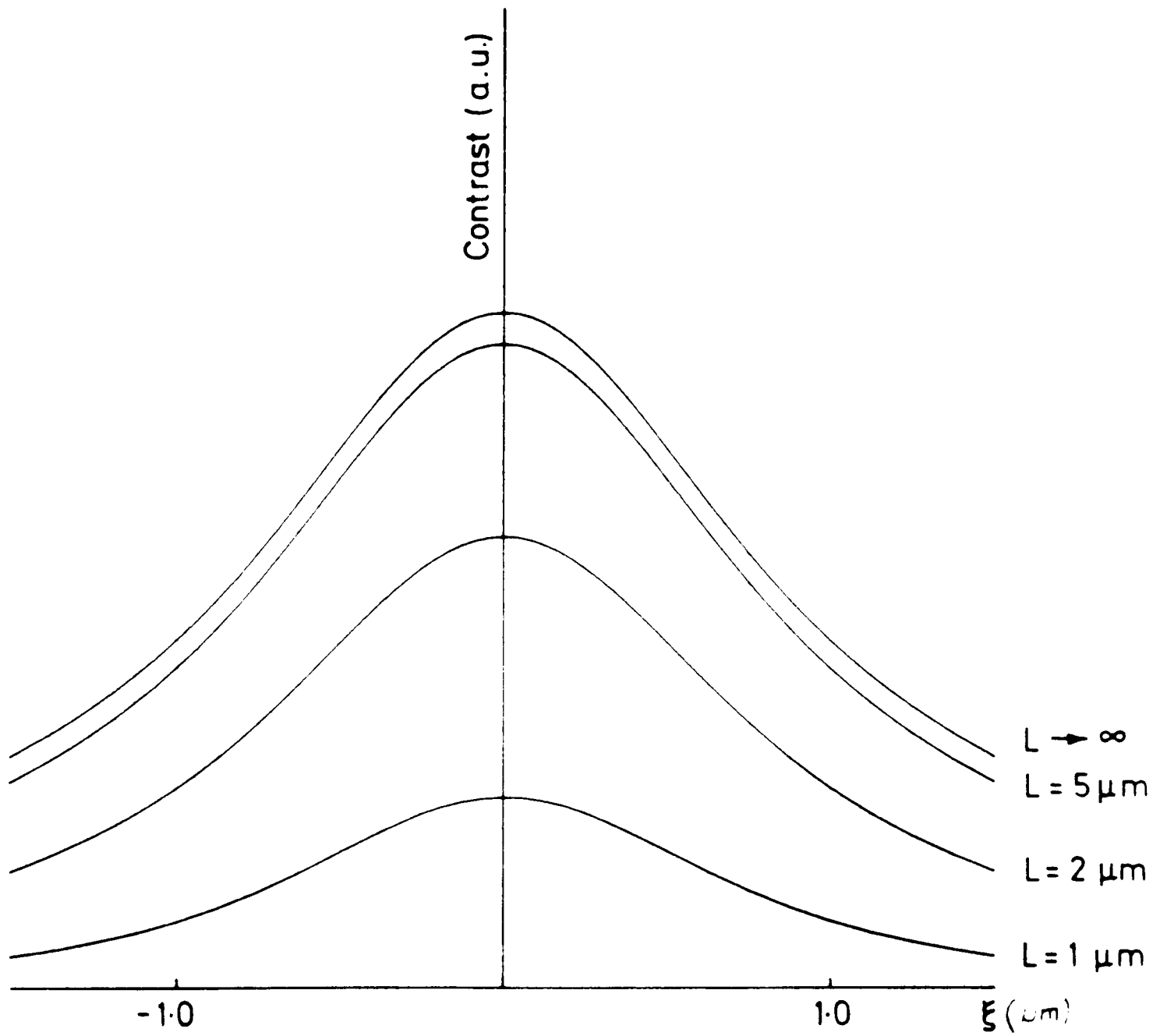


Fig.4.6

Plots of contrast vs. scan position for a defect  $2\mu\text{ m}$  deep in a semiconductor for various diffusion lengths. All the curves are for  $\alpha = 0.4\mu\text{m}^{-1}$ ,  $c = 0.5\mu\text{m}$  and all distances are measured in microns.

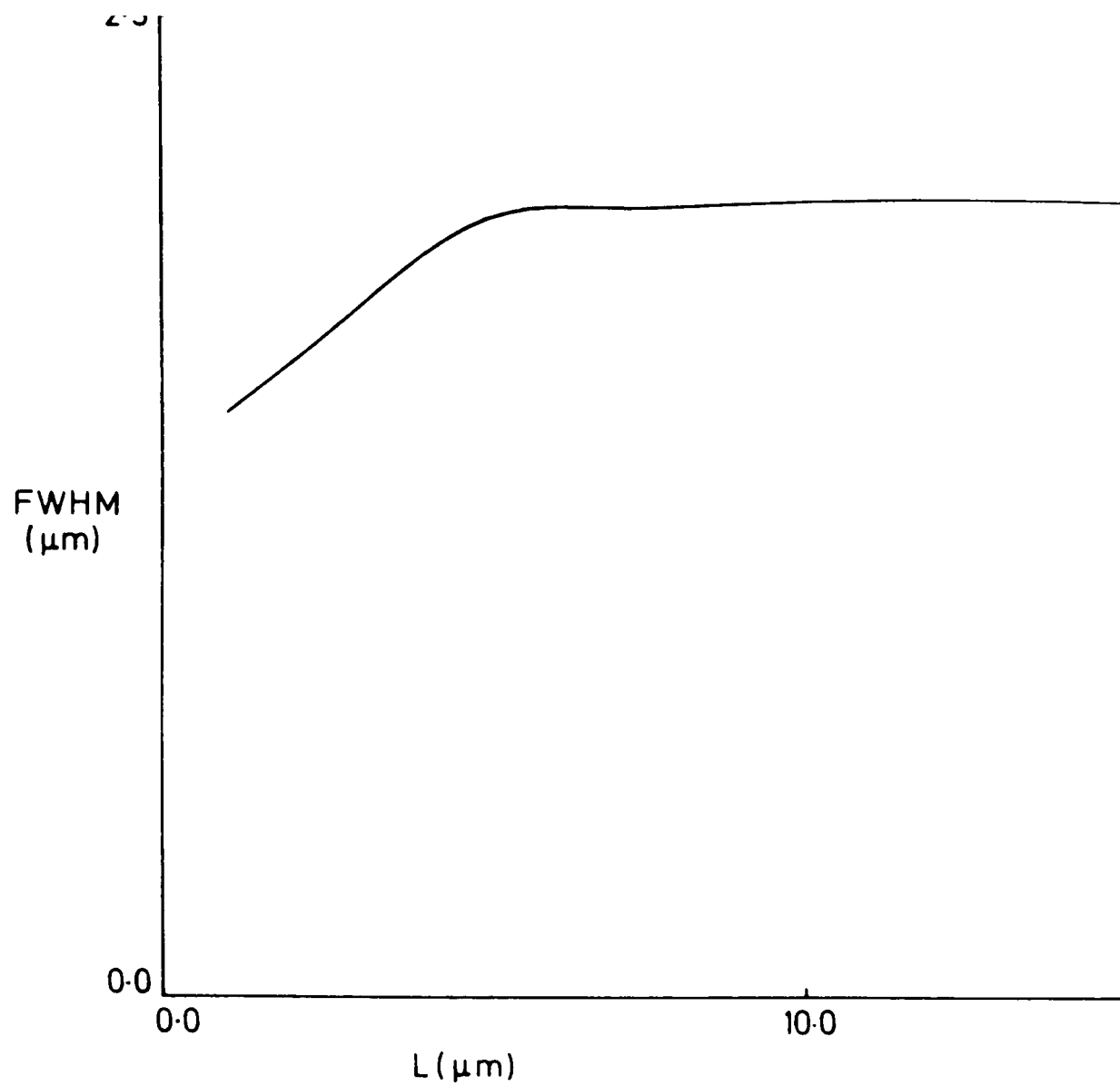


Fig.4.7

The full width half maximum of the contrast curves of Fig. 4.6 as a function of diffusion length.

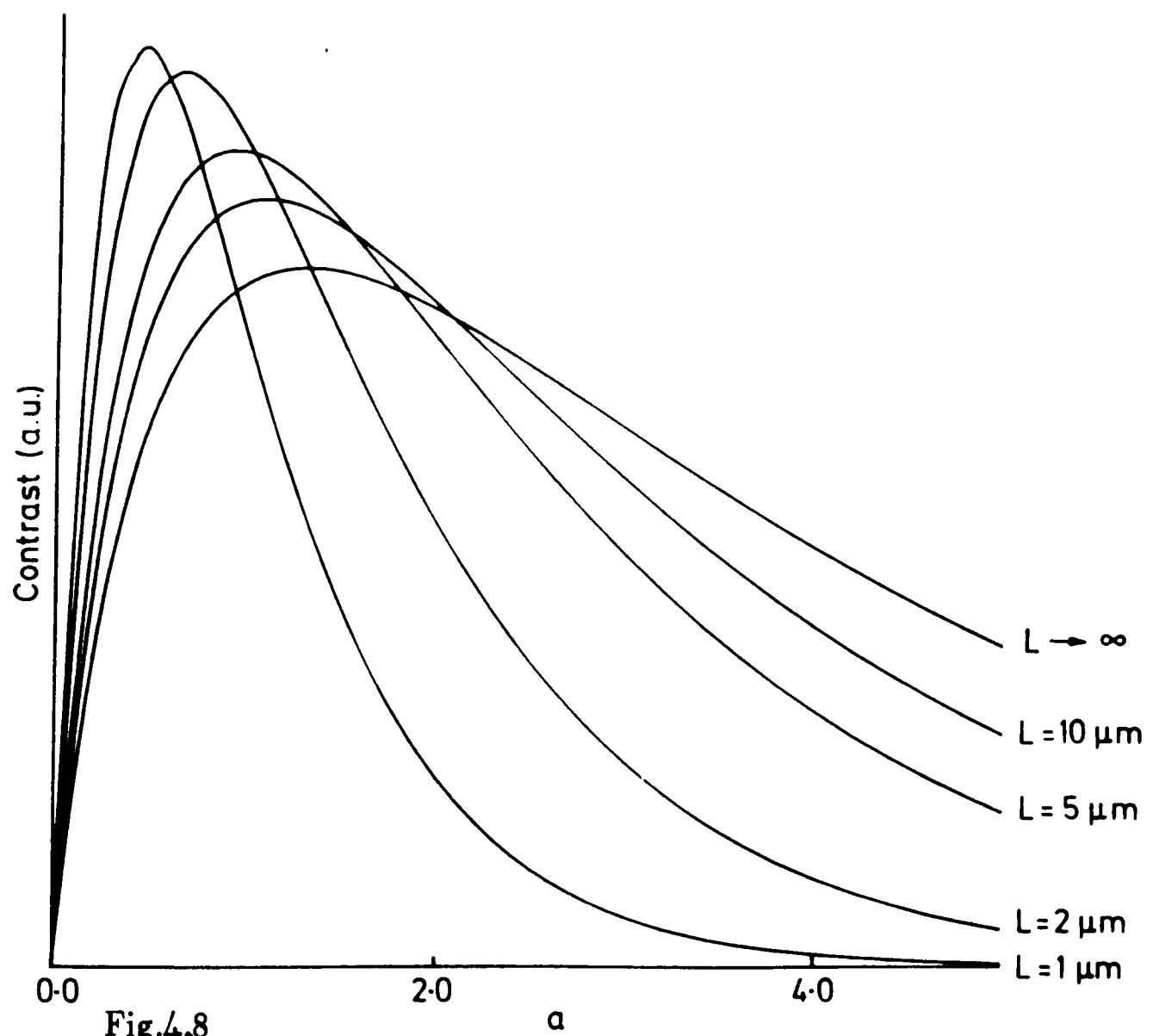


Fig.4.8

The variation of contrast on the axis with defect depth for various diffusion lengths.

## 4.6 THE IMAGING OF DISLOCATIONS OR LINE DEFECTS

If we now consider an extremely simple model of a straight dislocation perpendicular to the surface as a continuous distribution of equal strength point defects stretching from the surface to  $z \rightarrow \infty$  we can obtain the image either by taking  $\gamma(x, y, z) = \bar{\gamma}\delta(x)\delta(y)$  or by considering the defect current of Eq.4.31 for a point defect at depth,  $a$ , and integrating this expression with respect to  $a$  to obtain

$$I_d(\xi) = \left(\frac{\bar{\gamma}qg_0}{2\pi}\right) \frac{\alpha L}{1 + \alpha L} \int_0^\infty \frac{\exp(-\nu^2 c^2/4)}{(\beta + 1/L)(\beta + \alpha)} J_0(\nu\xi) \nu d\nu \quad (4.38)$$

We can also consider a line defect parallel to the surface at depth  $a$  beneath the surface i.e.

$$\gamma(x, y, z) = \bar{\gamma}\delta(x)\delta(z - a) \quad (4.36)$$

To find the defect current from Eq.4.31 we need to find  $p_0$ . It is convenient to find  $p_0$  by taking the inverse Fourier-Bessel transform of  $\bar{p}_0$  i.e. by integrating  $\bar{p}_0 J_0\left(\nu[\xi^2 + y^2]^{1/2}\right)$  with respect to  $\nu$ .  $\bar{p}_0$  is found by substituting the Green's function of Eq. 8.8 into Eq.4.28. This gives an expression for  $p_0$  in terms of exponentials. Hence the defect current is obtained from from Eq.4.31 as

$$I_d(\xi) = \bar{\gamma}q \frac{g_0\alpha}{\pi} \exp - \frac{a}{L} \cdot \int_0^\infty \left[ \exp(-\alpha a) - \exp(-\beta a) \right] \frac{\exp(-\nu^2 c^2/4)}{\beta^2 - \alpha^2} \cos(\nu r) \nu d\nu \quad (4.37)$$

where we have used the result<sup>4.9</sup>

$$\int_0^\infty J_0\left(\nu[\xi^2 + y^2]^{1/2}\right) dy = \frac{1}{\nu} \cos(\nu\xi) \quad (4.38)$$

and  $r^2 = x^2 + y^2$ . It is interesting to note that Eq. 4.37 is essentially a Fourier cosine transform of the same function whose Fourier-Bessel (Hankel) transform is taken in Eq. 4.29 with  $z = a$ .

Figs. 4.9 - 4.11 give plots of the contrast function which is to be expected in the case of a point defect and perpendicular and parallel line defects. We assume the

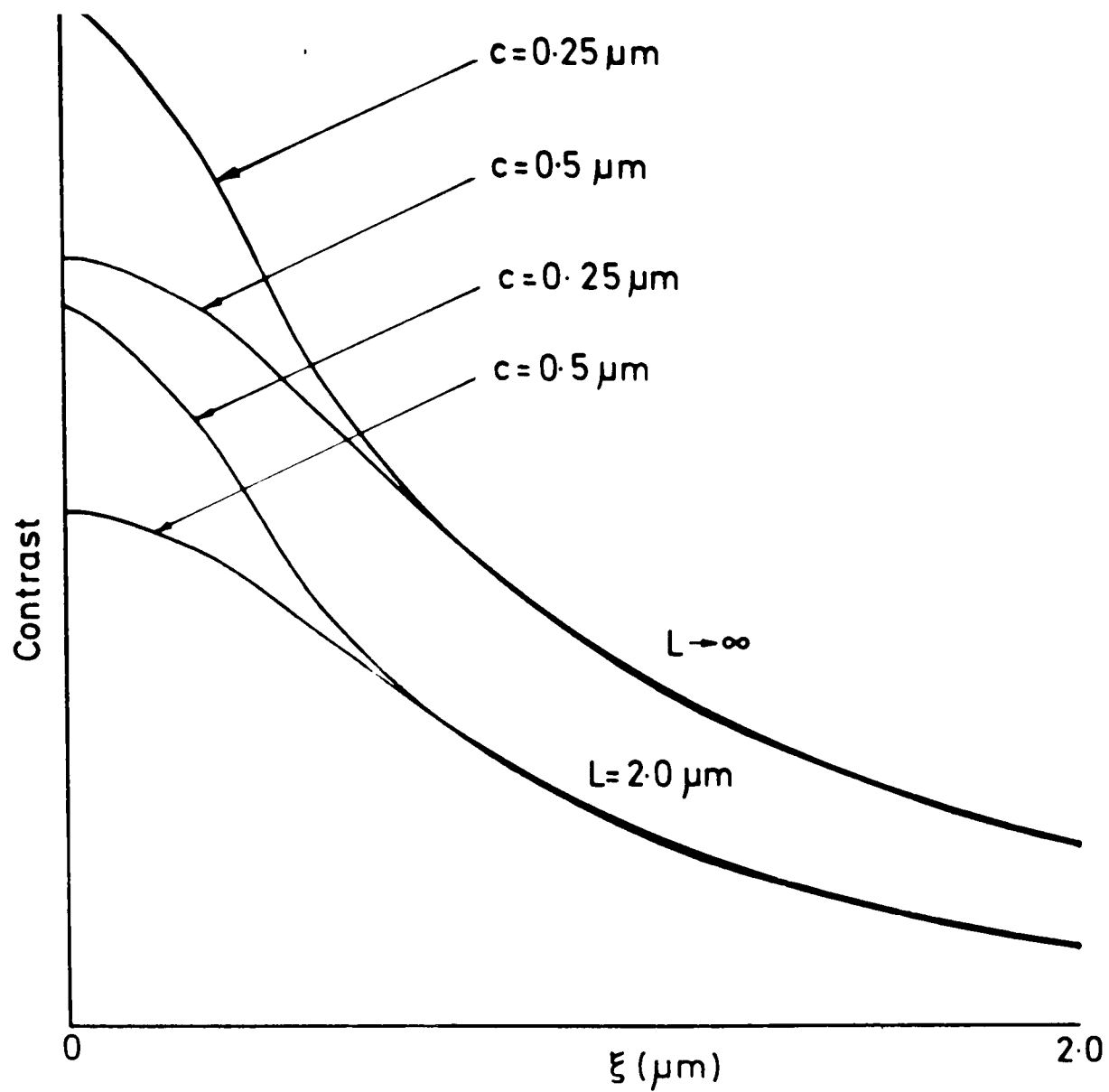


Fig.4.9

The contrast as a function of scan position for a point defect at depth  $2\mu\text{ m}$  beneath the surface for  $\alpha = 0.4\mu\text{ m}^{-1}$ .

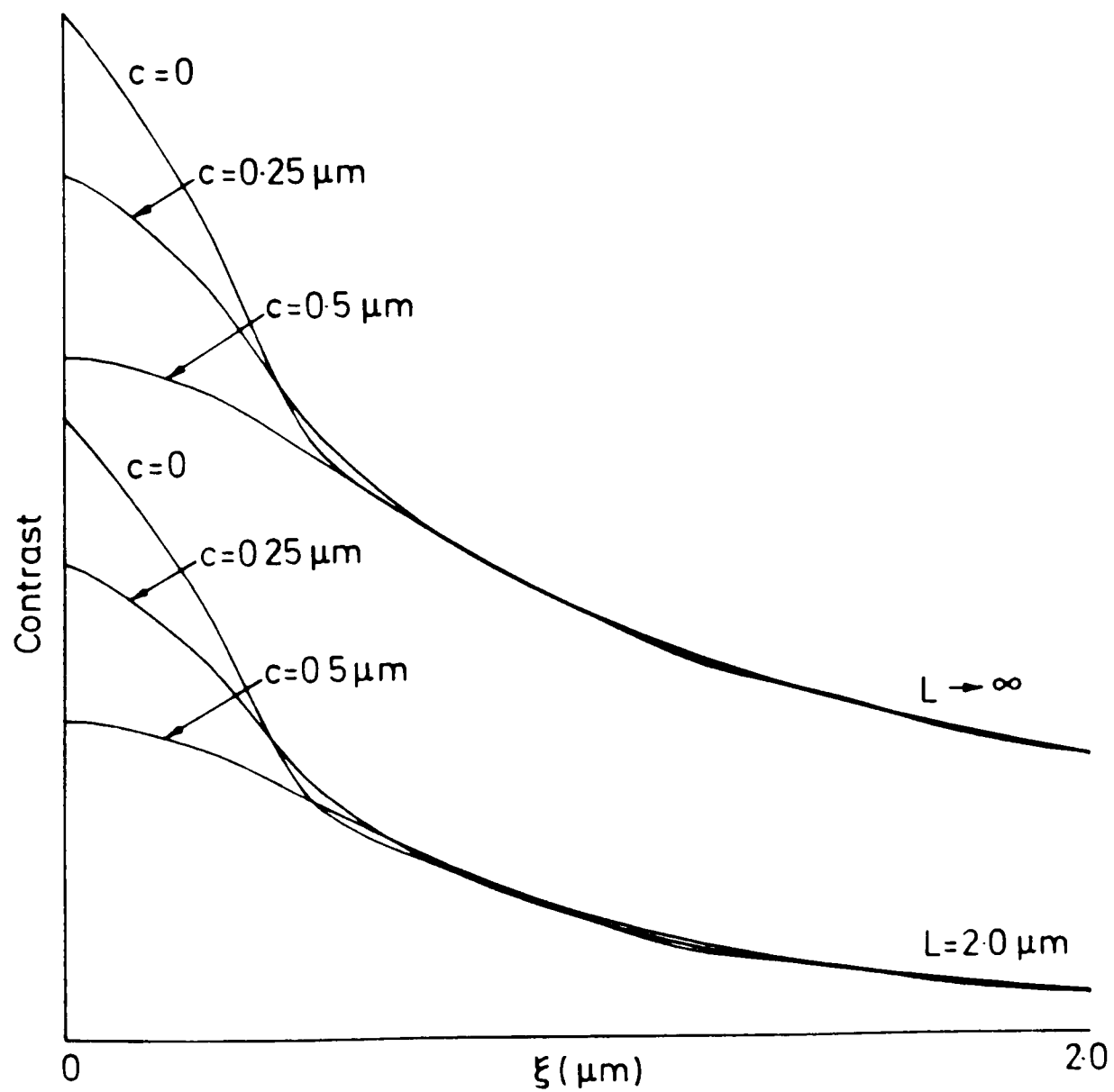


Fig.4.10

The contrast as a function of scan position for a line defect perpendicular to the surface for  $\alpha = 0.4\mu\text{ m}^{-1}$ .

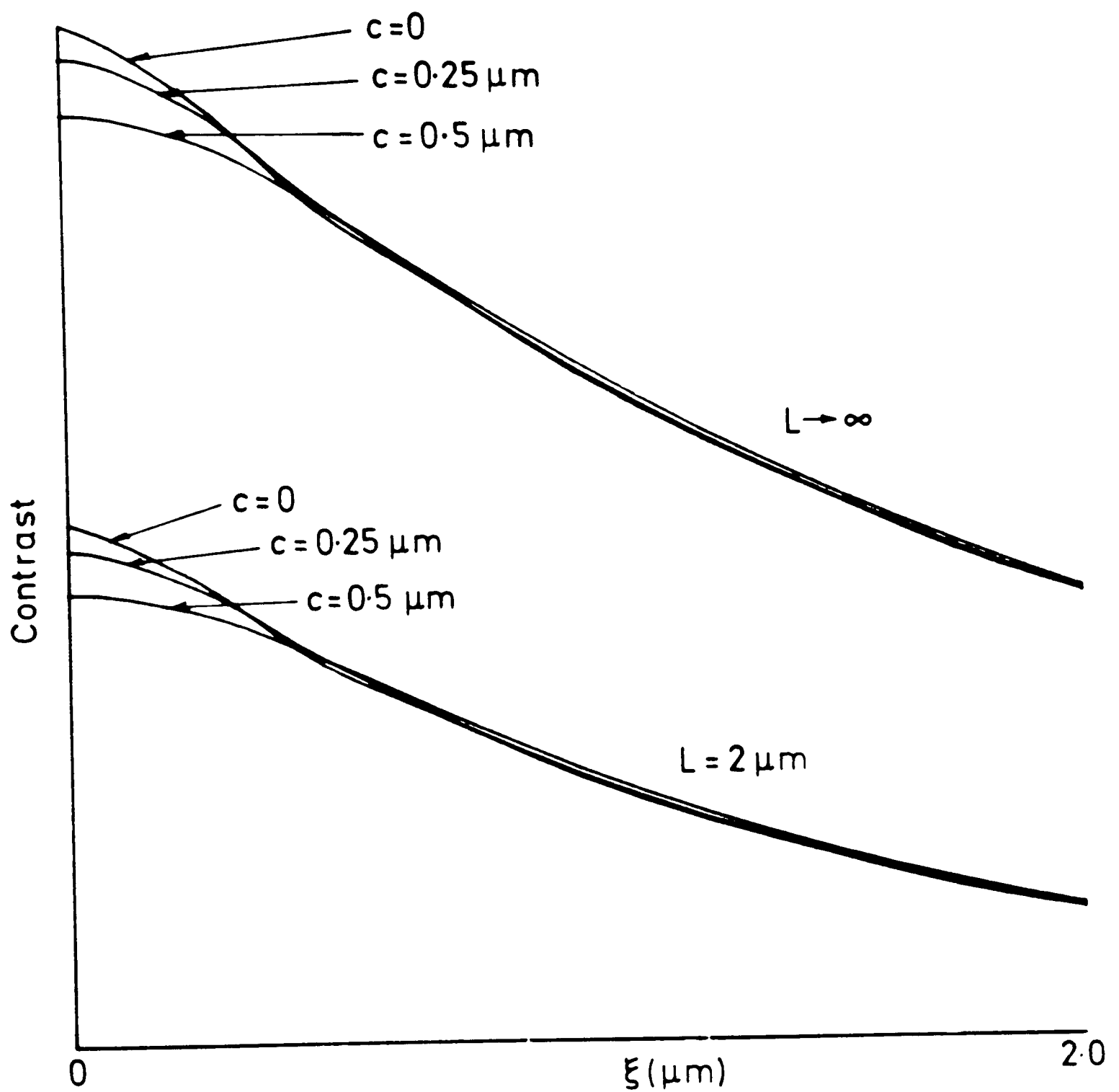


Fig 4.11

The contrast as a function of scan position for a line defect lying parallel to the surface at a depth of  $2 \mu\text{m}$  beneath the surface for the case of  $\alpha = 0.4 \mu\text{m}$

defects are in silicon which is probed with red light from a helium neon laser. As one might expect the plots are all of the same form and in no case is the resolution limited by the diffusion length. This is known to be the case in electron microscopy<sup>4.10</sup> and is clearly also the case for scanning optical microscopy. This is emphasised again in Fig. 4.12 where the full width half maximum is plotted as a function of diffusion length. We see that the resolution is relatively insensitive to the diffusion length except at very small values of  $L$  and there the effect is greatest in the parallel line defect case. The values of the contrast measured directly above the defect,  $\xi = 0$ , is similarly most sensitive for small values of diffusion length, Fig. 4.13.

Using the expression for the generation function of Eq.4.23 we may investigate the effect of the size of the probe beam,  $c$ , on resolution. Figs. 4.9 - 4.11 show the effect on the contrast on  $c$ . We see both here and in Fig. 4.14 that the resolution of the technique is sometimes relatively insensitive to the value of  $c$  until  $c$  becomes of the order of 0.4 microns. This would suggest that the point source approximation used by some authors<sup>4.7</sup> in similar problems is sufficient to roughly estimate resolution but not the accurate shape of the contrast profiles.

Finally we consider the effect of the defect depth on contrast. It is clear from the form of the boundary conditions and Fig.4.4 that the free carrier distribution will peak beneath the surface and so we would expect, via Eq. 4.19, that the contrast would also peak beneath the surface. This is illustrated in Fig. 4.15.

## 4.7 CONCLUSIONS

A theory has been presented of image formation in scanning optical microscopes operating in the OBIC mode. The general conclusions from the defects which have been considered are that the resolution and contrast are generally superior the narrower the probe beam width, although the improvement is not great below  $c \approx 0.4\mu m$ . The role of the diffusion length is such that in general reasonable

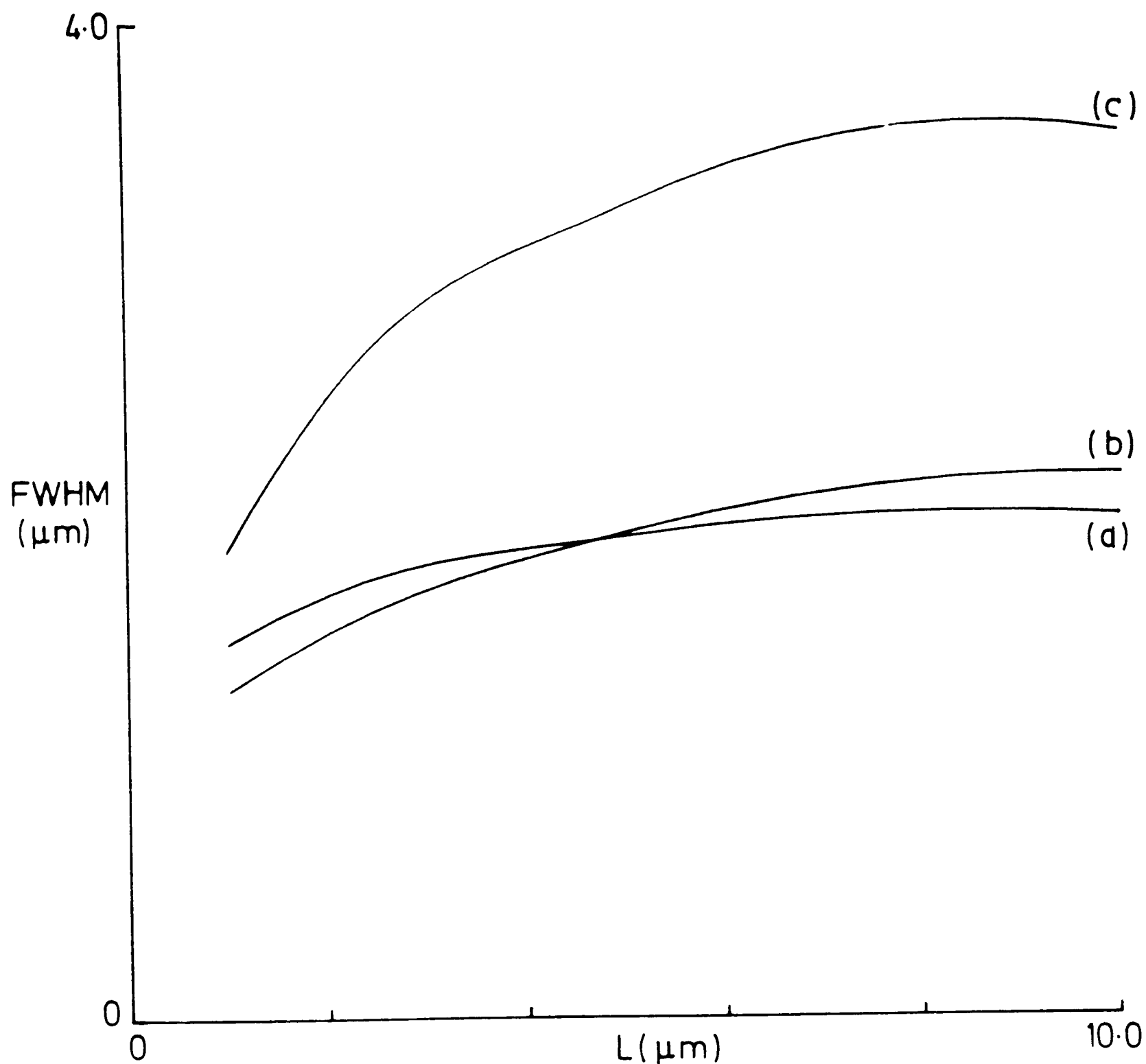


Fig.4.12

The full width half maximum (FWHM) of the contrast curves as a function of diffusion length for  $c = 0.5\mu\text{m}$  and  $\alpha = 0.4\mu\text{m}^{-1}$ .

Curve (a) represents a point defect  $2\mu\text{m}$  beneath the surface.

Curve (b) represents a line defect perpendicular to the surface.

Curve (c) represents a line defect lying parallel to the surface at a depth of  $2\mu\text{m}$ .

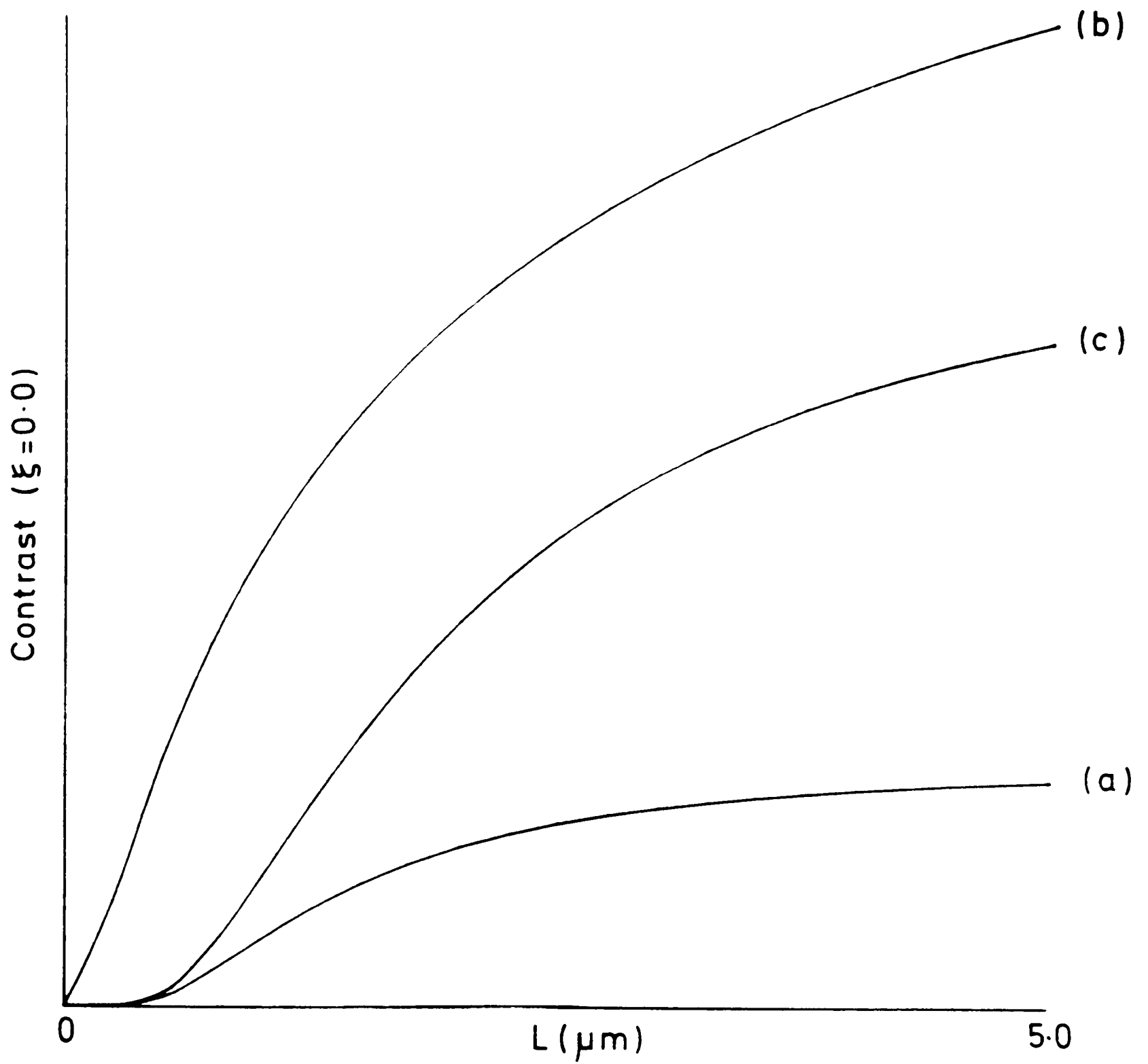


Fig.4.13 The contrast on axis as versus diffusion length for  $c = 0.5\mu\text{m}$  and  $\alpha = 0.4\mu\text{m}^{-1}$ .

Curve (a) represents a point defect  $2\mu\text{m}$  beneath the surface.

Curve (b) represents a line defect perpendicular to the surface.

Curve (c) represents a line defect lying parallel to the surface at a depth of  $2\mu\text{m}$ .

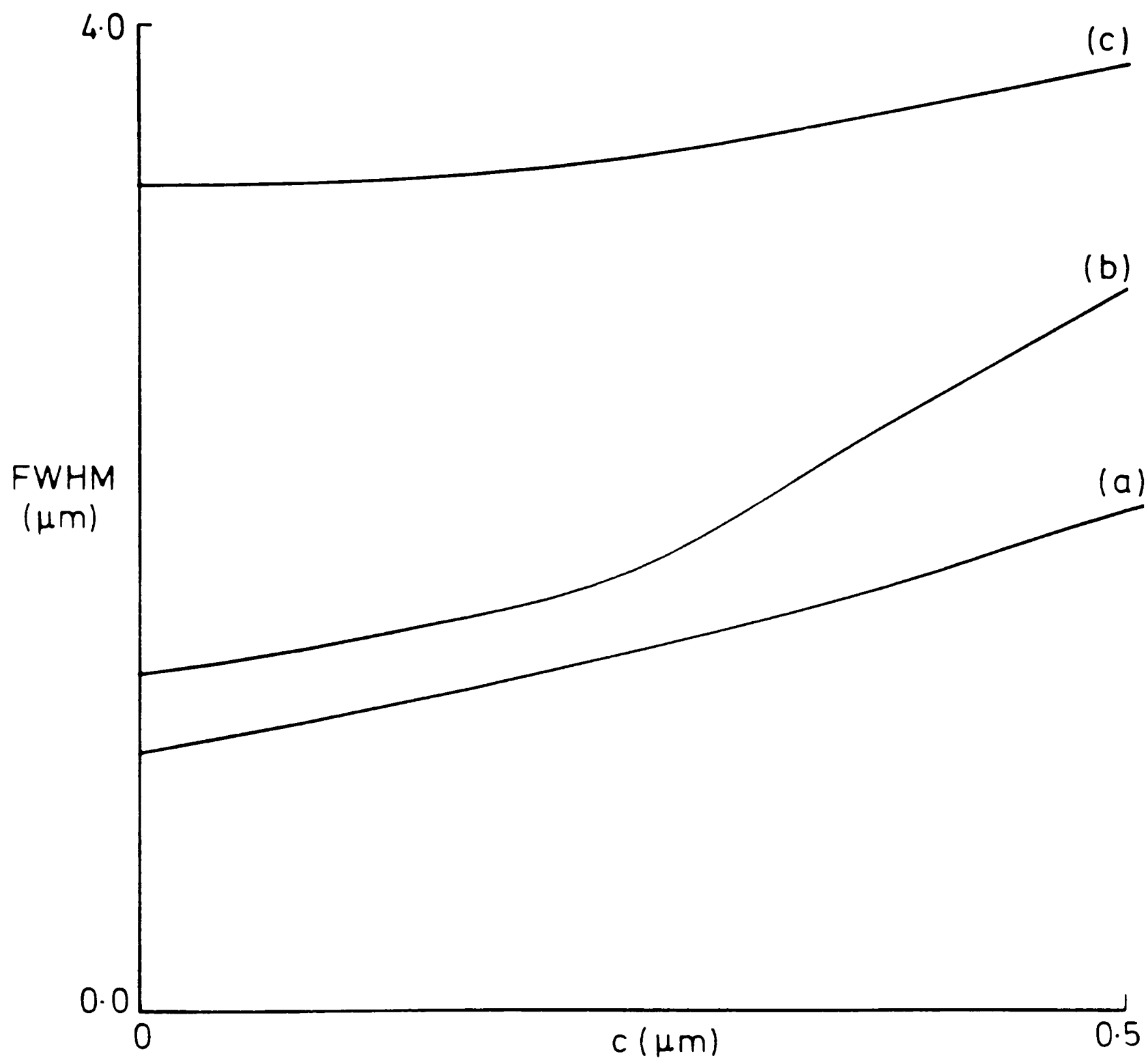


Fig 4.14

The full width half maximum of the contrast curves as a function of beam width  $c$  for the case of infinite diffusion length and  $\alpha = 0.4 \mu \text{ m}^{-1}$ .

Curve (a) represents a point defect  $2 \mu \text{ m}$  beneath the surface.

Curve (b) represents a line defect perpendicular to the surface.

Curve (c) represents a line defect lying parallel to the surface at a depth of  $2 \mu \text{ m}$ .

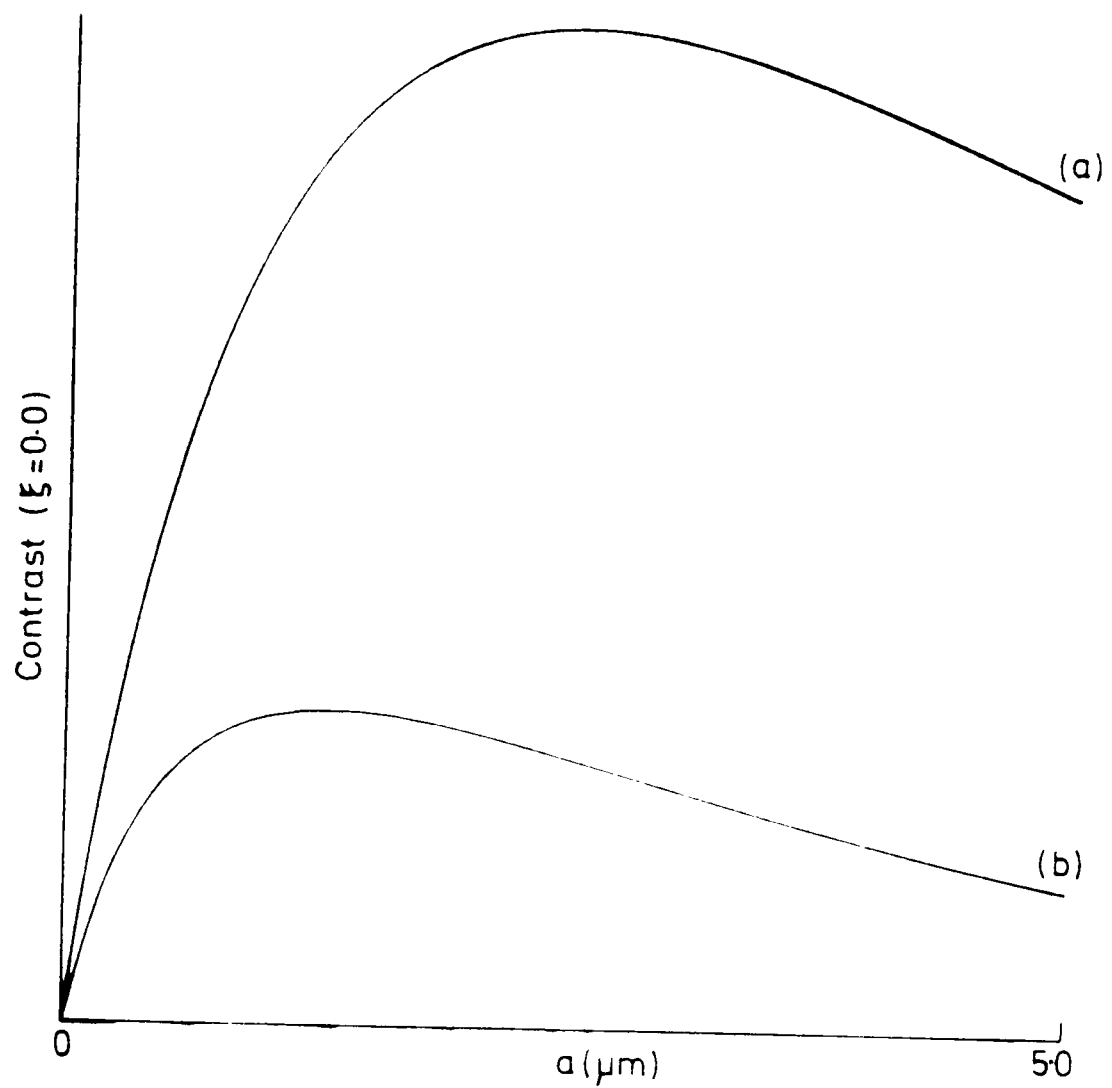


Fig4.15

The contrast on axis as a function of defect depth for the case of infinite diffusion length and  $\alpha = 0.4 \mu \text{ m}$  .

Curve (a) represents a line defect lying parallel to the surface .

Curve (b) represents a point defect beneath the surface.

resolution and contrast estimates may be made by considering the infinite diffusion length limit. The resolution which the theory predicts is in agreement with that found experimentally in bipolar transistors <sup>1,25,4.11</sup>.

The choice of analysing a Schottky barrier necessarily results in a free carrier distribution such as in Fig. 4.3. The presence of a peak in this distribution ensures that the image contrast will also exhibit a maximum value for defects positioned in the neighbourhood of this peak.

## Chapter 5

### OBIC IMAGING OF DEFECTS IN

#### (a). SCHOTTKY BARRIERS WITH FINITE DEPLETION WIDTH

#### (b). PLANAR JUNCTION DEVICES

### 5.1 INTRODUCTION

This chapter allows us to see the effect of varying the depletion width on the OBIC signal as the reverse bias voltage is altered. Chapter 4 has considered the theoretical expressions for the OBIC signal due to scanning a laser beam over the surface of a Schottky barrier device containing a defect. Now the effect of depletion width on defect imaging for a Schottky barrier is investigated. This Chapter also considers the important case of a planar junction device. Expressions are derived giving the OBIC signal as the laser beam is scanned across a defect which lies below the surface of a planar junction device. These expressions are of particular importance in their possible application to locate defects in p-n junction solar cells. In the case of the planar junction device we examine the effect of changes in the surface recombination velocity in addition to the effect of depletion width on OBIC imaging.

### 5.2 OBIC IMAGING OF A POINT DEFECT

In order to calculate the total current collected by the junction as a function of the position of the light beam relative to the defect we first consider the excess hole concentration  $p(\mathbf{r})$  which is governed by Eq.4.9 subject to the boundary conditions for the device in question. We can describe the presence of the defect by a modified generation function,  $g'(\mathbf{r})$ , where

$$\begin{aligned} g'(\mathbf{r}) &= g(\mathbf{r}) - D\gamma(\mathbf{r})u(\mathbf{r})p(\mathbf{r}) \\ &= g(\mathbf{r}) - g_d(\mathbf{r}) \end{aligned} \tag{5.1}$$

where  $u(\mathbf{r})$  is a function which is unity within the defect region and zero outside,  $\gamma(\mathbf{r})$  describes the defect distribution as in Eq.4.10 and  $g_d$  gives the modification of the generation function due to the defect. Thus Eq.4.9 becomes

$$\nabla^2 p(\mathbf{r}) - \frac{1}{L^2} p(\mathbf{r}) = -\frac{1}{D} g'(\mathbf{r}) \quad (5.2)$$

Taking the Fourier Bessel transform of Eq.5.2 and using a Green's function approach as described in chapter 4 we may obtain an expression for the Fourier-Bessel transform of the excess minority carrier distribution in the presence of the defect. This expression may be found from Eq.4.28 where  $\bar{p}_0$  is replaced by  $\bar{p}$  and  $\bar{g}$  is replaced by  $\bar{g}'$ .

Now the total diffusion current,  $I_{diff}$ , collected at the edge of the depletion region of the device may be calculated.

$$I_{diff} = I_0 - I_d \quad (5.3)$$

where  $I_0$  is the diffusion current obtained in the absence of a defect and  $I_d$  is the current reduction due to enhanced recombination at the defect. Consider a device with its depletion edge at depth,  $h$ , below the semiconductor surface. Then the total diffusion current is given by

$$I_{diff} = -qD \int_0^\infty \left. \frac{\partial p}{\partial z} \right|_{z=h} 2\pi r dr \quad (5.4)$$

It is clear that

$$\left. \frac{\partial p}{\partial z} \right|_{z=h} = \int_0^\infty \left. \frac{\partial \bar{p}}{\partial z} \right|_{z=h} J_0(\nu r) \nu d\nu \quad (5.5)$$

which gives

$$I_{diff} = -2\pi qD \left. \frac{\partial \bar{p}}{\partial z} \right|_{z=h}(0, h) \quad (5.6)$$

where  $q$  is the electron charge.

Inserting the expression for  $\bar{p}$  into the expression for the diffusion current,  $I_{diff}$  we obtain

$$I_0 = -2\pi q \int_0^h \left. \frac{\partial G(0, z|z_0)}{\partial z} \right|_{z=h} \bar{g}(0, z_0) dz_0 \quad (5.7)$$

and

$$I_d = -2\pi q \int_0^h \frac{\partial G(0, z|z_0)}{\partial z} \Big|_{z=h} \bar{g}_d(0, z_0) dz_0 \quad (5.8)$$

For a point defect at depth,  $a$ , where  $a < h$ , Eq.5.1 and Eq.4.30 show that  $g_d$  may be written

$$g_d(\mathbf{r}, z) = D\bar{\gamma}\delta(z - a) \frac{\delta(\mathbf{r} - \mathbf{r}_0)}{r} p_0(\mathbf{r}, z) \quad (5.9)$$

ie.

$$\bar{g}_d(0, z_0) = D\bar{\gamma}\delta(z_0 - a) p_0(r_0, z_0)$$

where  $p_0$  is the excess minority carrier distribution in the absence of a defect.

This gives

$$I_d = -2\pi q D\bar{\gamma} \frac{\partial G}{\partial z}(0, z|a) \Big|_{z=h} p_0(\mathbf{r}_0, a). \quad (5.10)$$

### **5.3 OBIC IMAGING OF DEFECTS IN A SCHOTTKY BARRIER WITH FINITE DEPLETION WIDTH**

Consider the particular case of a Schottky junction with depletion region extending distance,  $d$ , into the n-type semiconductor. The same assumptions as Chapter 4, including low injection, are used. Assume a point defect at depth,  $a$ , for  $a > d$ . Clearly a defect in the depletion region will not be resolved in the OBIC image because all carriers generated in the depletion region are collected by the electric field in this region. The current collected,  $I_{dep}$ , due to generation in the depletion region is given by

$$\begin{aligned} I_{dep} &= 2\pi q \int_{r=0}^{\infty} \int_{z=0}^d g(r, z) r dr dz \\ &= qg_0(1 - \exp -\alpha d) \end{aligned} \quad (5.11)$$

using the approximating generation expression given in Appendix 1.

An expression for the diffusion current,  $I_0$ , obtained for a defect free Schottky barrier with zero depletion width is given by Eq.4.34. For a Schottky barrier with depletion width,  $d$ , this diffusion current is reduced by the factor  $\exp -\alpha d$  to give

$$I_0(d) = qg_0 \exp -\alpha d \frac{\alpha L}{1 + \alpha L} \quad (5.12)$$

Similarly the defect current for a Schottky barrier with finite depletion width,  $d$ , and defect depth,  $a = a_0$  is given by

$$I_d(d, a) = \exp -\alpha d \quad I_d(d = 0, a = a_0 - d) \quad (5.13)$$

where  $I_d(d = 0, a = a_0 - d)$  is given by Eq.4.31.

Contrast is now defined as the ratio of defect current divided by the total background current which would be obtained in the absence of a defect and is given by

$$\begin{aligned} C &= \frac{I_d}{I_0 + I_{dep}} \\ &= \frac{I_d}{I_{back}} \end{aligned} \quad (5.14)$$

We are now in a position to see the effect of depletion width on resolution as the reverse bias applied to the Schottky barrier is varied.

#### 5.4 OBIC IMAGING OF DEFECTS IN PLANAR JUNCTION DEVICES

Now the particular case of a planar junction device is considered. Let us consider an n-type homogeneous semiconductor epitaxially grown on p-type substrate bounded by the surface,  $z = 0$ , and the metallurgical p - n junction at  $z = h_0$ , Fig.5.1. The point defect is in the n-type material at depth  $a$  below the surface which has normalised surface recombination velocity,  $s = v_s/D$ .

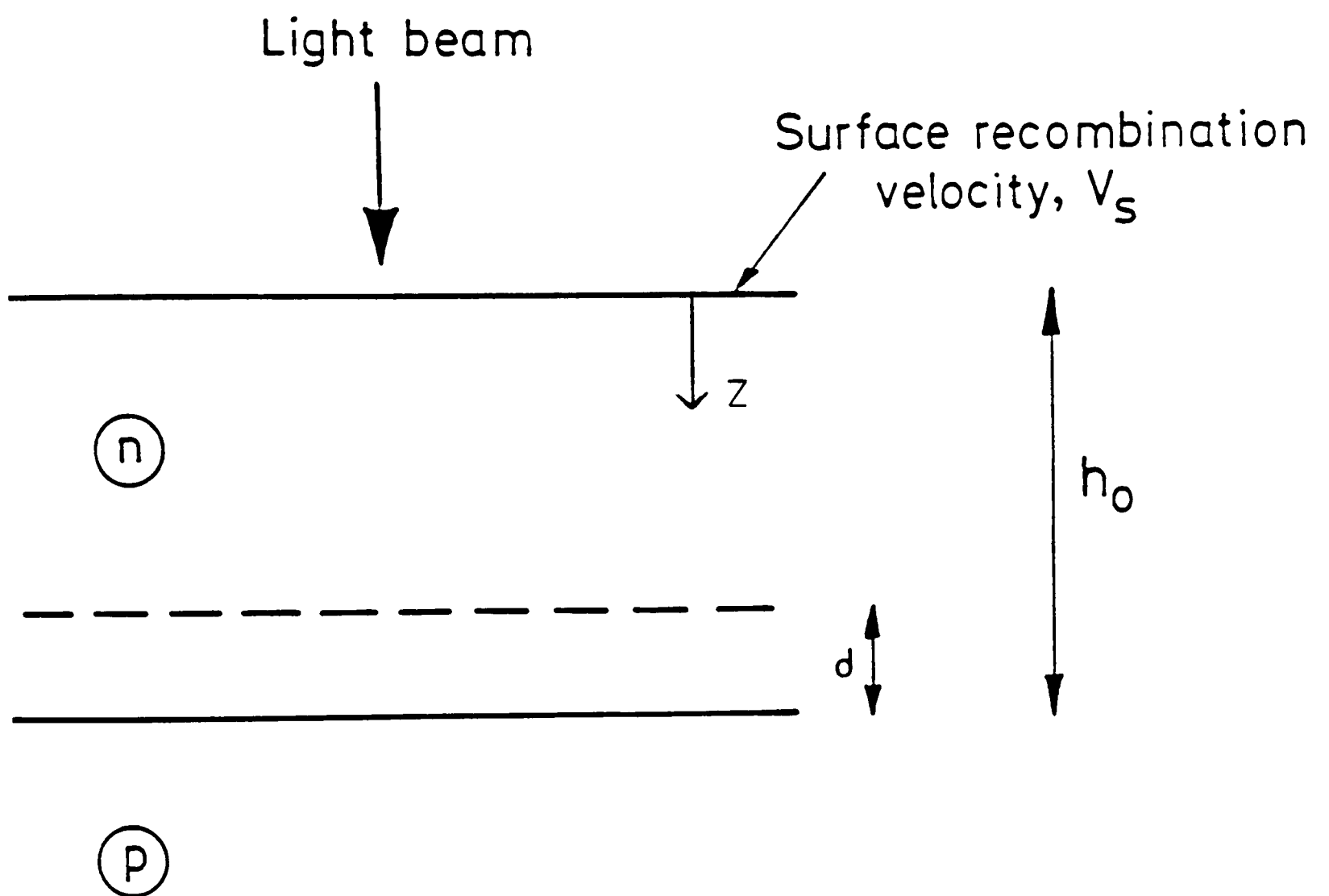


Fig.5.1

The geometry of the planar junction device.

For simplicity in the analysis we assume low injection conditions and that the edge of the depletion layer is deep relative to the absorption depth in the material so that the depletion current is negligible. Also we assume that the p-type substrate is very heavily doped relative to the epitaxially grown layer so that the depletion region lies essentially on the n-side of the junction only. This assumption is reasonable in that such a planar junction device may have doping levels typically one hundred times greater on the substrate than the n-side. The edge of the depletion layer is at depth  $h$  below the semiconductor surface and the width of this layer is  $d = h_0 - h$ . The laser beam is assumed to be focused on the surface of the material at distance  $\xi$  from the origin. The beam is assumed to have wavelength with corresponding energy greater than the band-gap of the material so that carriers are generated in the n-type semiconductor at rate  $g(\mathbf{r})$  per unit volume.

We consider the n-type semiconductor having minority carriers (holes) with diffusion coefficient  $D$  and diffusion length  $L$ . To find the diffusion current given by Eq.5.6 we need to find an expression for the excess minority carrier distribution,  $p_0$ , in the absence of a defect for a planar junction device. This involves solving Eq.4.9 subject to the boundary conditions

$$\left. \frac{\partial p}{\partial z}(\mathbf{r}, z) \right|_{z=0} = sp(\mathbf{r}, z) \quad (5.15)$$

and

$$p(\mathbf{r}, z) \Big|_{z=h} = 0$$

The Green's function for this case which satisfies the same boundary conditions as  $p$  is given by <sup>5.1</sup>

$$\begin{aligned} G(\nu, z|z_0) &= \frac{1}{\beta} \sinh(\beta(h - z_0)) \frac{\beta \cosh \beta z + s \sinh \beta z}{\beta \cosh \beta h + s \sinh \beta h} \quad ; z \leq z_0 \\ &= \frac{1}{\beta} \sinh(\beta(h - z)) \frac{\beta \cosh \beta z_0 + s \sinh \beta z_0}{\beta \cosh \beta h + s \sinh \beta h} \quad ; z \geq z_0 \end{aligned} \quad (5.16)$$

Substitution of this Green's function into Eq.5.10 allows the defect current,  $I_d$  to be found. To evaluate Eq.5.10 we need to find  $\left. \frac{\partial G}{\partial z}(0, z|a) \right|_{z=h}$ . This is given by

$$\left. \frac{\partial G}{\partial z}(0, z|a) \right|_{z=h} = - \left[ \frac{\cosh a/L + Ls \sinh a/L}{\cosh h/L + Ls \sinh h/L} \right] \quad (5.17)$$

$p_0$  may be found by taking the inverse Fourier-Bessel transform of Eq.4.28 where  $\bar{g}$ , the Fourier-Bessel transform of  $g$ , is given by

$$\begin{aligned} \bar{g}(\nu, z) &= \frac{g_0 \alpha}{\pi} \exp -\nu^2 c^2 \exp -\alpha z \\ &= \bar{f}(\nu) \exp -\alpha z \end{aligned} \quad (5.18)$$

This gives

$$\begin{aligned} \bar{p}_0(\nu, a) &= \frac{\bar{f}(\nu)}{\beta D(\beta \cosh \beta h + s \sinh \beta h)} \cdot \\ &\left\{ \int_0^a \sinh(\beta(h-a)) \cdot (\beta \cosh \beta z_0 + s \sinh \beta z_0) \exp -\alpha z_0 \, dz_0 \right. \\ &\left. + \int_a^h \sinh(\beta(h-z_0)) \cdot (\beta \cosh \beta a + s \sinh \beta a) \exp -\alpha z_0 \, dz_0 \right\} \end{aligned} \quad (5.19)$$

These integrals may be performed to give

$$\begin{aligned} \bar{p}_0(\nu, a) &= \frac{\bar{f}(\nu)}{D(\beta^2 - \alpha^2)} \left\{ \exp -\alpha a \right. \\ &\left. - \left[ \frac{(\alpha + s) \sinh \beta(h-a) + (\beta \cosh \beta a + s \sinh \beta a) \exp -\alpha h}{\beta \cosh \beta h + s \sinh \beta h} \right] \right\} \end{aligned} \quad (5.20)$$

Taking the inverse Fourier-Bessel transform of Eq.5.20 to obtain  $p_0$  and substituting back into Eq.5.10 the defect current,  $I_d$  may be obtained. To find the contrast,  $C$ , we need to find the diffusion current,  $I_0$  in the absence of a defect.  $I_0$ , is given by Eq.5.7. The Fourier-Bessel transform of  $g$  is given by Eq.5.18. This allows the following expression to be obtained for  $I_0$ .

$$\begin{aligned} I_0 &= 2qg_0\alpha \frac{L}{1 - \alpha^2 L^2} \cdot \\ &\left\{ \alpha L \exp -\alpha h + \frac{\sinh h/L + Ls \cosh h/L}{\cosh h/L + Ls \sinh h/L} \cdot \exp -\alpha L \right. \\ &\left. - \frac{L(\alpha + s)}{\cosh h/L + Ls \sinh h/L} \right\} \end{aligned} \quad (5.21)$$

Now the resolution for a planar junction device may be investigated using the same expression for contrast,  $I_d/I_0$  as defined in Eq.4.32.

## **5.5 DISCUSSION**

### **5.5(a). The Schottky barrier**

To investigate the resolution which may be obtained for a Schottky barrier as the depletion width is varied a plot of normalised contrast as a function of scan position is given in Fig.5.2. To check the program computing contrast, it was run for zero depletion width and for the same data as used for the Schottky barrier in chapter 4. The program gave the same results as in the last chapter. Fig.5.3 gives the resolution as a function of depletion width. The increase in resolution, ie. the decrease in the full width half maximum of the plots of Fig.5.2, as depletion width is increased may be explained as follows. The closer the defect is to the edge of the depletion region the larger will be the perturbation on the diffusion current being collected at the depletion edge due to the presence of the defect. Increasing the reverse bias means that the depletion region extends further into the device bringing the depletion edge closer to the defect. Hence a corresponding increase in resolution is expected.

Now consider the variation of contrast on the axis with depletion width. The contrast will be affected not only by variation in defect current but also by the variation in background current,  $I_{back}$ , which is the sum of diffusion current in the absence of a defect,  $I_0$ , plus the current collected in the depletion region,  $I_{dep}$ . Fig.5.4 shows how defect current varies with depletion width,  $d$ . First consider the case of low diffusion length. For low  $L$  and small depletion width relatively few light generated carriers may diffuse to the defect and recombine there, resulting in low defect current. As the depletion width increases and approaches the defect then

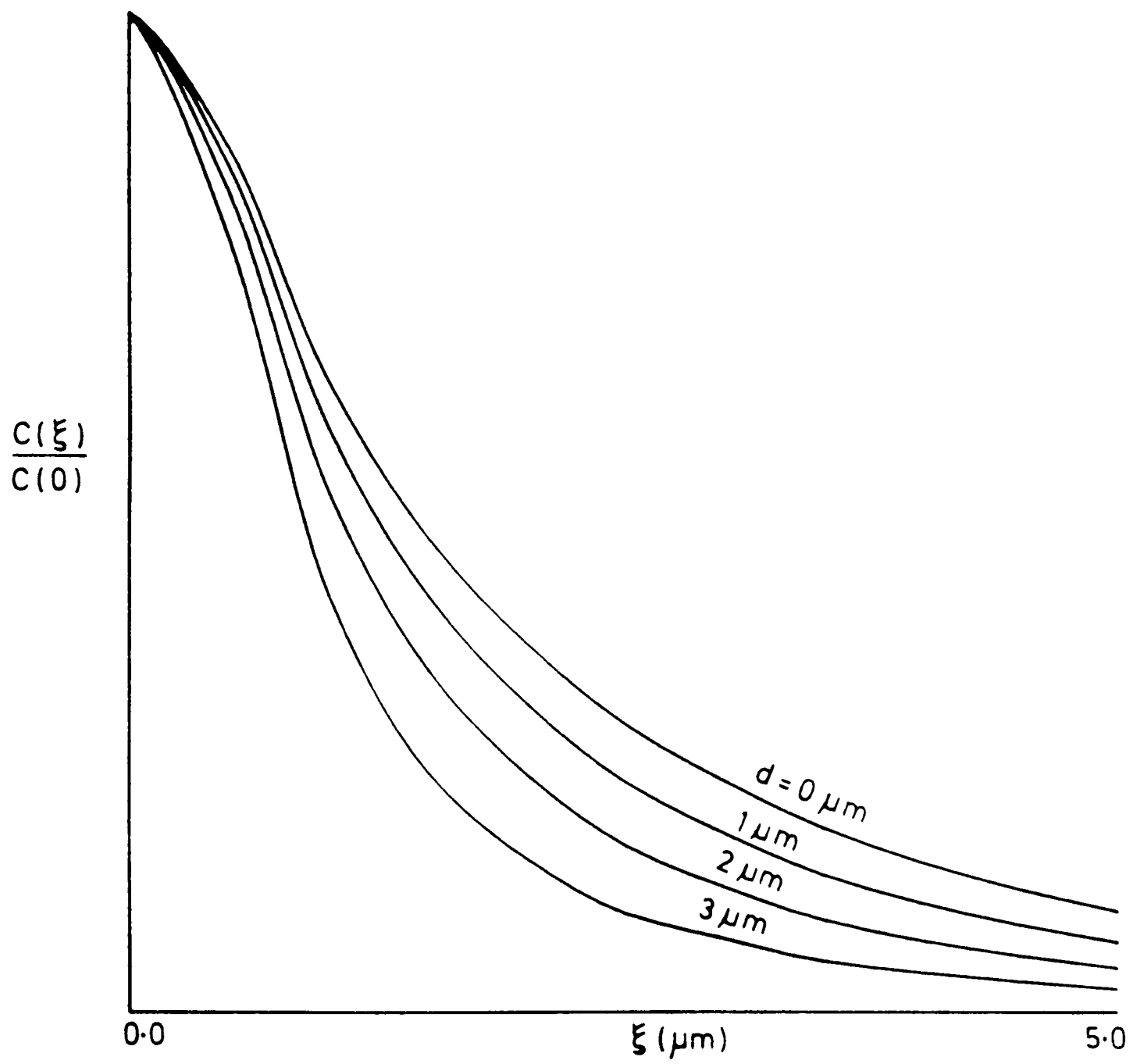


Fig.5.2

Plot of normalised contrast as a function of scan position for  
a point defect  $4\mu\text{m}$  below the surface.  $L = 10\mu\text{m}$ ,  $c = 0.5\mu\text{m}$  and  $\alpha = 0.4\mu\text{m}^{-1}$

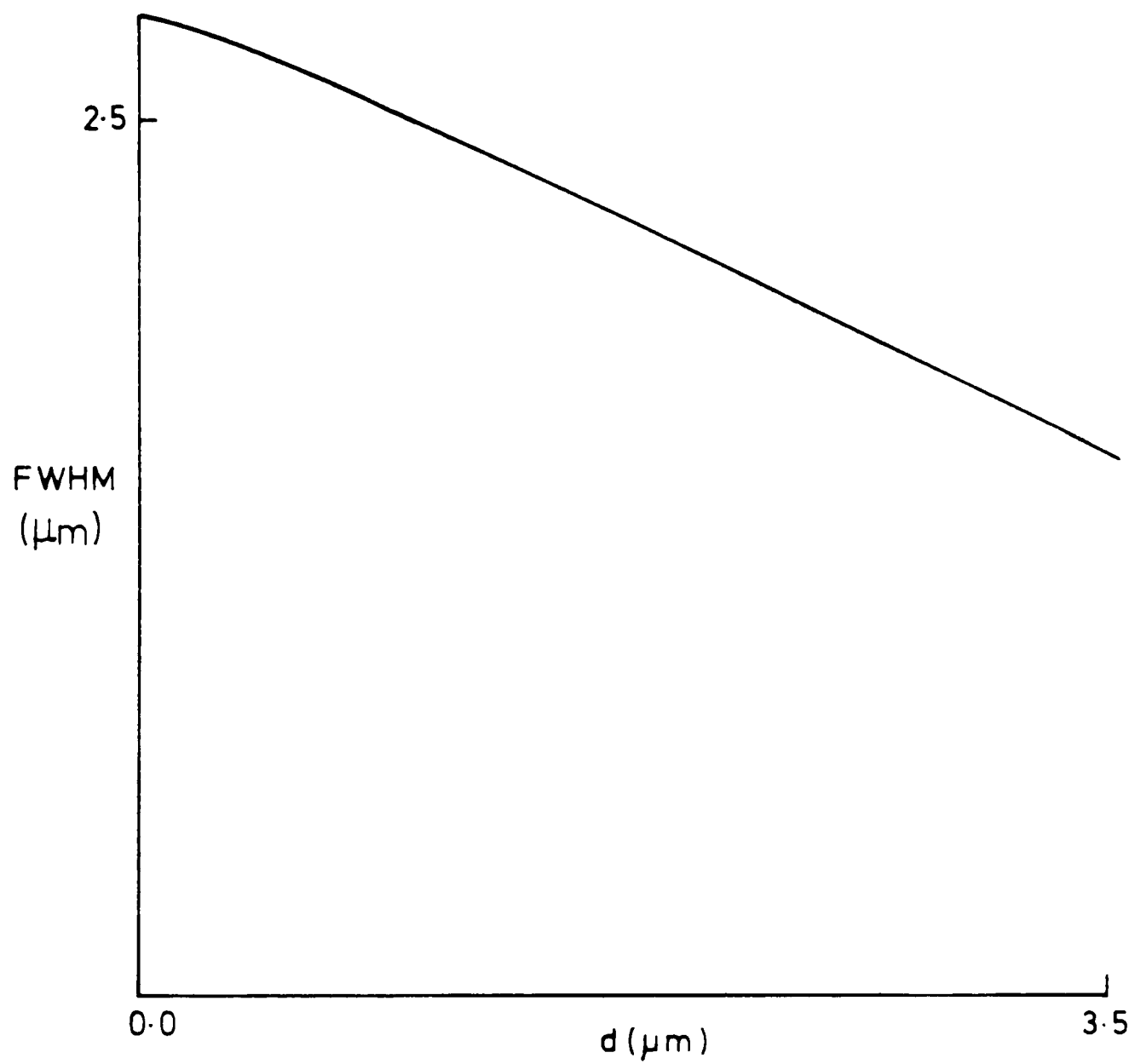


Fig.5.3

Plot of full width half maximum of the curves of Fig.5.2 vs. depletion width.  $L = 10\mu\text{m}$ ,  $c = 0.5\mu\text{m}$  and  $\alpha = 0.4\mu\text{m}^{-1}$

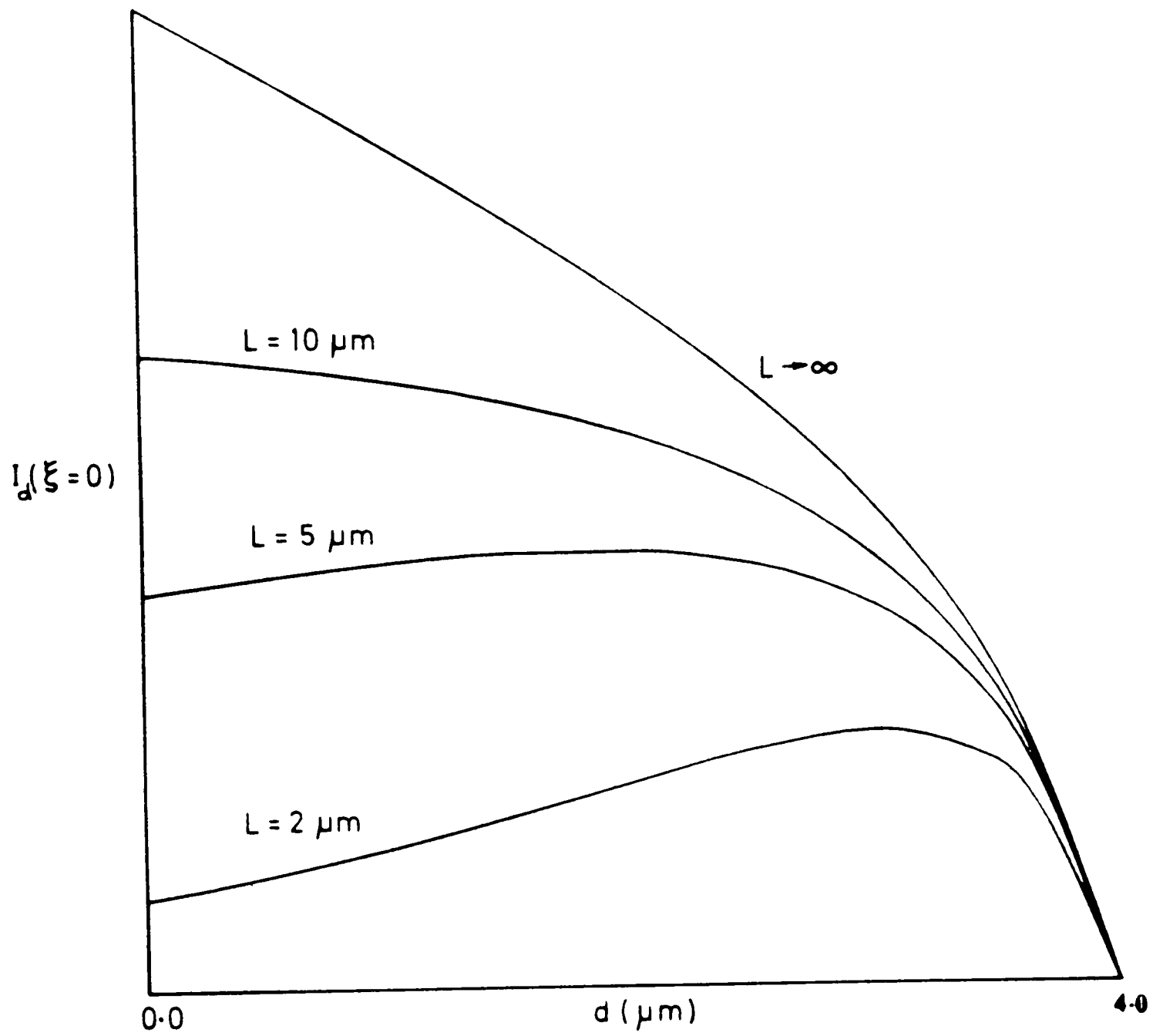


Fig.5.4

Plot of defect current on axis vs. depletion width for a point defect at depth  $4\mu\text{m}$ ,  $c = 0.5\mu\text{m}$  and  $\alpha = 0.4\mu\text{m}^{-1}$

more carriers may diffuse to the defect giving a larger contrast. Once the defect is in the depletion region the contrast must drop to zero since all carriers generated in the depletion region will be swept out by the field in this region. Hence for low  $L$  one expects a peak in the plot of axial contrast vs. depletion width. This is observed in Fig.5.4. As the diffusion length becomes large the defect current decreases with  $d$  because increasing the depletion width means that fewer carriers may diffuse to the defect.

Fig.5.5 shows the variation of background current with depletion width. As  $d$  is increased the depletion current increases and the diffusion current,  $I_0$ , decreases. However since most carriers are generated close to the device surface the change in the depletion current will be more significant than the change in  $I_0$ . Thus background current increases with  $d$  and approaches the value obtained in the infinite diffusion length limit.

The resulting variation of contrast with  $d$  is shown in Fig.5.6. It is clear that for the parameters used in this theory that the variation of defect current with depletion width dominates this contrast plot.

### 5.5(b). The planar junction

Fig.5.7 gives plots of normalised contrast as a function of the scan coordinate,  $\xi$ . The two cases of zero and infinite surface recombination velocity are considered. It is clear that there is greater resolution for the case of infinite surface recombination velocity. From Eq.5.10 we see that the defect current and hence the resolution depends on the excess minority carrier distribution,  $p_0$ . Figs.8.4(a) and (b) show the shapes of the minority carrier distribution in the cases of zero and infinite surface recombination velocity for a Schottky barrier. One expects similar distributions in the case of a planar junction device with a deep junction. The carrier distribution peaks beneath the surface in the case of infinite surface recombination velocity due

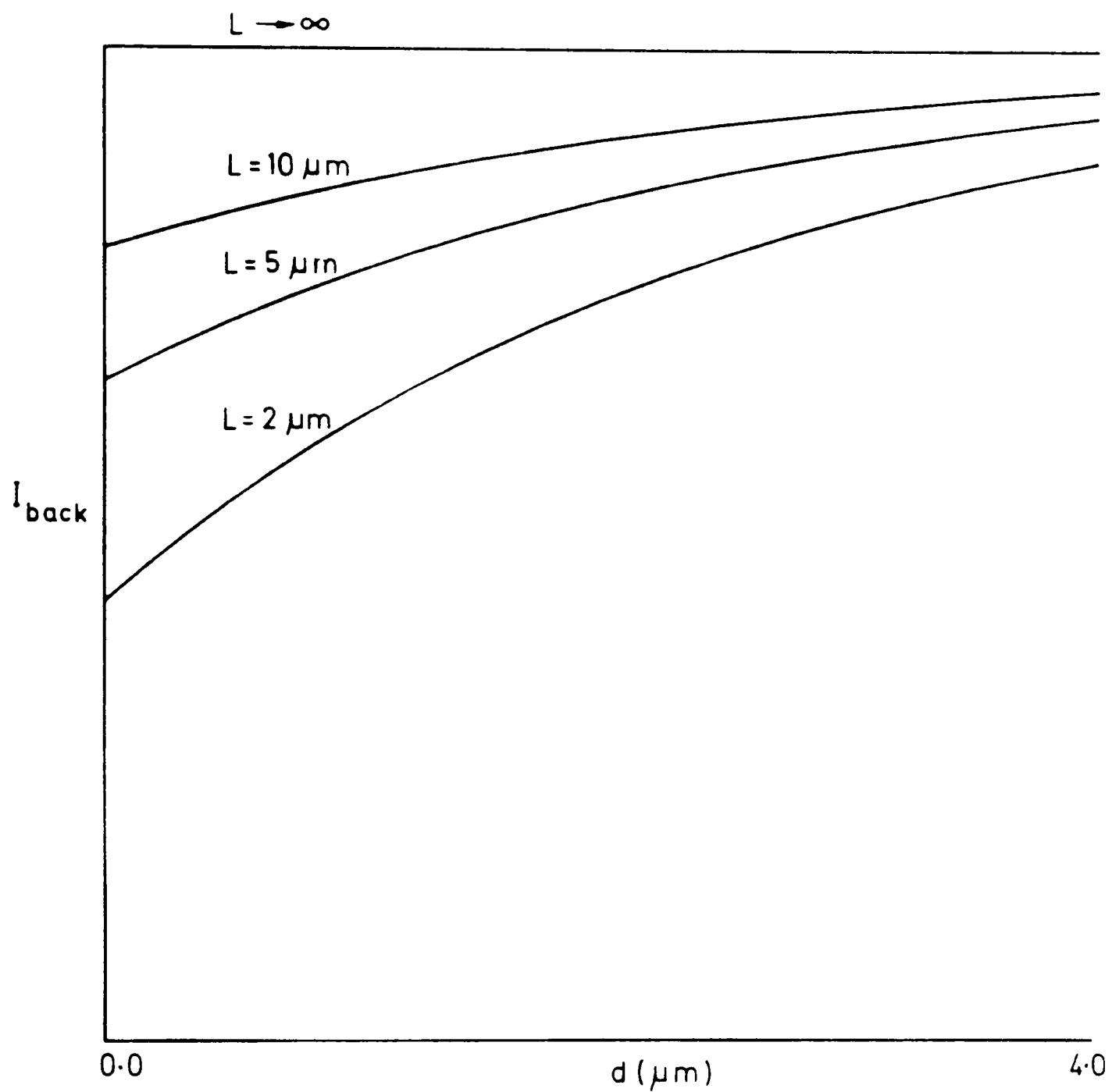


Fig. 5.5

Plot of background current vs. depletion width for a point defect at depth  $4\mu\text{m}$ ,  $c = 0.5\mu\text{m}$  and  $\alpha = 0.4\mu\text{m}^{-1}$

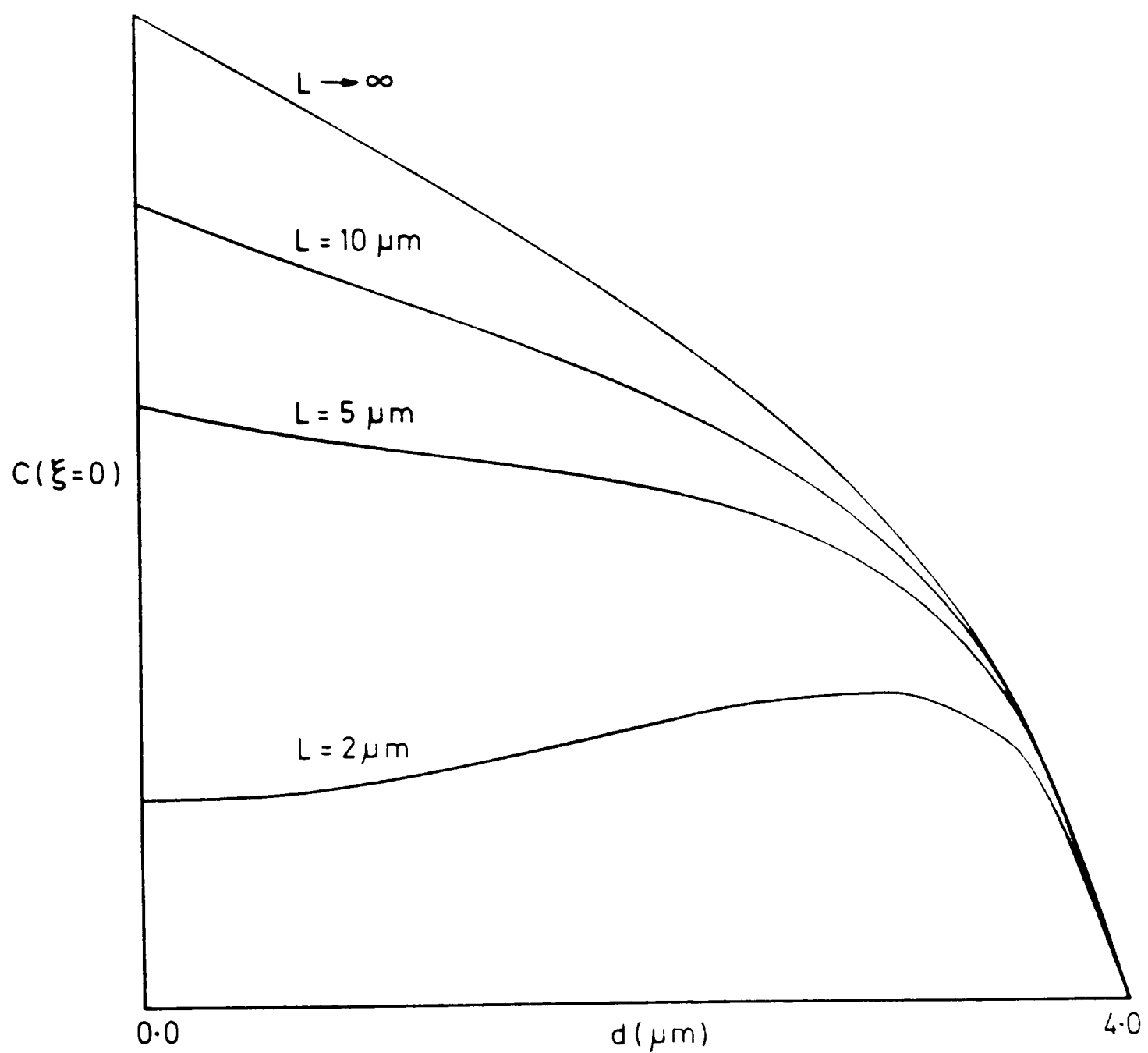


Fig.5.6

Plot of contrast on axis vs. depletion width for a point defect at depth  $4\mu\text{m}$ ,  $c = 0.5\mu\text{m}$  and  $\alpha = 0.4\mu\text{m}^{-1}$

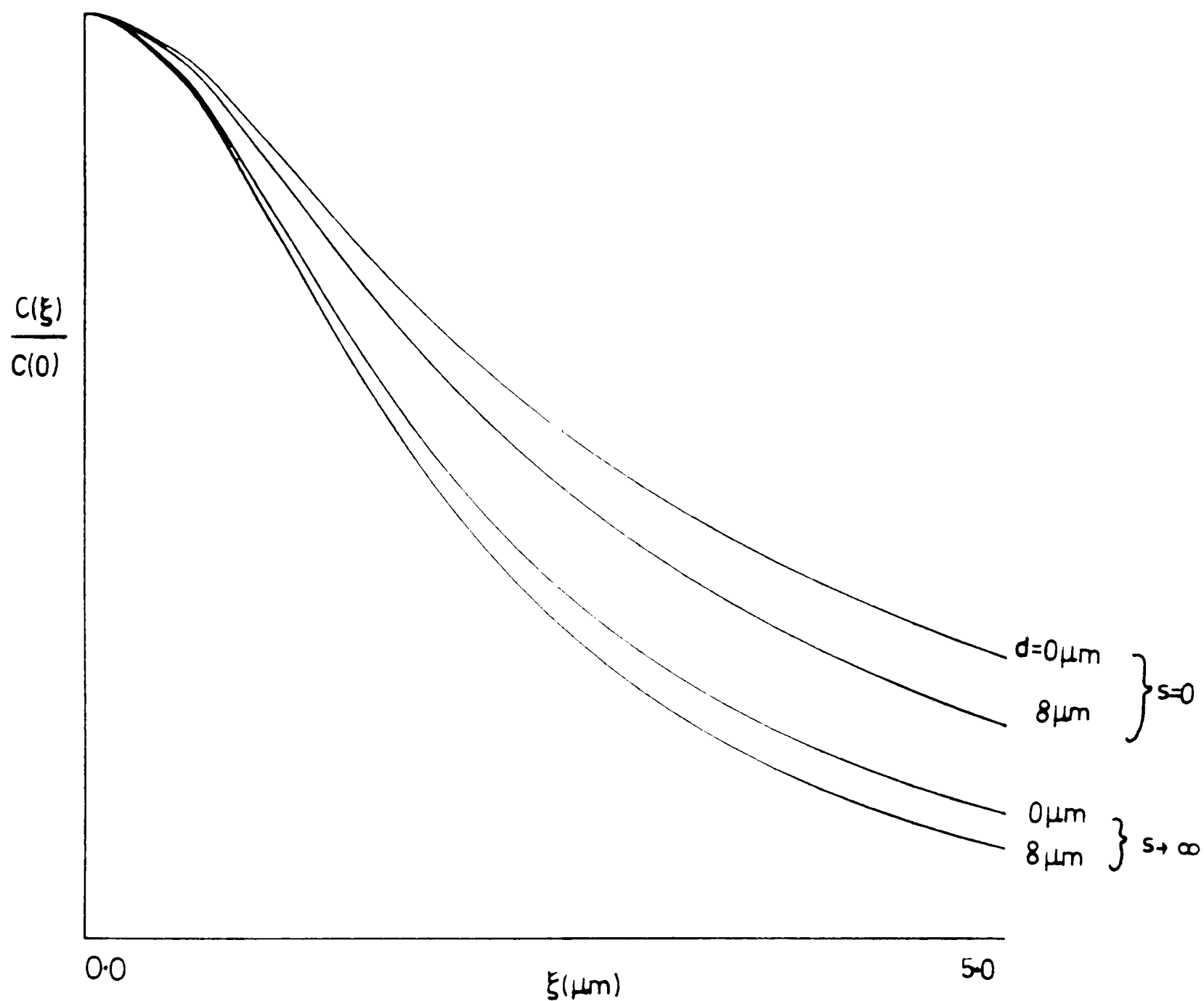


Fig.5.7

Plot of normalised contrast as a function of scan position

for a point defect at depth  $4 \mu\text{m}$ ,  $L = 10 \mu\text{m}$ ,  $c = 0.5 \mu\text{m}$ ,  $\alpha = 0.4 \mu\text{m}^{-1}$

and junction depth  $15.77 \mu\text{m}$

to the boundary conditions for the device. The position of the defect in relation to this peak is an important factor in determining the resolution of the defect. Thus it is reasonable to expect higher resolution for infinite surface recombination velocity when the defect is situated in the region of the peak in the corresponding minority carrier distribution.

Fig.5.7 also shows that resolution is higher for larger depletion width. This is reasonable in that the larger the depletion width the closer the defect is to the depletion edge. This means that the defect will have a larger effect on the diffusion current reaching the depletion edge and hence on the defect current which is a factor in determining the resolution. This effect on the depletion current is shown in Figs.5.8(a) and (b) for a range of diffusion lengths.

Now consider the effect of depletion width, ie. reverse bias, on the diffusion current,  $I_0$ , which would be obtained in the absence of a defect. As the depletion width increases the edge of the depletion region moves closer to the surface of the device. Hence more light generated carriers can diffuse to this edge giving rise to a larger background current. This is shown in Figs.5.9(a) and (b). The resulting plots of contrast on the axis as a function of reverse bias are shown in Figs.5.10(a) and (b). As the depletion edge moves closer to the defect the effect on the defect current will be less significant for larger diffusion lengths. This may explain the decrease in contrast observed in Fig.5.10(a) for  $L = 10\mu m$ .

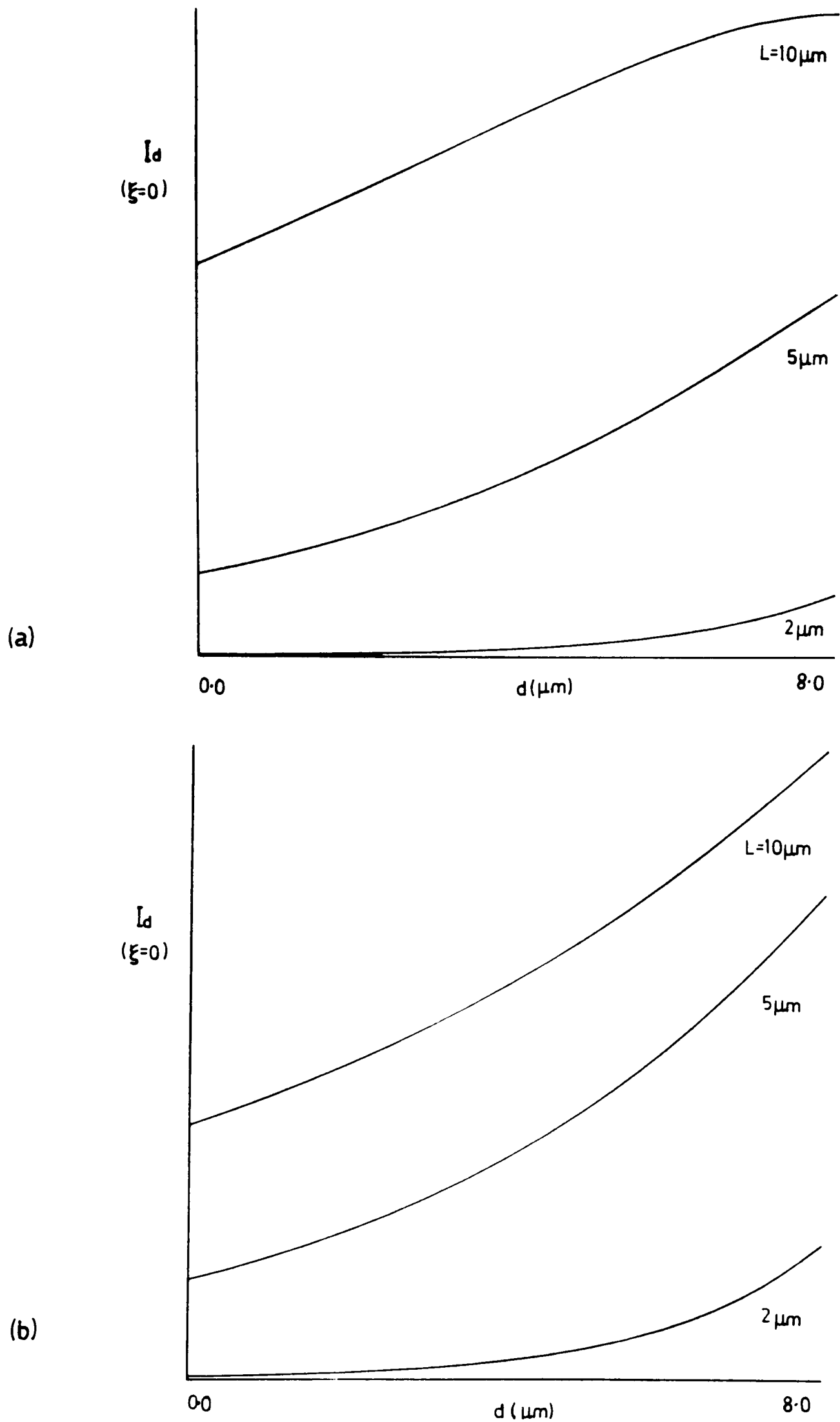


Fig.5.8

Plot of defect current on axis vs. depletion width for a point defect at depth  $4\mu\text{m}$ ,  $c = 0.5\mu\text{m}$ ,  $\alpha = 0.4\mu\text{m}^{-1}$  and junction depth  $15.77\mu\text{m}$

(a) Surface recombination velocity is zero

(b) Surface recombination velocity is infinite

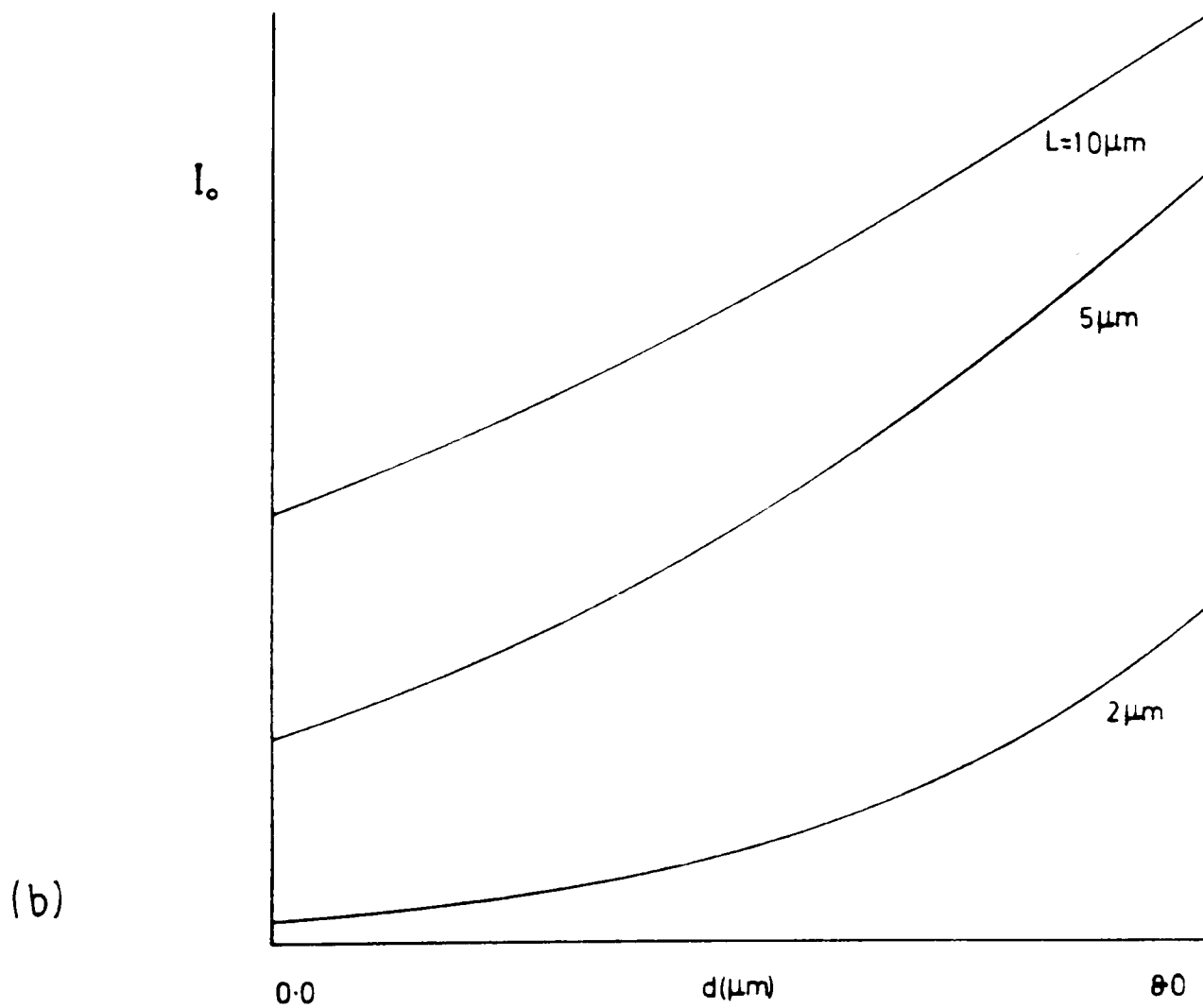
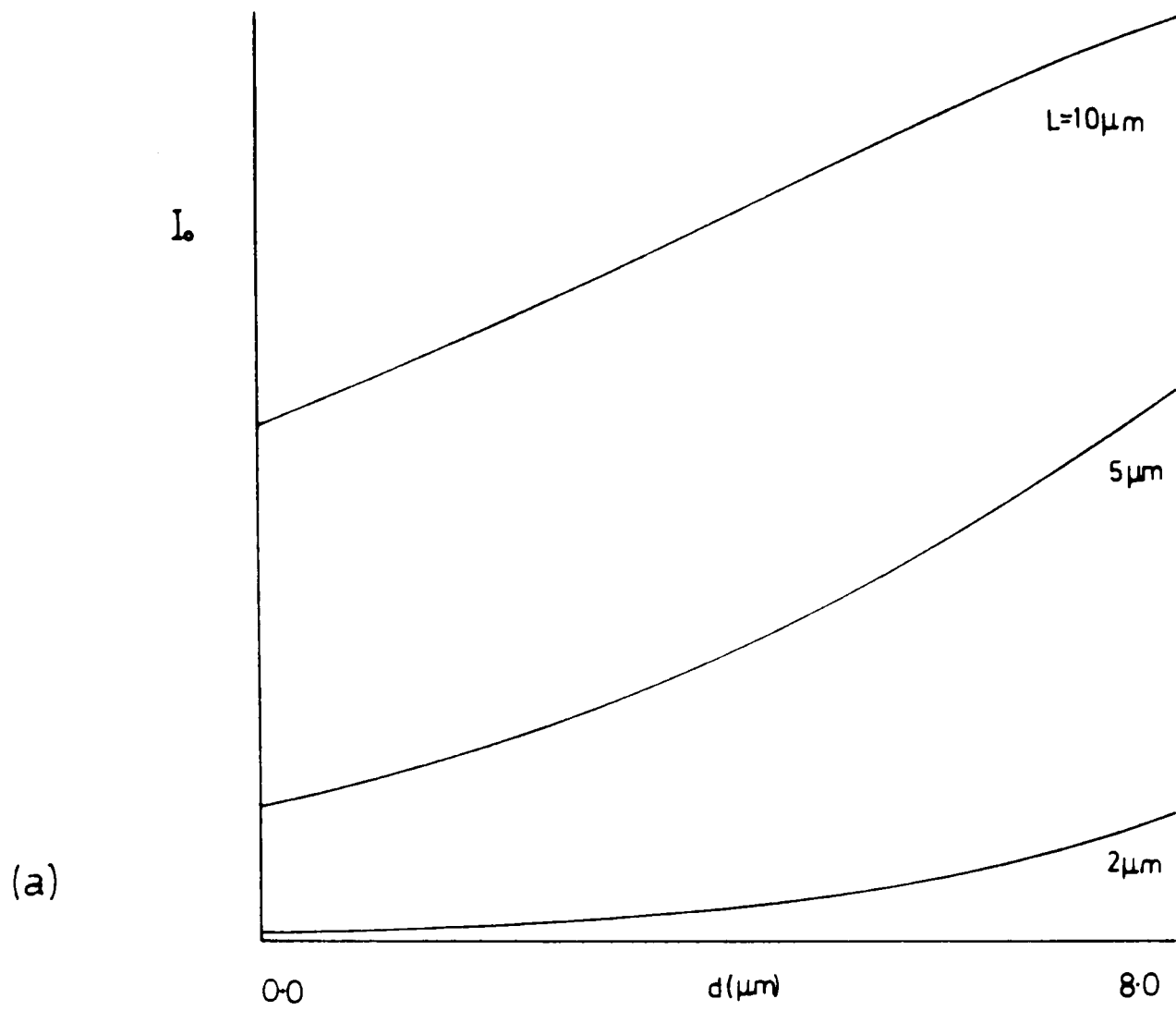


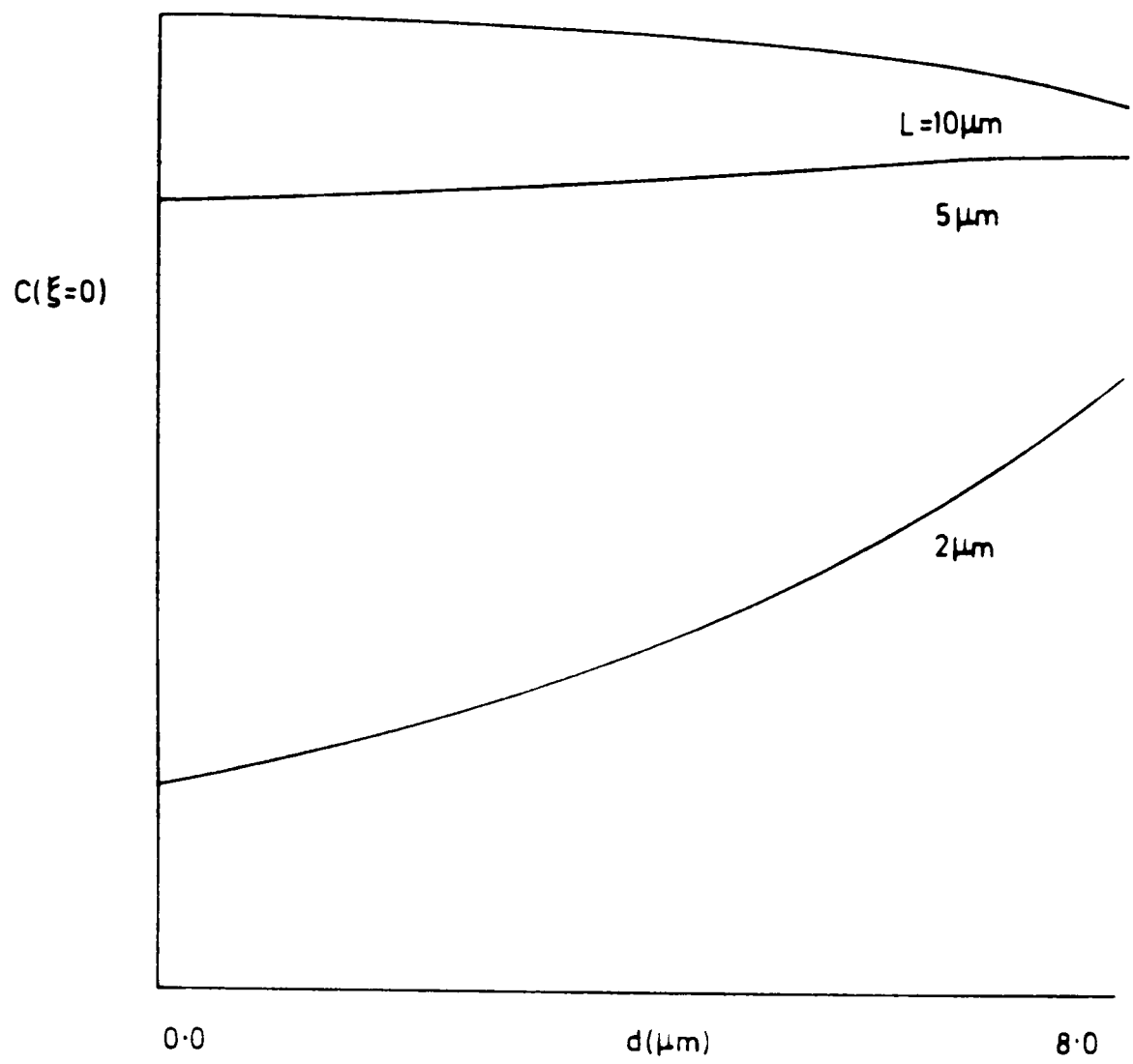
Fig.5.9 Plot of diffusion current in the absence of a defect for a point defect at depth  $4\mu\text{m}$ ,  $c = 0.5\mu\text{m}$ ,  $\alpha = 0.4\mu\text{m}^{-1}$

and junction depth  $15.77\mu\text{m}$

(a) Surface recombination velocity is zero

(b) Surface recombination velocity is infinite

(a)



(b)

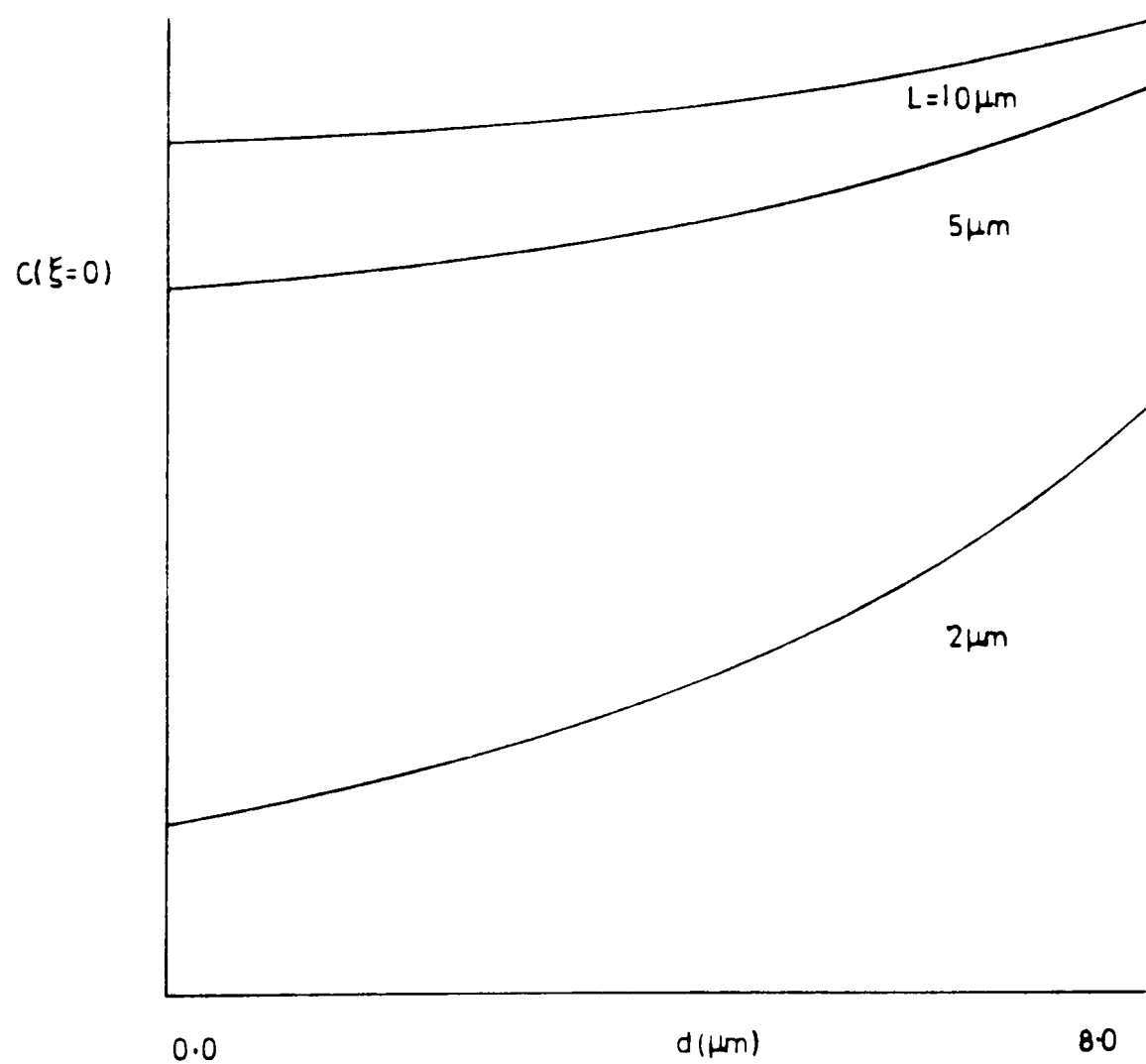


Fig.5.10

Plot of contrast on axis for a point defect at depth

$4\mu\text{m}$ ,  $c = 0.5\mu\text{m}$ ,  $\alpha = 0.4\mu\text{m}^{-1}$

and junction depth  $15.77\mu\text{m}$

(a) Surface recombination velocity is zero

(b) Surface recombination velocity is infinite

## **5.6 CONCLUSIONS**

The effect of varying the width of the depletion regions in both the Schottky Barrier and planar junction devices on the OBIC imaging of a point defect has been investigated. The resolution improves as the depletion width is increased in both cases. To understand the variation in contrast with applied reverse bias one must consider separately both the variation in the background current in the absence of a defect and also the variation in defect current. In the case of the planar junction device there may be improved resolution for larger surface recombination velocity for defects at appropriate depths.

**CHAPTER 6**

**EXPERIMENTAL OBIC - EBIC COMPARISON**

**6.1 INTRODUCTION**

Chapter 1 describes some of the distinct advantages of Optical Beam Induced Current Imaging over the analogue imaging technique EBIC using the electron beam. Table 6.1 gives a brief comparison of the two imaging methods in semiconductor examination.

**Table 6.1            OBIC - EBIC Comparison**

| PROPERTY                | OBIC | EBIC                                                                                                            |
|-------------------------|------|-----------------------------------------------------------------------------------------------------------------|
| Requires vacuum system? | No   | Yes                                                                                                             |
| Causes specimen damage? | No   | A high energy electron beam may damage the specimen. Oil-based diffusion pumps may leave a contaminating layer. |
| Charging problems?      | No   | Yes-in the case of some surface dielectric layers                                                               |
| Resolution              |      | Comparable with both methods                                                                                    |

Donolato's<sup>4.4</sup> theory of SEM charge-collection imaging of localized defects in semiconductors predicts the resolution which would be obtained for a point defect lying below the surface of a Schottky barrier device. This resolution is of the same order as the resolution predicted in Chapter 4 for OBIC imaging of defects in a similar device. However Donolato's work encounters the problem that the exact

form of the generation function is not known and an approximation must be used. Donolato<sup>4,4</sup>, for example, uses a uniform generation sphere approximation. This problem is completely removed for OBIC imaging in that the exact form of the generation function is known and is given in chapter 2.

This chapter directs its attention towards a qualitative comparison of OBIC and EBIC techniques from an experimental viewpoint and an estimate of the resolutions which may be obtained using both methods.

## **6.2 The SCANNING ELECTRON MICROSCOPE**

In the SEM the surface of a sample is bombarded with a fine probe of electrons, generally less than  $100\text{\AA}$  in diameter. The sample emits secondary electrons that are generated by the action of the primary beam. These secondary electrons are collected and amplified by the SEM. The image is displayed on a cathode ray tube.

A resolution of  $200\text{\AA}$  may be obtained in secondary electron images, with a depth of field several hundred times that of a conventional optical microscope. However the resolution of electrically active defects using the electron beam induced current (EBIC) imaging mode is dramatically poorer than that obtained in secondary electron imaging and is close to the resolution obtained using OBIC<sup>1,25</sup>. From the form of the contrast expression of Eq.4.33 it is clear that it is the distribution of excess minority carriers which determines the resolution and not the incident probe beam. This distribution is determined by the diffusion length and surface recombination among other factors.

### **Practical problems associated with EBIC :**

There are several problems associated with the practical application of electron beam test techniques<sup>6,1</sup>. These include:

### **Contamination :**

Contamination layers on the semiconductor device surface generated by the polymerisation of hydrocarbons by the electron beam cause a reduction of the secondary electron yield. Such surface contamination will also affect the EBIC and subsequent OBIC images. Use of oil free vacuum pumps can reduce the contamination rate. Care must be taken to avoid introducing materials into the vacuum chamber with high outgassing rates such as epoxies, wires with plastic insulation and plastic IC sockets.

### **Irradiation effects**

The susceptibility of a semiconductor device to electron beam damage depends on device type, passivation, beam voltage and exposure time. As the electron beam penetrates into the semiconductor device it generates electron hole pairs of which the holes may be trapped in silicon dioxide layers <sup>6.1</sup>. In Metal Oxide Semiconductors device these trapped charges alter the threshold voltage and create surface states which may result in complete failure of the device. Bipolar devices may show modified parameters e.g. loss of gain and increased leakage current <sup>6.2</sup>.

### **Vacuum system :**

In addition to the routine specimen mounting involved in both OBIC and EBIC imaging the use of the vacuum system of the SEM in EBIC analysis requires additional time to pump down the vacuum to the desired level. Also in addition to the initial capital cost of a SEM to perform EBIC the cost of the maintenance of the SEM must be taken into account.

### **Specimen preparation - common to OBIC and EBIC examinations :**

There are commonly two types of packaging used for integrated circuits (ICs) :

(a) hermetic packages such as ceramic packages with soldered or welded coverplate. These are easily opened by lifting the coverplate with a sharp knife.

(b) Epoxy packaged devices. These present a greater problem in trying to remove the plastic encapsulation. Complete immersion in hot sulphuric acid will remove the whole plastic package. However the device loses its mechanical integrity. A jet-etch technique using sulphuric acid is a more favourable technique which allows a suitably sized hole in the epoxy to be etched.

### **6.3 EBIC IMAGING**

To obtain correlation between device yield or performance and crystallographic imperfections it is necessary to be able to image defects which are electrically active. Holt and Ogden <sup>6.3</sup> claim the first unambiguous observation of electrically active dislocations by means of the barrier electron voltaic effect current or EBIC method. An EBIC image is obtained in a method analogous to OBIC. Wilson et al. <sup>1.25</sup> have made a qualitative comparison of OBIC and EBIC images of dislocations.

In the case of EBIC it is important to be aware that the volume in which the electron beam energy is being dissipated, the excitation volume, is large with respect to the diameter of the electron beam itself <sup>1.25</sup>. This volume depends on the beam voltage being used. Acceleration voltages of from two to five kV to as high as 50kV will be needed for various samples, dependent on device type and passivation. Beall <sup>6.4</sup> uses a beam energy of typically 15kV to obtain EBIC images of bipolar transistors.

### **6.4 EXPERIMENT**

A Cambridge Instrument Scanning Electron Microscope in the DEC facility in Ayr, Scotland was used for the SEM work.

### OBIC and EBIC images :

Fig.6.1 shows a secondary electron image of a silicon BFY51 bipolar transistor.

Fig. 6.2(a) shows a Type 1 reflected light image of the lower right hand corner of a BFY51 device at a higher magnification. In the lower part of this photograph we see a pear-shaped area which reflects diffusely. It is clear that this pear-shaped region is a surface contaminant because in an OBIC image taken at this magnification there is a corresponding dark region where light is prevented from being absorbed by the semiconductor. An image of the specimen is first obtained using OBIC to avoid excessive damage of the specimen. The subsequent EBIC imaging of the sample is performed by slowly increasing the accelerating voltage until a good EBIC image is obtained. The accelerating voltage is then maintained at this level to avoid excessive specimen damage.

Fig. 6.2(b) gives an OBIC image of the lower right corner of the device. High contrast enhancement is used to display the line defects which appear as dark lines in the image. Fig. 6.3 gives an OBIC linetrace across the line defect which lies close to the vertical. This gives a resolution of the defect of approximately  $1.25\ \mu\text{m}$ .

An EBIC image of the same area of the transistor is shown in Fig. 6.4. The two line defects are also evident in this image. A linetrace taken across the same line defect as before gives an EBIC resolution of approximately  $3\ \mu\text{m}$ . This resolution agrees closely with Donolato's<sup>4,4</sup> calculated results. The much lower resolution found using EBIC instead of OBIC is probably because the beam acceleration voltage used is not high enough.

The same transistor was mounted once again in the SOM after imaging in the EBIC mode. A line of contamination was observed in the reflected light image where the electron beam had been scanned. In addition more line defects were observed in the OBIC image taken after EBIC imaging than had been observed in the first

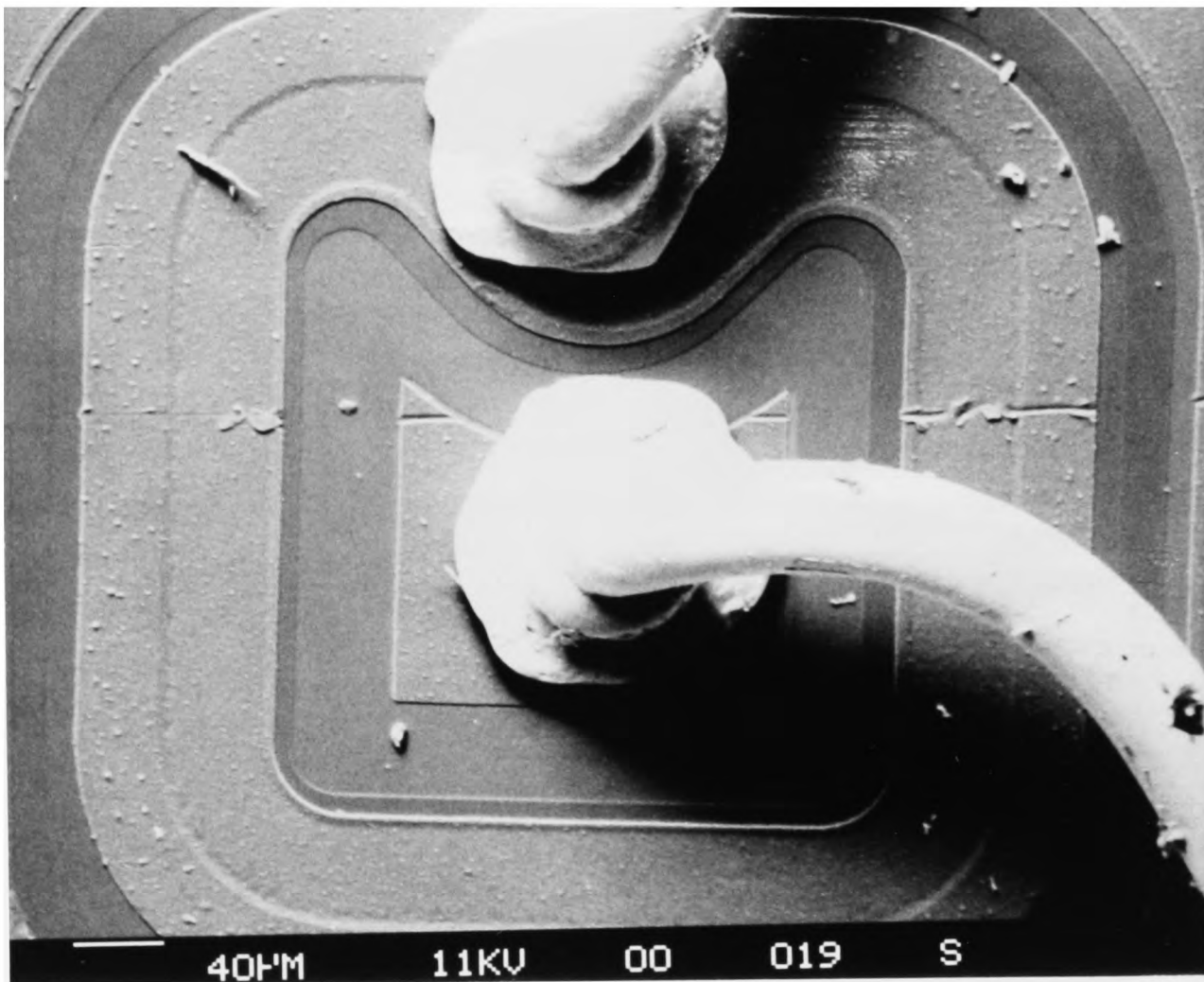
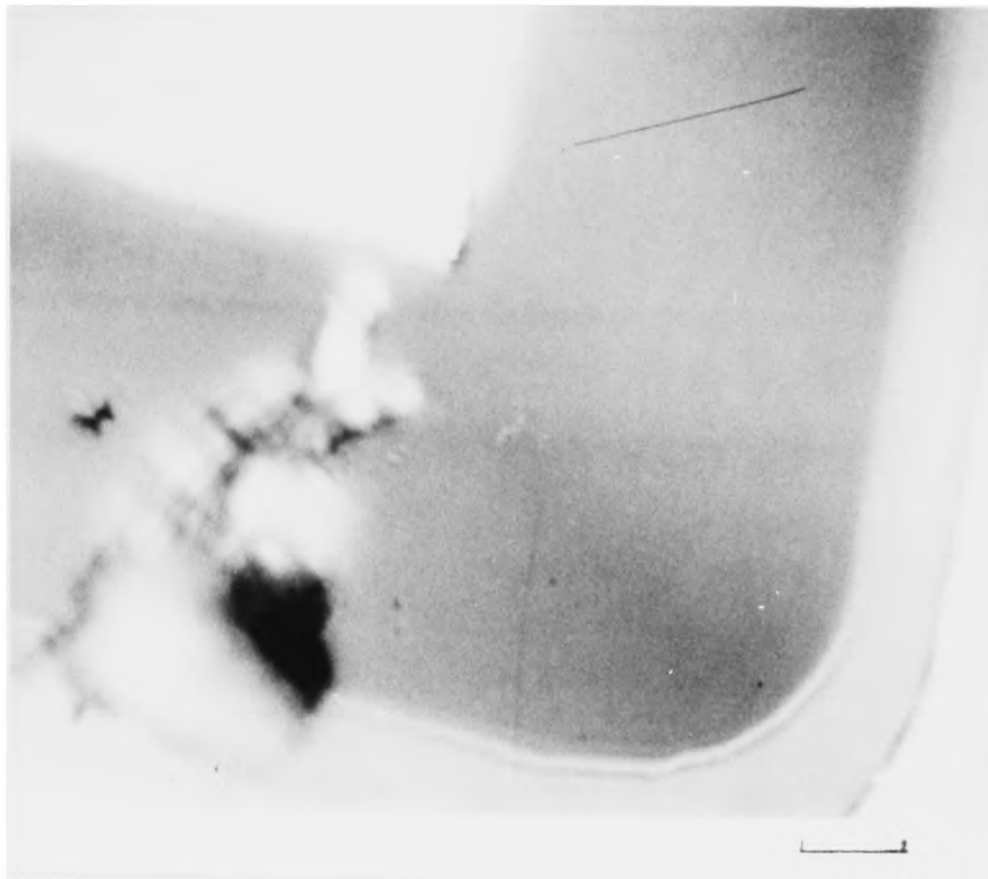


Fig. 6.1 Silicon Bipolar Transistor

Secondary Electron Image



(a)



(b)

Fig.6.2 Silicon Bipolar Transistor

(a) Type 1 Reflection Image  $\text{—} = 5 \mu\text{m}$

(b) OBIC Image  $\text{—} = 2.5 \mu\text{m}$

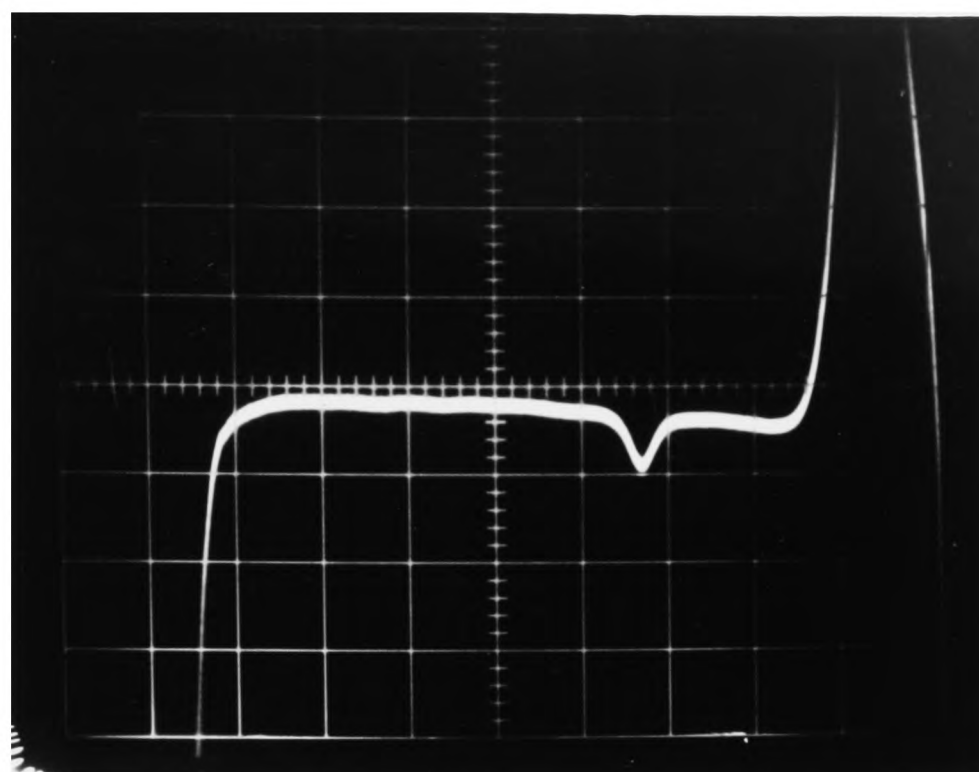


Fig. 6.3 OBIC Linetrace Across a Line Defect in Fig. 6.2 (b)

One Large division =  $4.2\mu\text{m}$

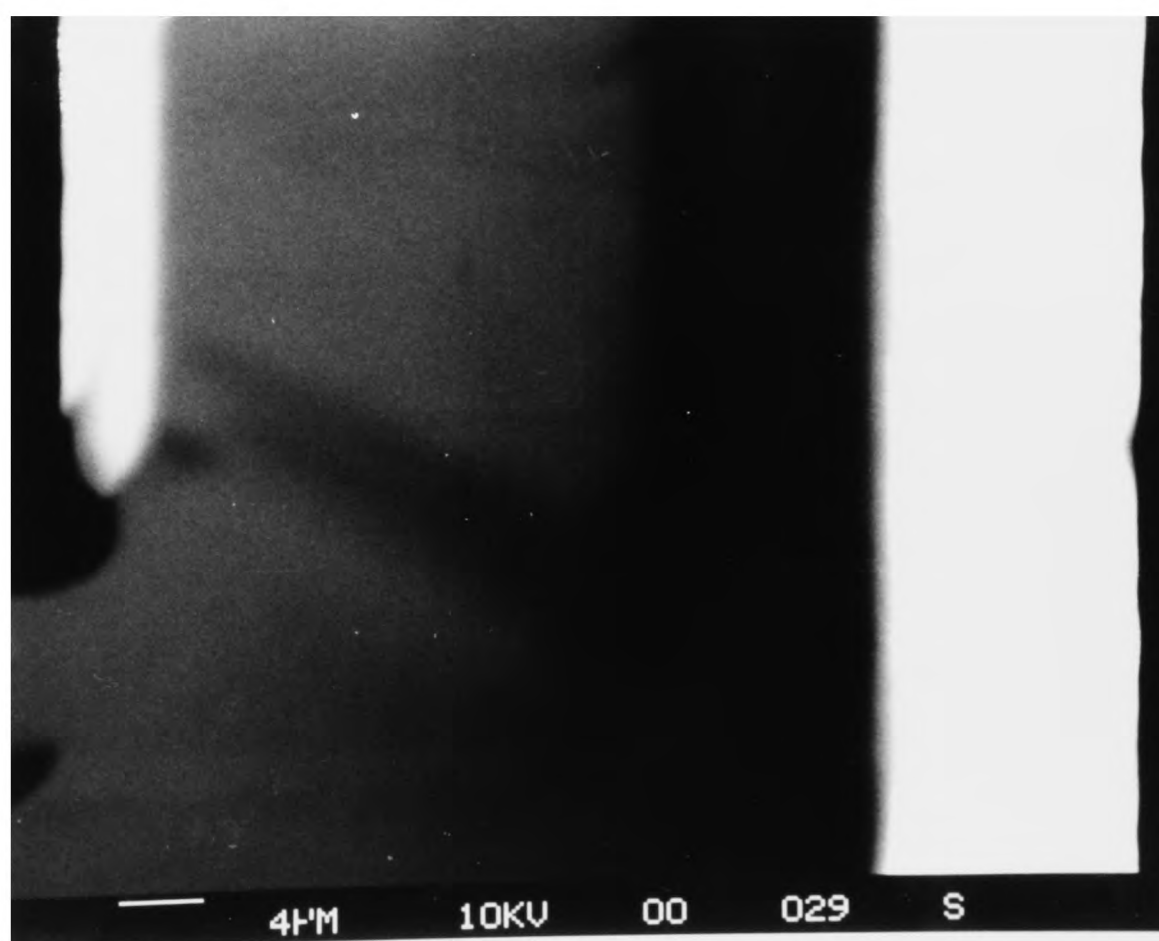


Fig. 6.4 Bipolar Transistor, EBIC Image

OBIC image.

## **6.5 CONCLUSIONS**

This chapter has explored some of the practical problems which arise using the scanning electron microscope to image electrically active defects in a semiconductor device. It is found that OBIC and EBIC imaging of line defects gives resolutions in the micron range. It is also found that EBIC imaging has damaged the specimen. Schick <sup>6.5</sup> suggests recharacterization of the device after EBIC examination to determine the extent of electron beam damage since the alteration of the characteristics of the device being analysed can also alter the results of the EBIC analysis.

## CHAPTER 7

### EXAMINATION OF THE SILICON/ SILICON-DIOXIDE INTERFACE IN METAL OXIDE SEMICONDUCTOR DEVICES

#### 7.1 INTRODUCTION

Defects may be induced in semiconductor devices by many methods such as irradiation of the device or avalanche effects encountered during device operation. Defects may also be found during the processing of devices which have not undergone the final annealing stage. One needs to be able to image such defects in order to correlate the number and nature of these defects with the electrical properties of the device under examination. Current trends in Metal Oxide Semiconductor (MOS) technology are towards higher chip packing density, more complex devices and larger substrates. These advances involve scaling down MOS dimensions and minimising high temperature processing steps. Further generations of MOS devices will require very high quality, very thin ( $< 100 \text{ \AA}$ )  $\text{SiO}_2$  gate dielectrics <sup>7.1</sup>. To estimate the yield for such devices, it is necessary to be able to image defects at this dielectric-silicon interface.

Capacitance techniques have been used <sup>7.2</sup> to investigate the interface trap level density as a function of gate bias. Previous work <sup>7.3</sup> has introduced a scanned light pulse technique to investigate the interface properties of metal-insulator-semiconductor (MIS) structures. This Chapter describes a novel method of using a continuous Helium Neon (633 nm) light beam to obtain a spatial map of defects such as interface states and trapped charge at the silicon/ silicon-dioxide interface. By obtaining this information for devices with many defects the method may be extended to examine interface defects in unirradiated devices with relatively few defects.

It is desirable to have the quiescent current in MOS devices as low as possible. Any inhomogeneity in charge trapped in the oxide of a MOS device means that

different areas of the gate turn on at different gate voltages. Thus, inhomogeneity in trapped oxide charge may result in a device which does not turn on sharply. In addition trapped oxide charge reduces the mobility of the inversion layer carriers by Coulomb scattering. This method of examination can provide very useful information by examining the inhomogeneity of trapped oxide charge under the gate. Information about charge injection is also important. Charge injection occurs when energetic carriers cross the silicon/ silicon-dioxide interface. As shorter channel MOS devices are made, higher fields are encountered and the problem of charge injection becomes more serious.

The use of a laser beam ensures freedom from charging problems. These charging problems are the key to the reason why a SOM is used to examine devices in this work. The high energy electron beam of a SEM causes electron-hole pairs to be formed in the silicon dioxide. The holes can give rise to interface states and positive trapped charge in the oxide. This charging problem means that the SEM is not suitable to examine the Si-SiO<sub>2</sub> interface since the electron beam itself causes defects at the interface.

## **7.2 THEORY**

### **7.2(a). The MOSFET and the MOS capacitor**

Fig. 7.1 shows a cross-section through a MOS capacitor. It may be described<sup>7.4</sup> as a structure consisting of an n-type or p-type semiconductor covered by a thin film of insulating material (normally oxide). It is assumed that the film is perfectly insulating and is characterised by a certain trap distribution. A voltage applied to the upper plate of the capacitor (the metal gate) gives rise to a uniform electric field in the insulating SiO<sub>2</sub> which induces a charge in the lower 'plate' (the silicon). This is the field effect. If the silicon is doped lightly n-type, a negative gate voltage will

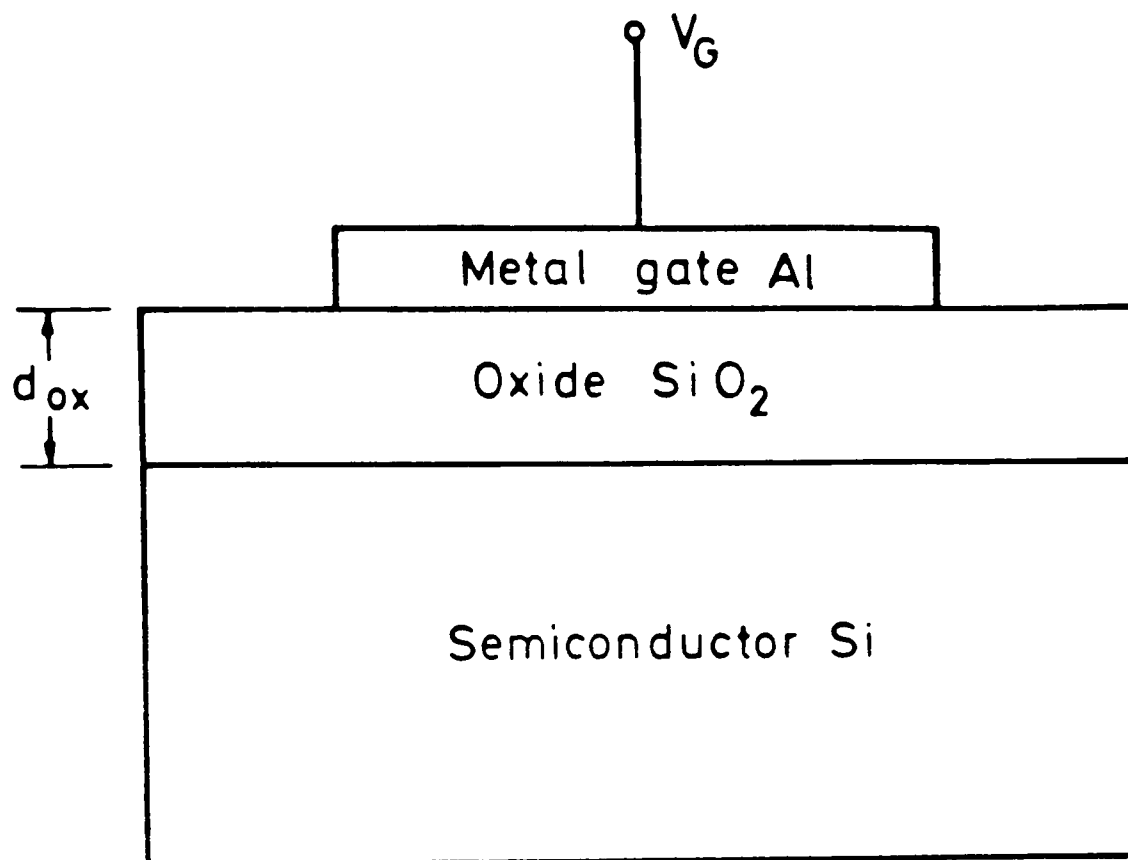


Fig.7.1

A cross-section through a MOS capacitor (not to scale)

deplete the silicon surface of carriers leaving positively charged ionised acceptors. The space-charge region, or depletion region, extends deeper into the silicon as the gate voltage,  $V_g$ , becomes more negative. Energy band diagrams for the p-type MOS capacitor show that when  $V_g$  is made yet more negative, an inversion layer, i.e. a layer of conducting holes, forms in the narrow potential well at the Si-SiO<sub>2</sub> interface. A positive gate voltage causes electrons to be attracted to this interface. This is called accumulation.

In the p-channel MOSFET, there are two heavily doped regions called the source and drain as illustrated in Fig. 7.2. Each forms a p-n diode with the substrate. In the enhancement mode device the source-drain impedance is normally high. Applying a sufficiently negative gate voltage causes a depletion region to form in the region of the n-type silicon under the gate. Making the gate voltage yet more negative causes inversion of the silicon under the gate providing a channel of p-type carriers which connects the source and drain. This simple picture of a MOS device is complicated by a number of factors including ionic contamination in the oxide, for example Na<sup>+</sup> (Nicollian and Brews).

### The electrical properties of the Si-SiO<sub>2</sub> interface:

The Si-SiO<sub>2</sub> interface has charge centres called oxide fixed charge. These centres are predominantly positive, although a small number of compensating negative centres may be present. This oxide fixed charge does not respond to gate voltage. It is located within about 30 nm of the Si-SiO<sub>2</sub> interface<sup>7.5</sup> and has magnitude typically 10<sup>15</sup> charges m<sup>-2</sup>. There are also centres throughout the bulk of the oxide which can trap both positive and negative charges.

An imperfection may be defined<sup>7.4</sup> as any cause of a disturbance in the perfect periodicity in the potential inside a solid. Such imperfections can introduce localised electronic energy states which can be either in an allowed or a forbidden band.

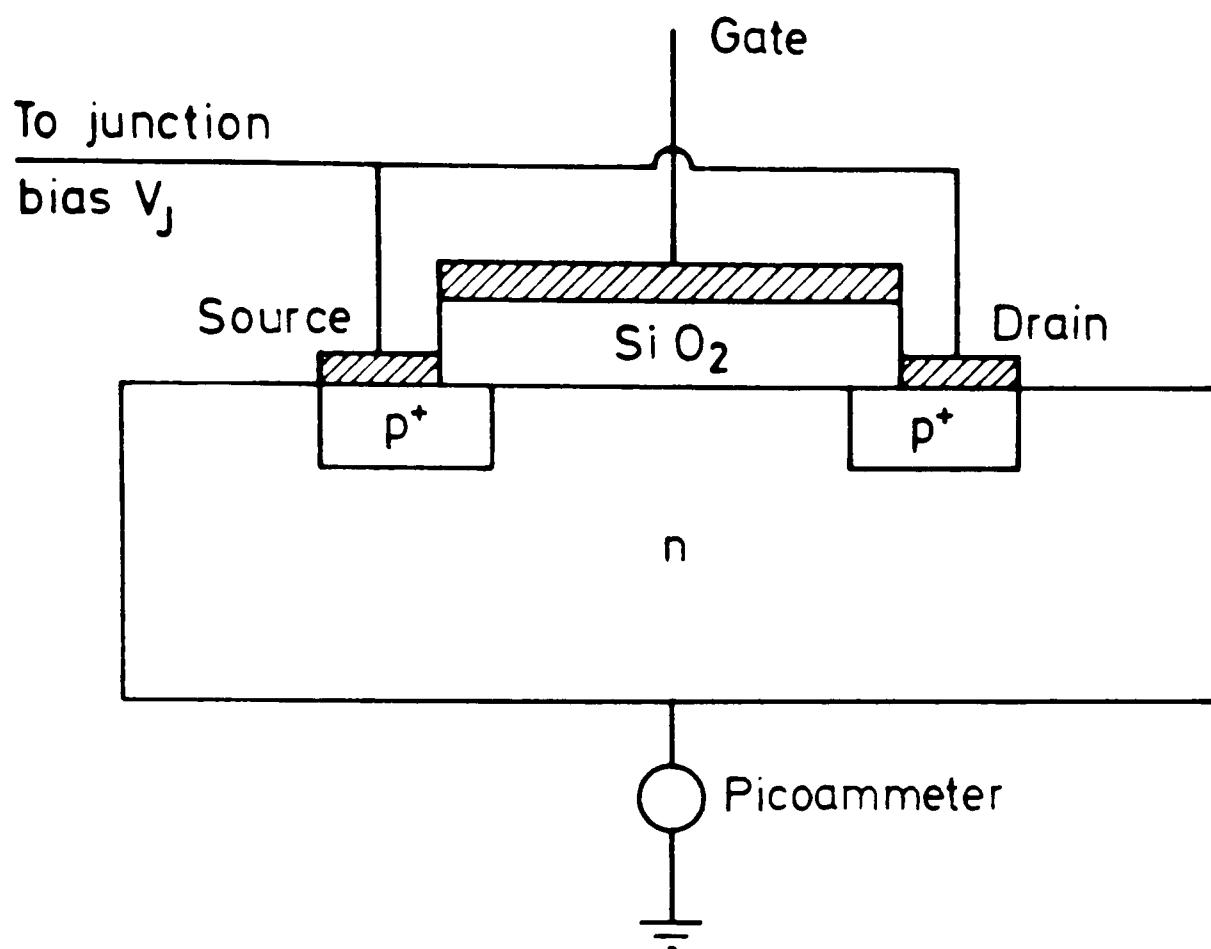


Fig.7.2

p-channel MOSFET

A major imperfection such as the surface of the silicon in contact with silicon-dioxide will manifest itself in localised electronic energy states. Since these states are localised at the surface they are called surface states. These surface states have energies throughout the bandgap and can change their charge as the gate voltage is altered and the Fermi Level sweeps through the bandgap. The charge is referred to as interface trapped charge. If the interface state density is too large, the operation of the MOSFET is hindered by the trapping of carriers which would otherwise go into the inversion layer.

### 7.2(b). The substrate current - gate voltage characteristics for pMOS devices

#### The dark substrate current - gate voltage characteristics :

When neither laser nor background light is incident on the MOS device the device is said to be operating in the 'dark'. Consider a pMOS device as in Fig. 7.2. The source and drain are connected in parallel to a junction bias voltage source where  $V_j$  is the junction bias voltage. The forward bias current is given by

$$I_{dc} = R \exp\left(\frac{eV_j}{2kT}\right) + D \exp\left(\frac{eV_j}{kT}\right) \quad (7.1)$$

where  $R$  and  $D$  give the relative magnitudes of the recombination and diffusion currents and  $k$  is Boltzman's constant. Defects can act as centres for recombination or generation. When the depletion region is formed under the gate in the n-type silicon by applying a negative gate voltage, any surface states at the interface can contribute to the recombination current. It is desirable, in our case, that the current across the pn diodes under forward bias should not be dominated by diffusion current so that the contribution to the recombination current due to interface states may be observed. This is achieved in practice by limiting the junction voltage to  $0V < V_j < 0.4V$ .

The effect of the variation of gate voltage,  $V_g$ , on the size of the dark current can be seen in Fig. 7.3. The labels a, b and c refer to the accumulation, depletion and inversion of the n-type silicon respectively. The corresponding depletion regions are sketched in Figs. 7.4a, b and c.

#### (i) Accumulation

For a positive gate voltage and a p-channel device accumulation occurs at the Si-SiO<sub>2</sub> interface. The resulting current registered by the picoammeter of Fig. 7.2 is due to the sum of diffusion and recombination currents of the two pn diodes. Varying the positive gate voltage should have little effect on this current. Hence one gets the portion (a) of the  $I - V_g$  curve of Fig. 7.3. For  $V_g^* < V < 0V$  there is no depletion region under the gate. Hence the current remains approximately constant at the value  $I_1$  of Fig. 7.3.

#### (ii) Depletion:

As  $V_g$  is swept more negative, then the n-type silicon surface under the gate becomes increasingly depleted under the influence of the oxide field. Hence the depletion region extends further along the Si-SiO<sub>2</sub> interface. Now defects at the interface find themselves in the depletion region and hence can contribute to the recombination current. As the depletion region extends down further into the n-type silicon, then defects in the silicon below the interface can also contribute to the recombination component of the dark current. Hence if one assumes that the depletion region has formed under the gate at a gate voltage of  $V_g^*$  then the dark current at this gate voltage is the sum of the recombination current from both pn junctions and also recombination current due to the interface defects and defects in the ' field-induced junction ' beneath the interface. Hence the current increases to the value  $I_2$  shown in Fig. 7.3

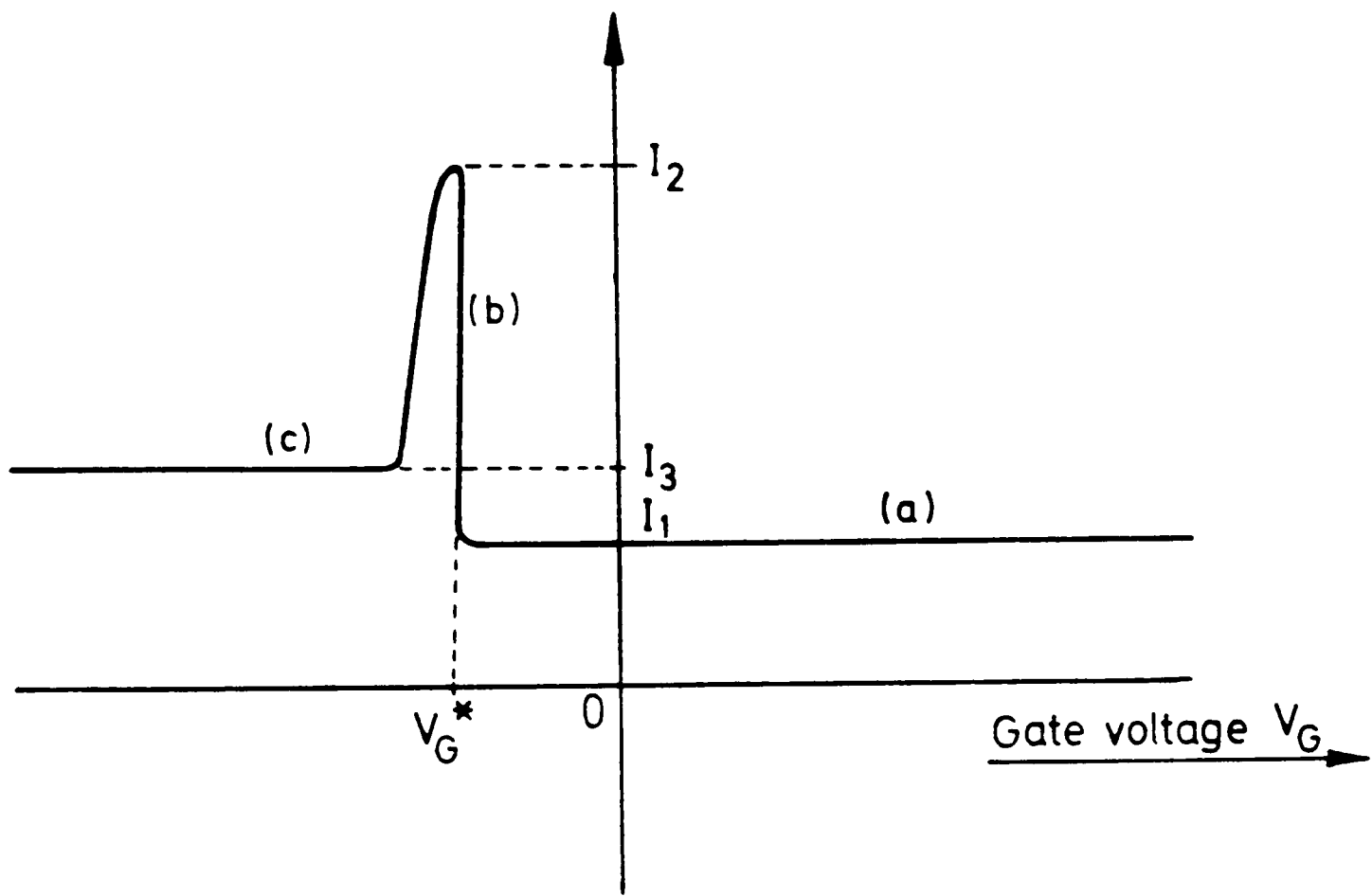


Fig.7.3

Dark substrate current plotted against gate voltage with a forward bias voltage applied to both diffusion regions in parallel

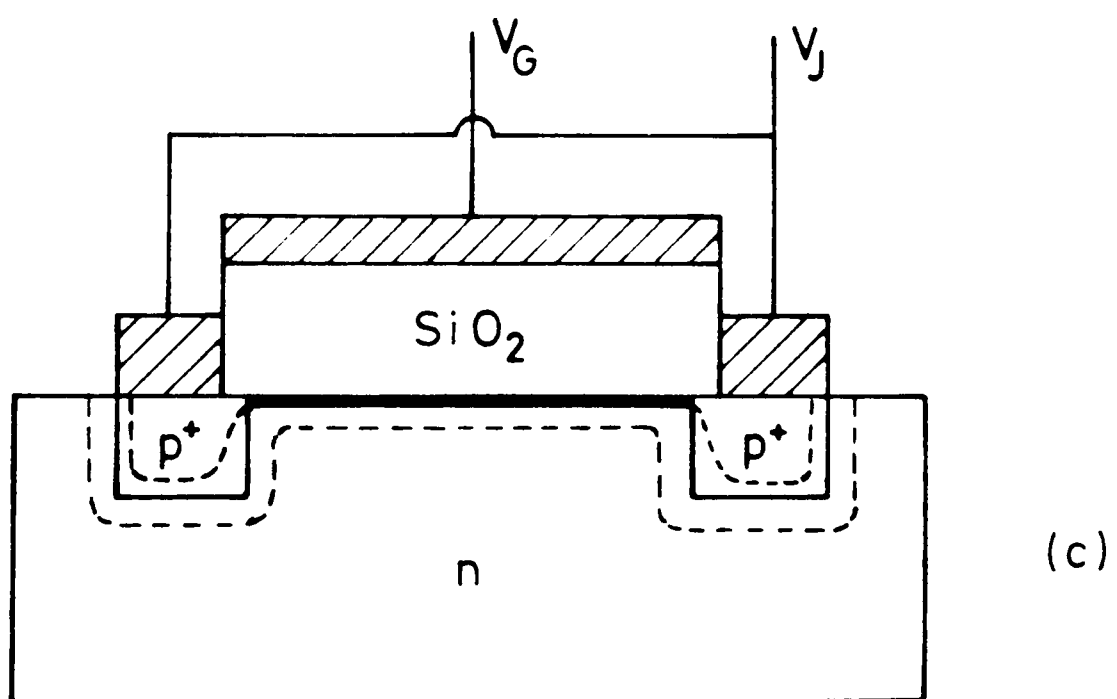
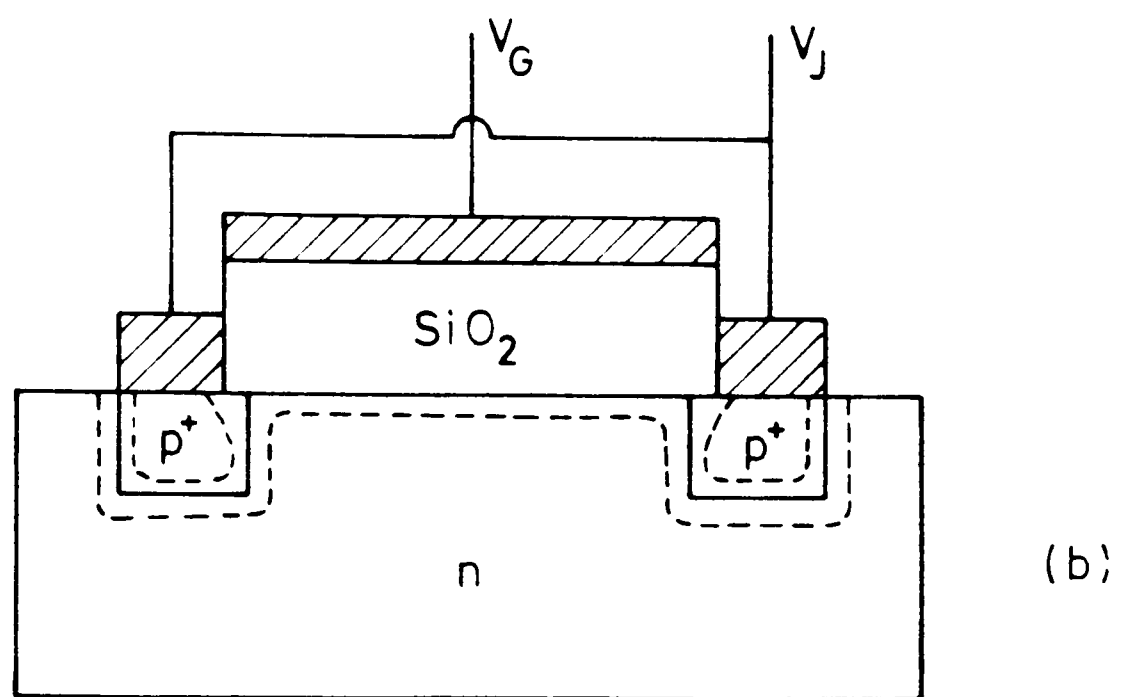
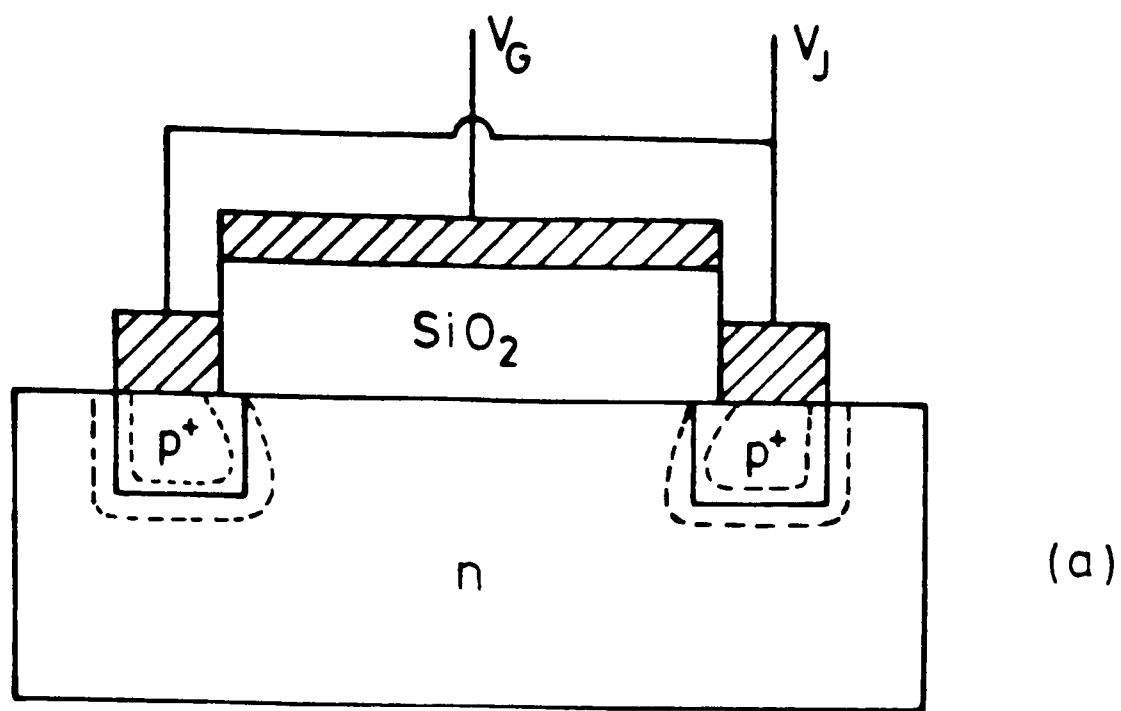


Fig.7.4

Depletion region shapes for a MOS device in  
(a) Accumulation ( $p^+$  region depleted)

(b) Depletion

(c) inversion

(iii) Inversion:

When  $V_g$  is sufficiently negative to invert the silicon the depletion region is no longer in contact with the interface defects. Hence these defects can no longer contribute to the recombination current. Thus the amount by which the current falls  $I_2 - I_3$  of Fig. 7.3 is the interface recombination current.  $I_3$  is the sum of currents due to the two pn diodes and defects in the silicon below the interface in contact with the depletion region.  $|I_1 - I_2|$  indicates the number of the latter defects.

Laser probing of a thin metal gate MOSFET :

We now consider the non-destructive probing of the MOSFET device with light. This section discusses how such probing can give spatial information on defects at the  $\text{SiO}_2$  interface. Thin aluminium gates are often used in MOS devices. This is fortunate as laser light can penetrate through the metal and reach the silicon under the oxide. A helium-neon laser, wavelength 632.8 nm, has a suitable photon energy (1.96 eV) such that silicon dioxide with a bandgap of about 8 eV is transparent at this wavelength. Silicon has a bandgap of about 1.1 eV such that a helium-neon laser can excite electrons from its valence to conduction band. This means that when laser light is incident on the metal gate photogeneration occurs i.e. electron-hole pairs are generated in the n-type silicon. This process gives rise to a photogeneration current if it occurs in a depletion region or close enough to a depletion region so that carriers may diffuse to this region and be swept out by the electric field in this region. This process is discussed earlier in the thesis.

The net recombination-generation rate at defects (called recombination-generation centres) in the depletion region in the presence of light is given by Appendix 2 as:

$$U = \sigma v_{th} N_t \left( \frac{pn - n_i^2}{n + p + 2n_i \cosh[(E_t - E_i)/kT]} \right) - G \quad \text{m}^{-3}\text{s}^{-1} \quad (7.2)$$

where the first term on the right of Eq. 7.2 gives the contribution due to recombination and generation at single level traps in the band gap.  $E_t$  is the trap energy,  $\sigma$  is the capture cross-section (assumed to be the same for electrons and holes),  $v_{th}$  is the thermal velocity of the carriers and  $N_t$  is the trap density.

This recombination or generation is 'driven' by the imbalance between the product of carrier concentrations  $pn$  and the equilibrium product  $n_i^2$  in the absence of incident light. The second term,  $G$ , gives the rate contribution due to the incident laser light (photogeneration).

When light is suddenly incident on the device,  $G$  of Eq. 7.2 is large and positive. There is net carrier generation. Thus  $p$  and  $n$  increase until a new steady state is reached where the first and second terms of Eq. 7.2 sum to zero. When laser light is incident on the gate of the MOS device electron-hole pairs are formed in the silicon under the gate and thus  $n$  and  $p$  are both larger than their equilibrium values. Without a depletion region these carriers would recombine. The existence of the depletion region, however, means that the carriers are swept out of this region by the electric field across it. Hence in the presence of a depletion region a large generation current is recorded and a current step results as illustrated in Fig. 7.5.

The case of device operation in the absence of light has already been considered. In this case applying a sufficiently negative gate voltage causes a depletion region to form under the gate at the Si-SiO<sub>2</sub> interface. On making the gate voltage even more negative, an inversion layer forms at the Si-SiO<sub>2</sub> interface. The laser beam still penetrates into the depletion region, however. Hence the generation current remains essentially unaltered.

This assumes that the laser intensity is high enough that any recombination at defects does not degrade the generation current significantly. This is not the case if either the intensity of the beam is reduced to give a generation current comparable to that of the recombination current or there are a very large number of defects at

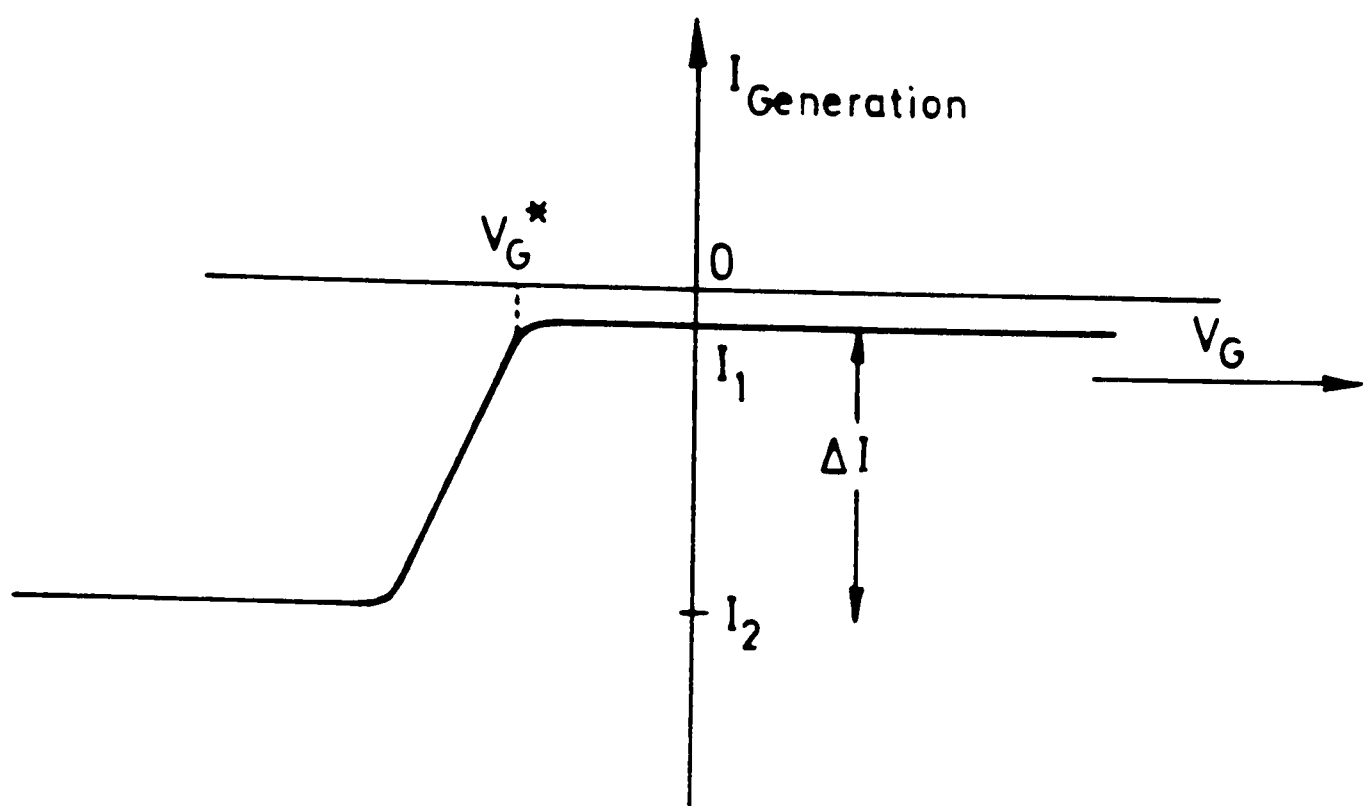


Fig.7.5

Generation current plotted against gate voltage

$I_1$ =light generated current from the  $p^+n$  depletion regions

$\Delta I$ =light generated current from the depletion region under the gate

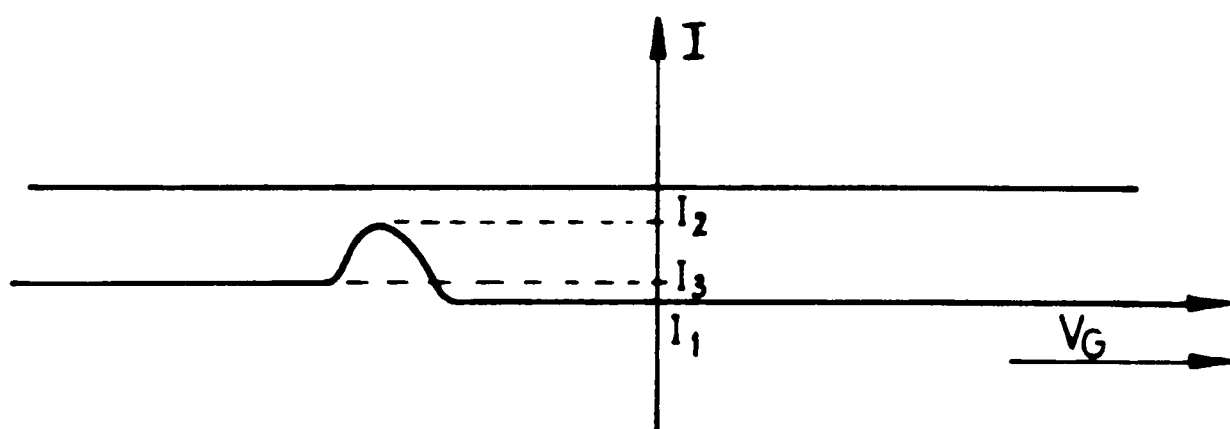


Fig.7.6

Net current-gate voltage characteristic for generation and recombination currents of the same order of magnitude

the interface itself or below it in the silicon. The latter is the case when the device is irradiated causing a large interface state density. In such cases the resultant current is the sum of the currents shown in Figs. 7.3 and 7.5. This gives a possible substrate current-gate voltage profile as shown in Fig. 7.6. In this way a scanning laser beam can probe each area of the gate to locate the different values of  $V_g^*$  at which the depletion region is formed. A different  $V_g^*$  value will result if the positive trapped charge in the oxide under the gate is inhomogeneous. The larger the positive trapped charge in a given location in the oxide the more negative a gate voltage is required to form a depletion region under that area of the gate. Hence positive oxide charging shifts the current-gate voltage plots in the negative gate voltage direction.

If the laser intensity is adjusted to give a current-gate voltage plot as in Fig. 7.6 then  $|I_2 - I_3|$  for a given point on the gate indicates the interface state density at that point. In this way, a qualitative picture of interface state density and positive trapped charge under the gate may be obtained.

### **7.3 EXPERIMENTAL APPROACH**

This work falls into 5 sections:

7.3(a). Dark Current-Gate Voltage characteristics for irradiated and unirradiated devices

7.3(b). Laser Probing and OBIC imaging of MOS devices

- Gate Inhomogeneity

- Predicted OBIC images

7.3(c). Mask Misalignment Detection

7.3(d). The Source-Drain Current,  $I_{SD}$  - Gate Voltage,  $V_g$  Characteristic

7.3(e). An Unirradiated Polysilicon Gate Device

### 7.3(a). Dark substrate current - gate voltage characteristic of a thin aluminium gate MOS device

Consider the pMOS device of Fig. 7.2 where the source and drain are connected. Separate bias voltages using batteries are applied to the source-drain junction and also to the gate. The substrate current is registered by the picoammeter. For a series of junction voltages plots of dark current versus applied gate voltage may be obtained. It is important that the bias circuits for the source-drain junction and the gate are screened.

Fig. 7.7 shows a typical experimental plot of dark current versus gate voltage for a series of junction voltages for a thin unirradiated metal gate bar geometry device. Fig. 7.8 shows a similar plot for an unirradiated square geometry device. This square geometry is shown in Fig. 7.9. From now on all experimental work carried out on metal gate devices uses this square geometry device. The plots of Figs. 7.7 and 7.8 have the same general shape predicted by the theory. Fig. 7.8 illustrates that the depletion region under the gate forms for this device at  $V_g \approx -1.75V$ . On sweeping  $V_g$  more negative the inversion layer forms and the current decreases to a value  $I_3 > I_1$ . Thus there are clearly defects at the interface indicated by  $|I_2 - I_3|$  and below the interface corresponding to  $|I_3 - I_1|$ . The latter must be relatively few in number because for  $V_j = 0.15V$ ,  $|I_2 - I_3| \gg |I_3 - I_1|$ .

On increasing the junction voltage the following may be observed. As  $V_j$  increases, Eq. 7.1 indicates that the recombination current becomes dominated by diffusion current. Hence the bumps in the dark  $I - V_g$  plots become smaller.

#### **The effects of irradiating a device :**

Fig. 7.10 shows the dark current vs. gate voltage characteristic for a heavily irradiated pMOS device, (device TOT202 sample Z1). The device is irradiated using a Cobalt source. Throughout the rest of this chapter the irradiated metal

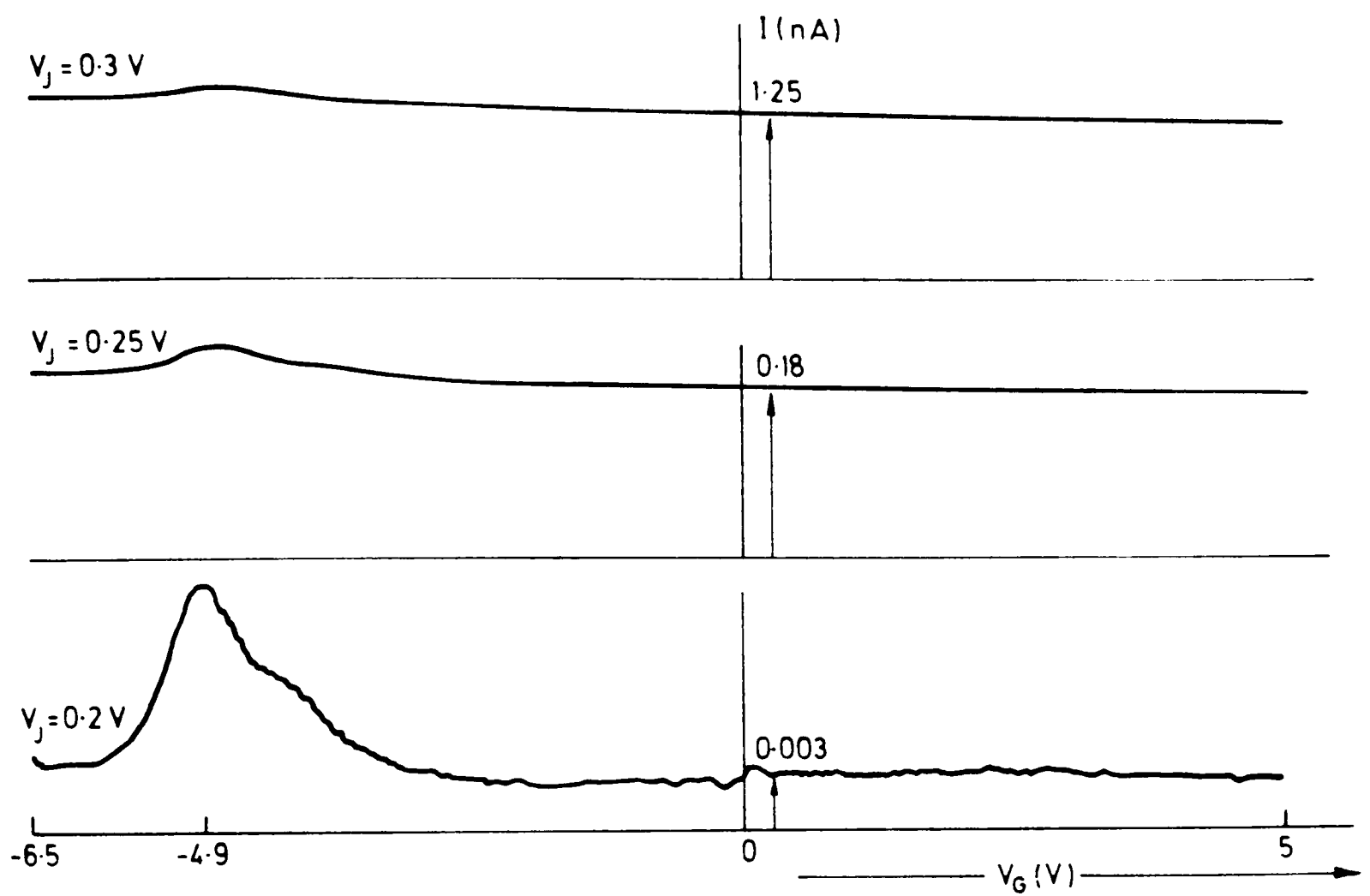


Fig.7.7

Plot of dark substrate current against gate voltage for the  $\rho$ MOS thin metal gate device with bar geometry

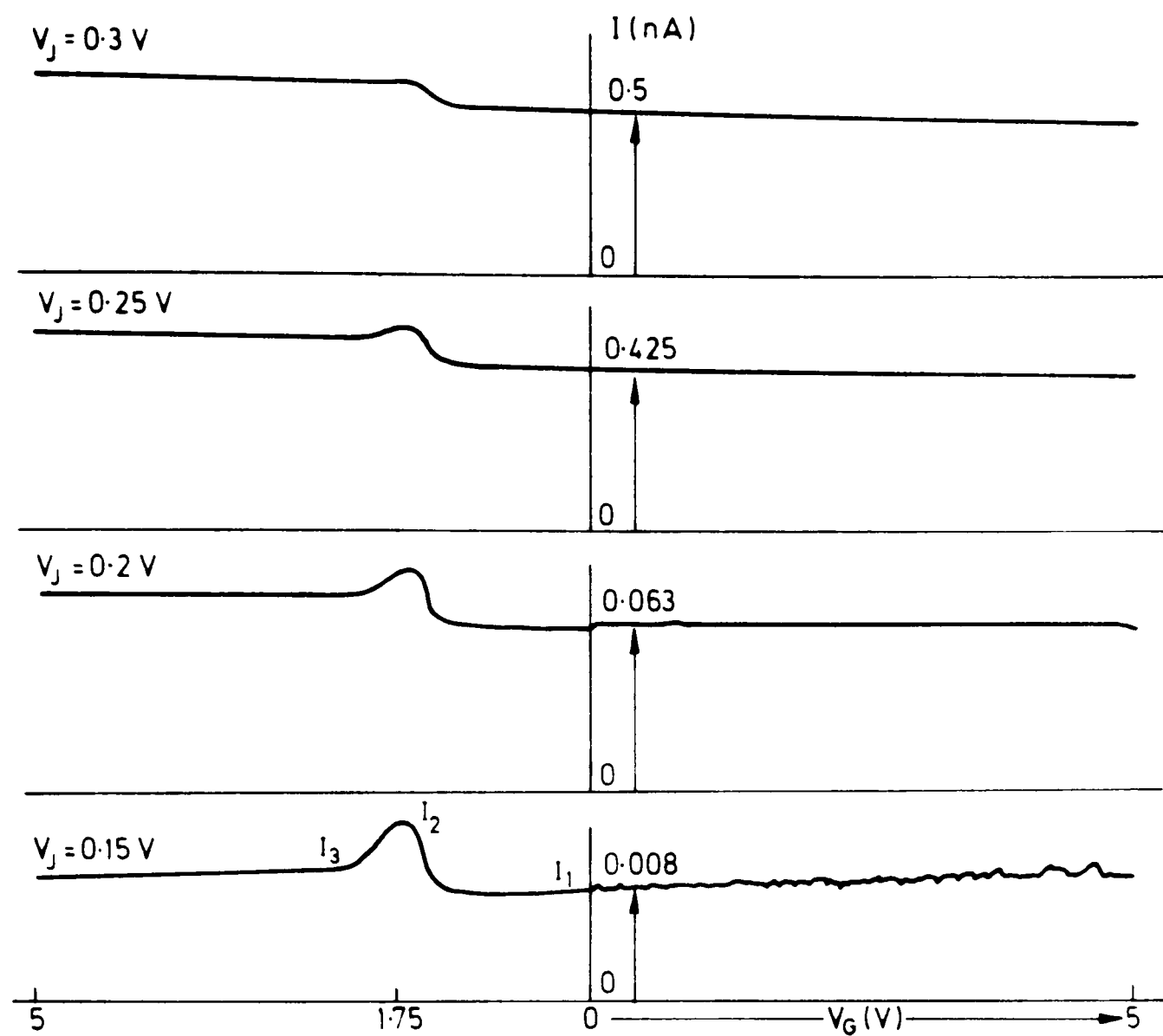


Fig.7.8

Plot of dark current vs. gate voltage for the unirradiated pMOS device with square geometry

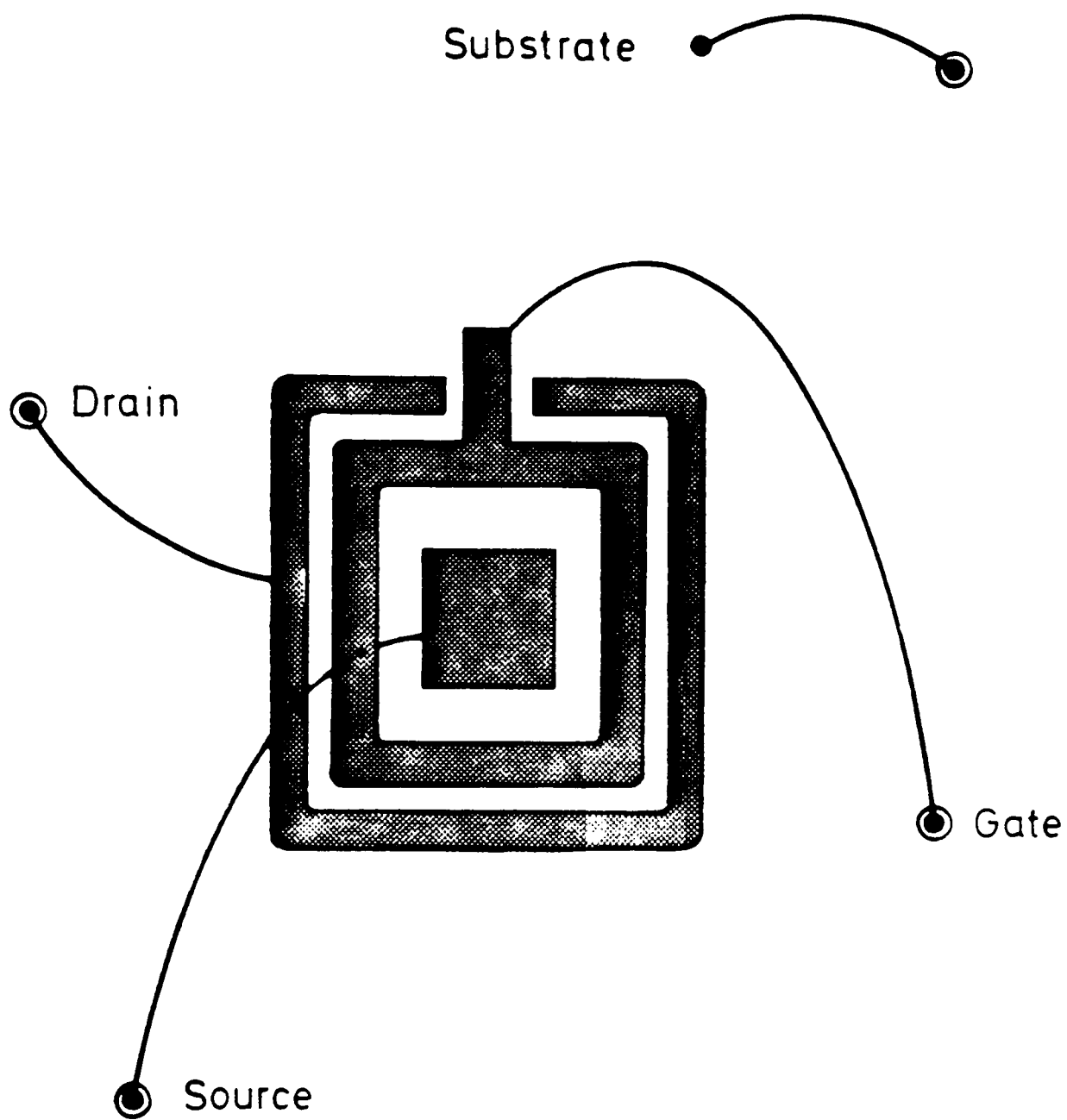


Fig.7.9

The square geometry of the device of Fig. 7.8

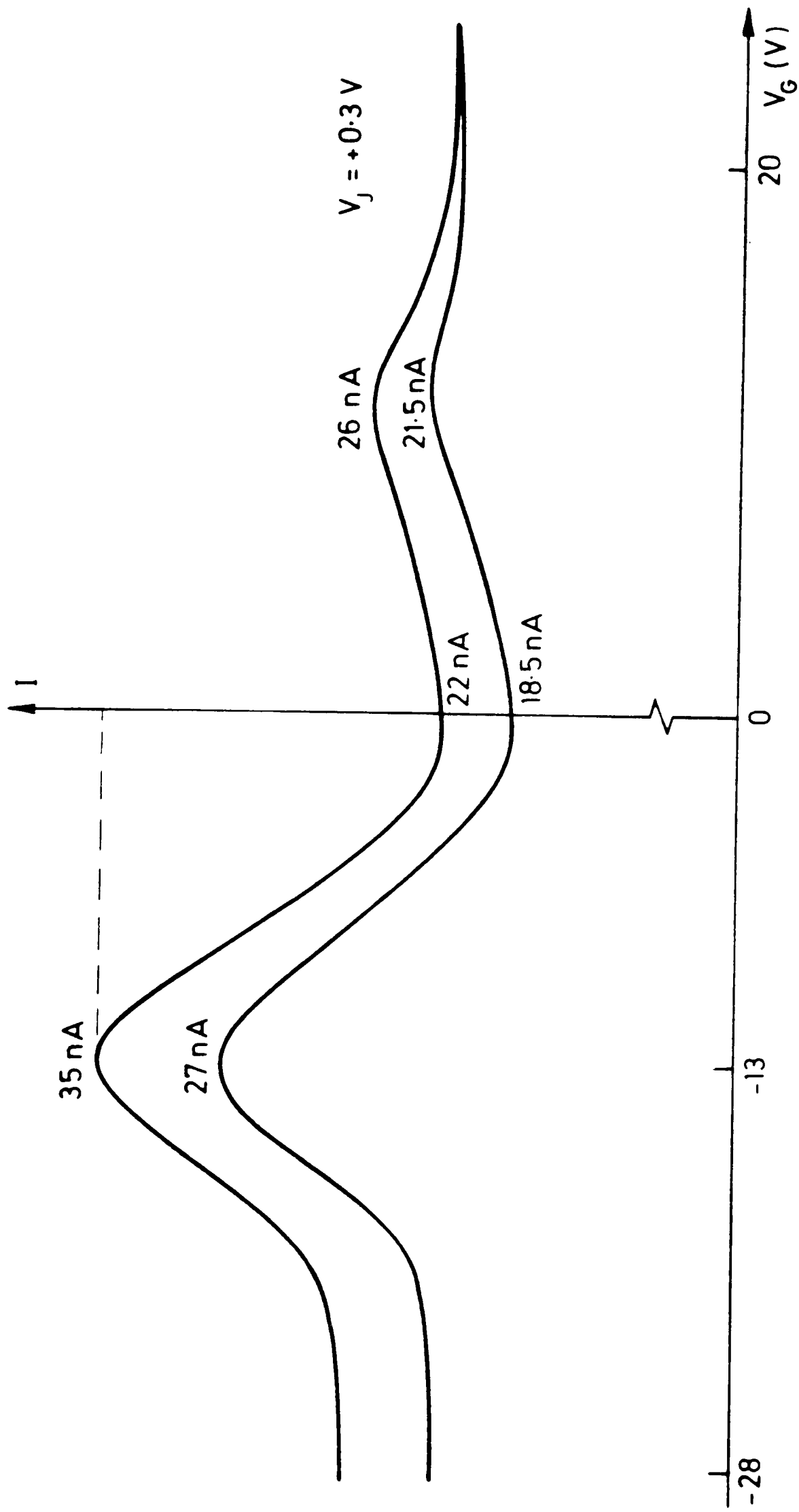


Fig.7.10

Plot of dark substrate current against gate voltage for the heavily irradiated  
( $2 \times 10^7$  rad) pMOS thin metal gate device with square geometry

gate device under consideration is the same device TOT202 sample Z1. Comparison of the characteristic of Fig.7.10 with that of a similar device in Fig. 7.8 shows some effects of irradiating a device.

(i) The gate voltage at which the dark current peaks is shifted to a much more negative voltage in the irradiated device. This may be explained by noting that irradiation causes a larger positive trapped charge. Hence a more negative gate voltage is required to create a depletion region under the gate.

(ii) The current bump for negative gate voltages has become much wider in the irradiated device. This is due to the inhomogeneity in trapped positive charge in the oxide caused by irradiation. This means that the formation of the depletion region at different regions of the gate occurs over a much wider range of gate voltages.

(iii) The dark recombination currents are much larger (by a factor of 10) for the irradiated device. This is because irradiation has caused a large number of defects at which recombination can occur.

(iv) The current bump for positive gate voltage probably occurs for the same reasons as for negative gate voltage except that now the n-type silicon region under the gate is accumulated and it is the  $p^+$  region under the gate which is becoming more depleted and eventually inverted as  $V_g$  is increased. One would normally not expect inversion to occur in the heavily doped  $p^+$  region. However, irradiation can cause a very large positive trapped charge in the oxide directly above the  $p^+$  regions because heavy doping can cause defects which make the device more sensitive to radiation damage. Hence a positive gate voltage may cause inversion in the  $p^+$  material and the consequent bump on the curve for positive  $V_g$ .

**7.3(b). The use of laser light to probe the Si-SiO<sub>2</sub> interface**

**Laser probing of an unirradiated device :**

As light penetrates the gate whose thickness is nominally 0.12 $\mu$ m, one should observe a current voltage characteristic as in Fig. 7.5. If light does not penetrate the gate, then there is no increase in photogeneration current at the negative gate voltage value for which a depletion region forms. Using the unirradiated MOS device of Fig. 7.8, a junction voltage,  $V_j \approx 0V$ , and different levels of attenuation of the incident laser beam, the beam is focused on a single area of the gate. Current steps between current levels  $I_1$  and  $I_2$  of Fig. 7.5 are recorded. Thus light is penetrating the gate. The recorded values of  $I_1$  and  $I_2$  for this device are given in Table 7.1.

Table 7.1

| Attenuation Factor | $I_1$         | $I_2$         |
|--------------------|---------------|---------------|
| No attenuation     | -5.25 $\mu$ A | -5.65 $\mu$ A |
| 10                 | -0.39 $\mu$ A | -0.41 $\mu$ A |
| 100                | -4.4nA        | -4.6nA        |
| 1000               | -0.68n A      | -0.74n A      |

Clearly  $I_2$  decreases with increasing attenuation. This is to be expected since the number of electron-hole pairs which can contribute to the generation current decreases with increasing attenuation. One should find that there is very little current for  $V_g > V_g^*$  because in the absence of a depletion region generated electron-hole pairs should recombine. The reason why the recorded  $I_1$  values are non-zero is that generated hole-electron pairs can diffuse to the junctions before recombining thus registering the current  $I_1$  .

## Laser probing of an irradiated pMOS device

Figs. 7.11(a) shows SOM reflection images of the gate of a heavily irradiated device - the same type of device as the unirradiated device discussed above. In Fig. 7.11  $V_g = V_j \approx 0V$ . The dark spots on this photograph appear bright in the OBIC image of Fig. 7.11(c). This is consistent with the presence of pinholes in the gate metal. These appear dark in reflection because less light is reflected from them, and bright in the OBIC image since light of greater intensity has been absorbed in these spots giving rise to a larger OBIC signal. This observation highlights the problem of pinholes and metal islands in making very thin metal gates. Clearly, the SOM can be used as a very valuable tool in examining the quality of metallisation layers to see if there are any pinholes present. Note that the size the pinholes appear to be in the OBIC image is determined by the area of the focused laser beam and the extent to which carriers diffuse from this region.

Fig. 7.11(b) gives a Type 1 reflection image with different contrast enhancement. Comparison of this photograph with the OBIC image of Fig. 7.11(c) shows the gate to appear much thinner in the OBIC than in the reflection image. This indicates that the gate overlaps a portion of the two  $p^+$  regions of the source and the drain. The entire gate width is shown in the reflection image of Fig. 7.11(b).

Since the gate voltage is zero the n-type silicon under the gate is accumulated. There is a depletion region under the  $p^+$  regions, however. Photocarriers near the  $p^+ - n$  junction in the n-type silicon, diffuse to the  $p^+$  region and are separated in the depletion region field with the result that  $p^+$  regions under the gate appear bright in OBIC. Thus the difference in the apparent width of the gate in Figure 7.11(b) and 7.11(c) shows the extent to which the  $p^+$  regions extend under the gate on either side of it.

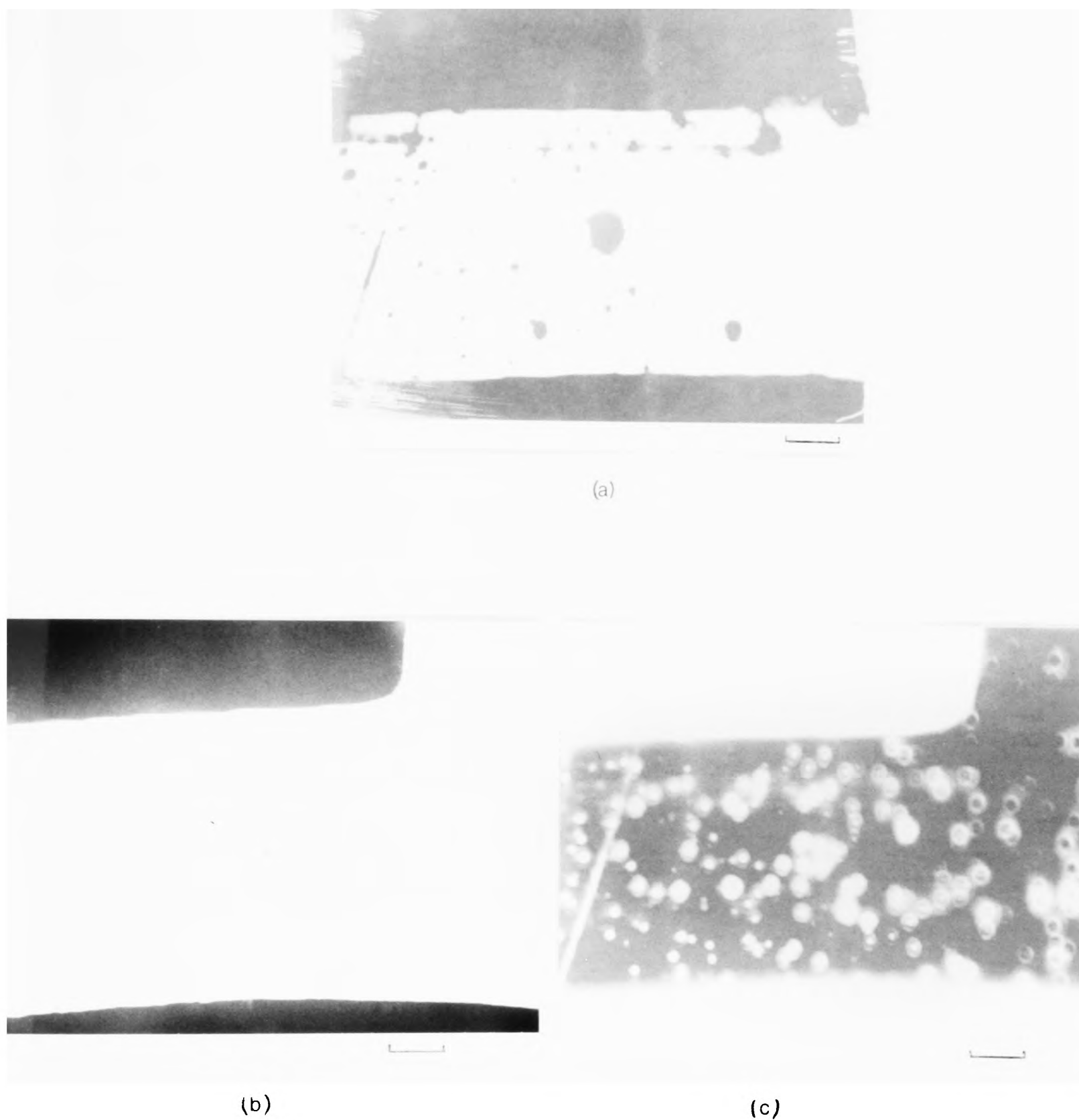


Fig. 7.11 Gate of A PMOS Device-Heavily Irradiated

(a) Type 1 Reflection Image

(b) Type 1 Reflection Image

(c) OBIC Image

— = 5  $\mu$ m

### Inhomogeneity of the gate.

The laser beam is focused on a single area of the gate of the heavily irradiated device. The OBIC current is recorded repeatedly with varying gate voltage giving the plots of Fig. 7.12. Clearly this  $I - V_g$  plot is repeatable over a gate voltage range of  $\pm 1V$ . Now the laser spot is moved to a number of other points on the gate. At each point the  $I - V_g$  characteristic is recorded giving the plots of Figure 7.13. The range of values of gate voltage for which a current peak occurs is  $3V$ . This range is larger than the repeatability tolerance of  $\pm 1V$ . This indicates that different portions of the gate turn on at significantly different gate voltages ie. the positive trapped charge in the oxide under the gate is inhomogeneous.

### Predicted OBIC images of the device

Consider Fig. 7.14 which shows an expected OBIC contrast profile which could be obtained by scanning the laser beam across the device. We consider an accumulated gate and the general case where the gate overlaps a large area of the  $p^+$  region to illustrate how the OBIC image may be understood.

For the heavily irradiated device, TOT202 sample Z1, it is not necessary to attenuate the laser to obtain the desired  $I - V_g$  characteristic of Fig. 7.13. When the laser is focused on the  $p^+$  region outside the gate area in region (1) of Fig. 7.14 the OBIC image will appear bright because the light can penetrate the shallow  $p^+$  region and generate carriers which may be swept out by the field in the depletion region of the  $p^+ - n$  junction.

In region (2) consider the general case where there is no depletion region in contact with the oxide. In region (3) the depletion region in the  $p^+$  silicon is in contact with the oxide whereas in region (4) the depletion region is in the  $n$ -silicon.

Photogenerated carriers in region (2) may diffuse to region (3) or to the  $p^+ - n$  junction at depth,  $h$ , below giving an OBIC signal. But this signal will not be as

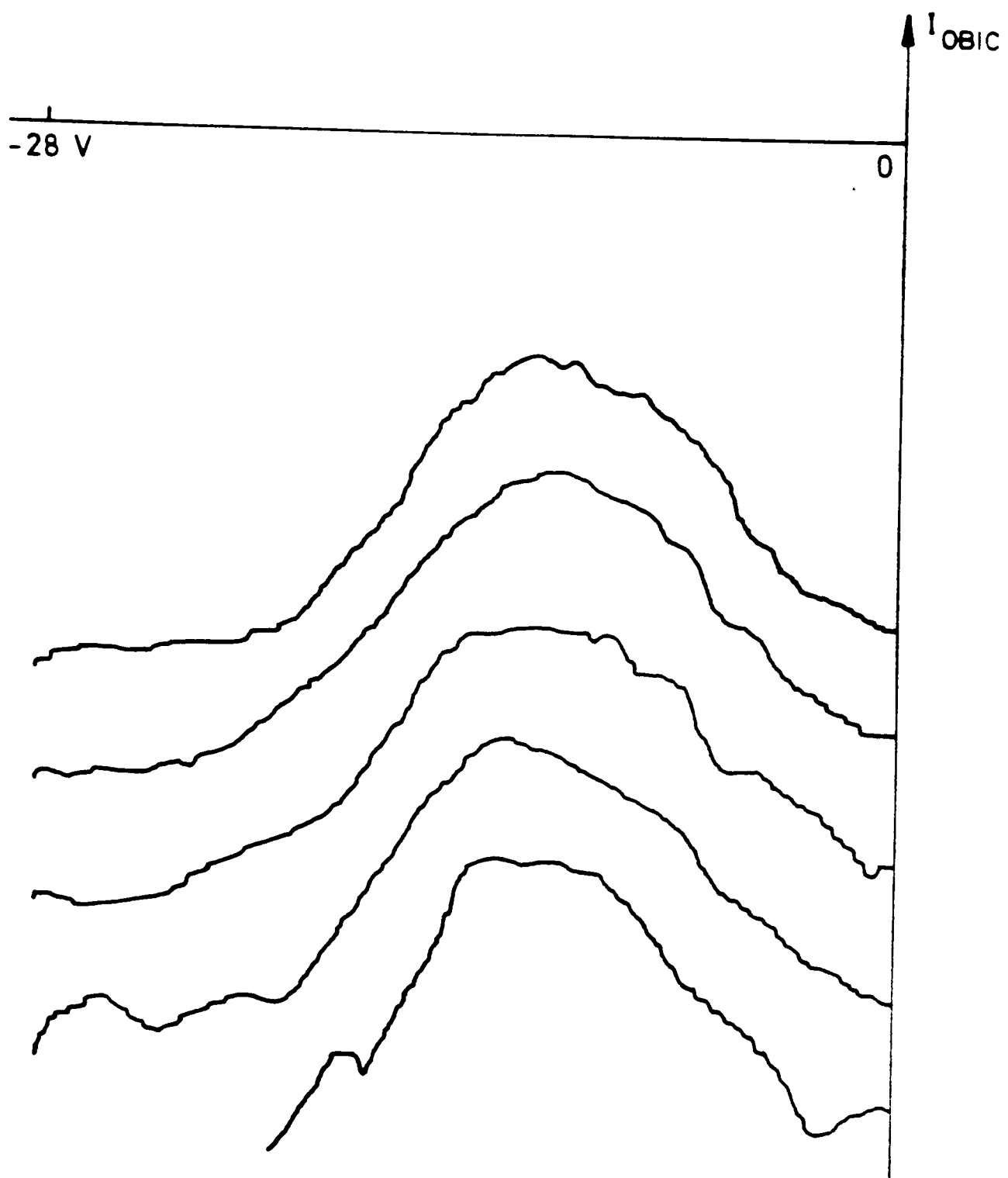


Fig.7.12

Plot of substrate current against gate voltage for the heavily irradiated pMOS device of Fig.7.10 with the laser beam focused on just one area of the gate. The laser light is unattenuated.

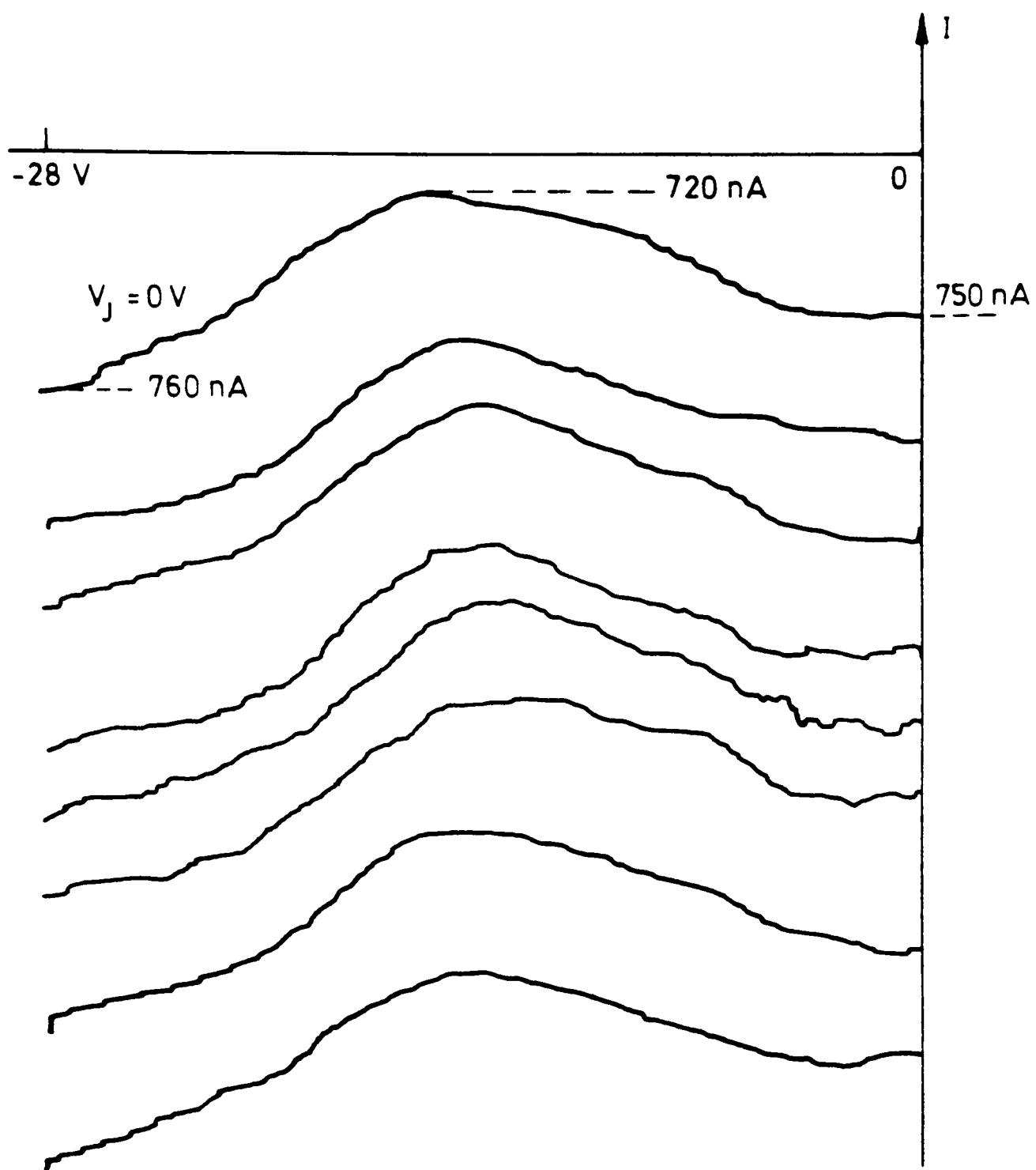


Fig.7.13

Plot of substrate current against gate voltage for the heavily irradiated pMOS device of Fig.7.10 with the laser beam focused on several areas of the gate. The laser light is unattenuated.

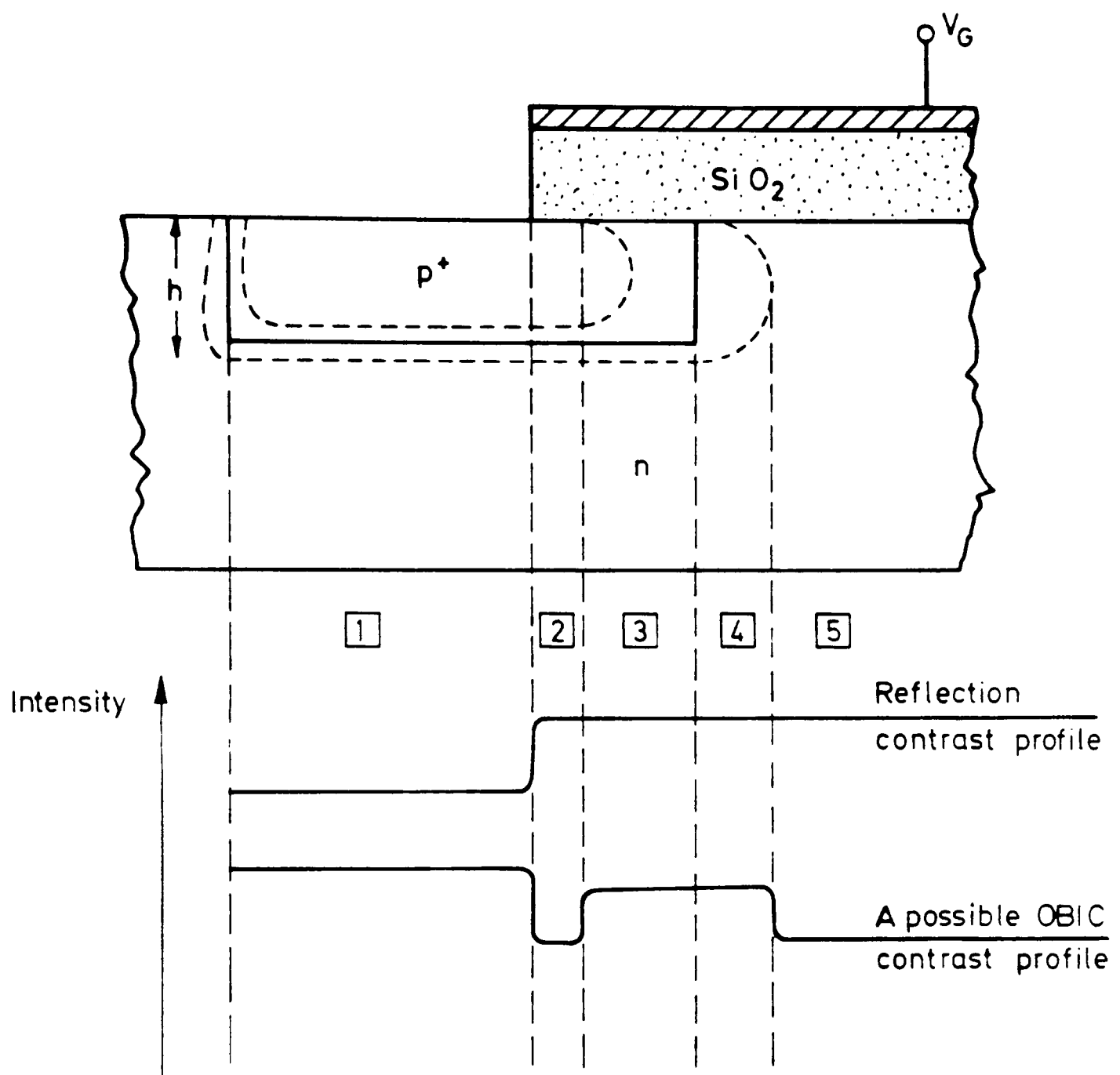


Fig.7.14

Depletion regions and a corresponding OBIC profile at the overlap of the gate and the  $p^+$  region

high as that obtained when focused on region (1) because of attenuation of the beam by the metal gate. This signal will also be lower than that obtained when the laser is focused on region (3) if the minority carrier diffusion length in the  $p^+$  material is low and if the number of defects at the Si-SiO<sub>2</sub> interface in region (3) is not large enough to cause significant reduction in the OBIC signal.

Clearly it is possible to have the OBIC profile bright-dark-bright-bright-dark from left to right, regions (1) to (5) in Fig. 7.14. The relative contrast profile in regions (2) to (4) depends on diffusion lengths and defect density.

### OBIC images of the gate in accumulation, depletion and inversion

Fig. 7.15(a) shows an OBIC image of the gate with  $V_g = V_j \approx 0V$ . The pinholes in the metal show up clearly in the OBIC image. The n-silicon under the gate is accumulated. When the laser is focused on the centre of the gate, fewer photocarriers diffuse to the regions (3) and (4) of Fig. 7.14 to contribute to the photogeneration current since these carriers have a larger distance to diffuse. Thus the centre of the gate is not as bright as the horizontal strips nearer the edges.

The bright horizontal strips which are separated from the edge of the gate probably correspond to depletion regions (3) and (4) of Fig. 7.14. This indicates that the  $p^+$  region extends several microns under the gate.

In Figure 7.15(b),  $V_g = -5.0V$ . The gate has become darker because the n-silicon region under the gate has started to become depleted. Hence photocarriers are recombining at interface defects and at defects below the interface in the n-silicon in contact with the depletion region, causing the gate to appear darker. In Figs. 7.15(c) and (d),  $V_g$  becomes progressively more negative and the gate becomes even darker. This is because the depletion region has extended over a greater area under the gate.

At  $V_g = -18V$ , inversion has clearly occurred, since the gate in Fig. 7.15(e)

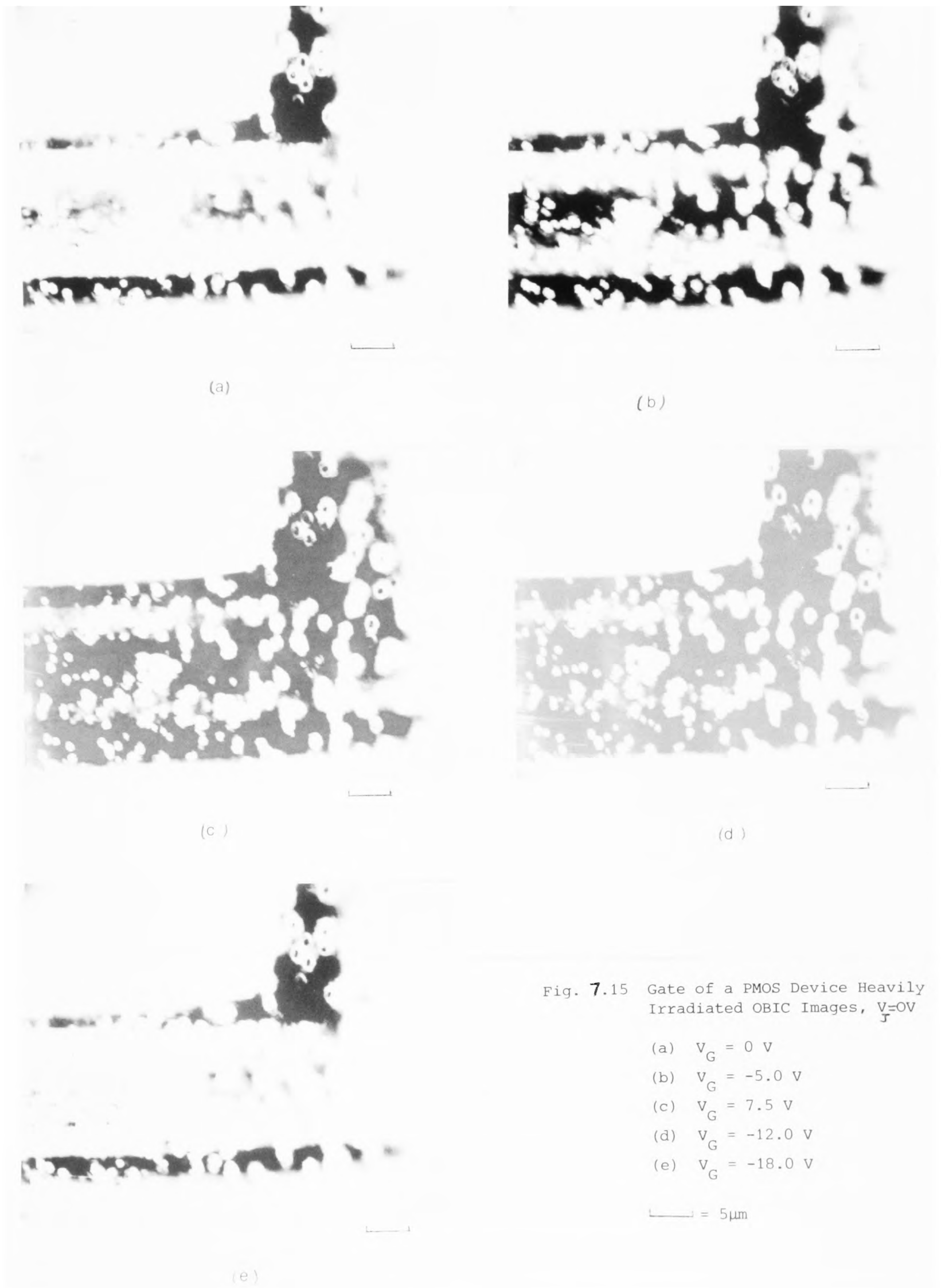


Fig. 7.15 Gate of a PMOS Device Heavily Irradiated OBIC Images,  $V_J=0\text{V}$

- (a)  $V_G = 0 \text{ V}$
- (b)  $V_G = -5.0 \text{ V}$
- (c)  $V_G = 7.5 \text{ V}$
- (d)  $V_G = -12.0 \text{ V}$
- (e)  $V_G = -18.0 \text{ V}$

5 μm

is bright again. The recombination of photocarriers has been reduced since the inversion layer has separated the interface defects from the depletion region. The centre of the gate in Fig. 7.15(e) is brighter than that in Fig. 7.15(a) where the n-silicon under the gate is accumulated. This shows the step between accumulation and depletion of Fig. 7.5.

### **7.3(c). Mask misalignment**

Fig. 7.16(a) shows the OBIC image of the gate of the heavily irradiated device, TOT202. On reverse biasing the source-drain junction with  $V_j = -1.0V$ , the depletion region at the  $p^+$  junctions is seen to extend as bright regions under the gate in Fig. 7.16(b). Placing a positive voltage of  $+28V$  on the gate with  $V_j = 0V$ , Fig. 7.16(c), also serves to deplete the  $p^+$  regions under the gate causing a high electric field in this region which can sweep out any photogenerated hole-electron pairs and contribute to the photocurrent.

The  $p^+$  depletion regions do not appear to extend uniformly under the gate and extend further on the right hand edges of the vertical portions of the gate. This greater overlap of the  $p^+$  regions and the gate on one side than the other could be due to misalignment of the gate metal as illustrated in Fig. 7.17. Clearly the method used in this experiment could be used to detect mask misalignment.

### **7.3(d). The source-drain current - gate voltage characteristic**

The source-drain current is measured by connecting the substrate to earth, a voltage supply to the source and an ammeter to the drain. A laser beam is focused on one area of the gate. Fig. 7.18 shows the plots of source-drain current,  $I_{SD}$ , versus gate voltage for a bias voltage of 100mV and for three different light intensities incident on the device. For a given gate voltage and source bias, increasing the intensity of light incident on the device increases the source-drain current. This is

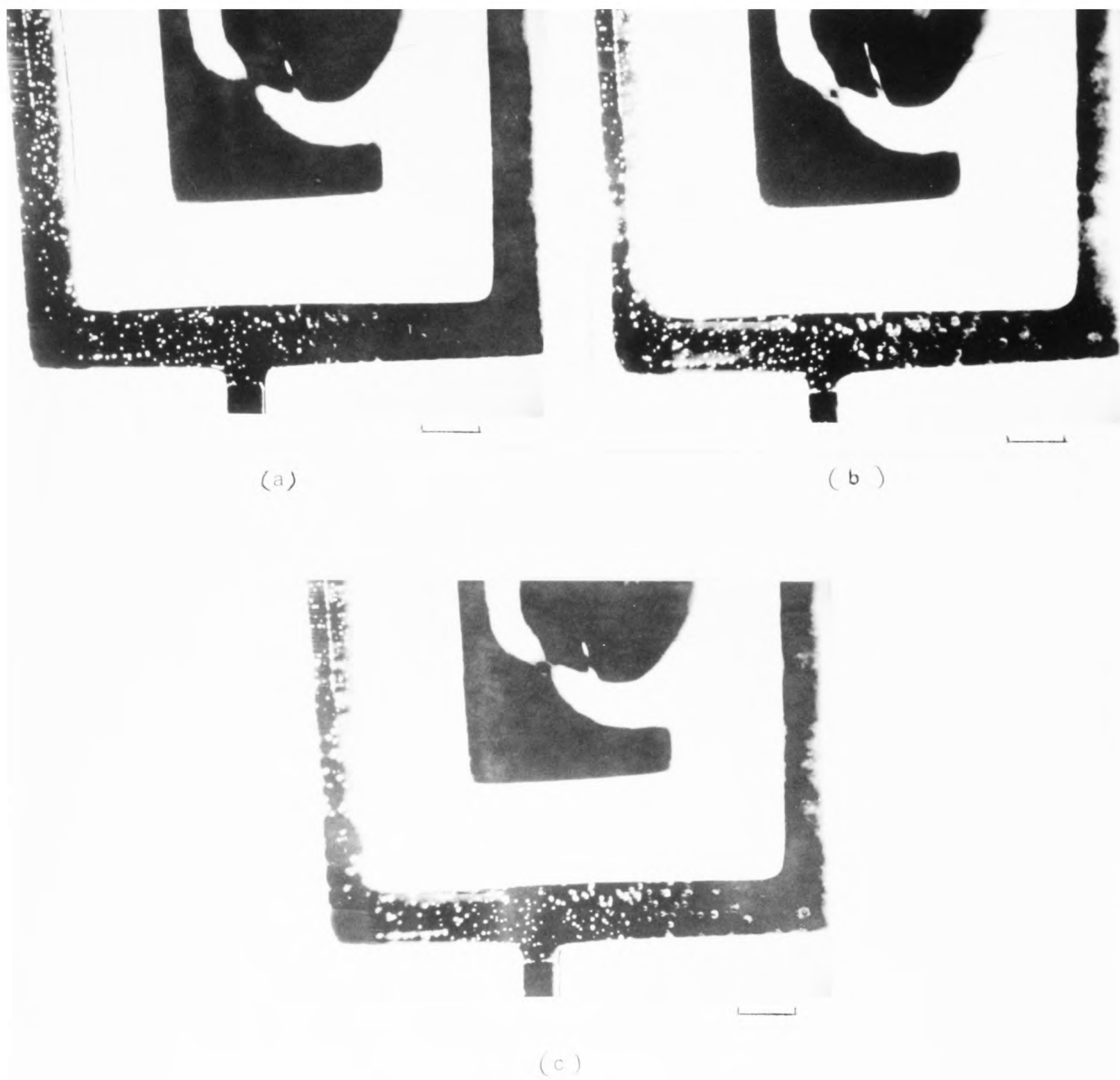


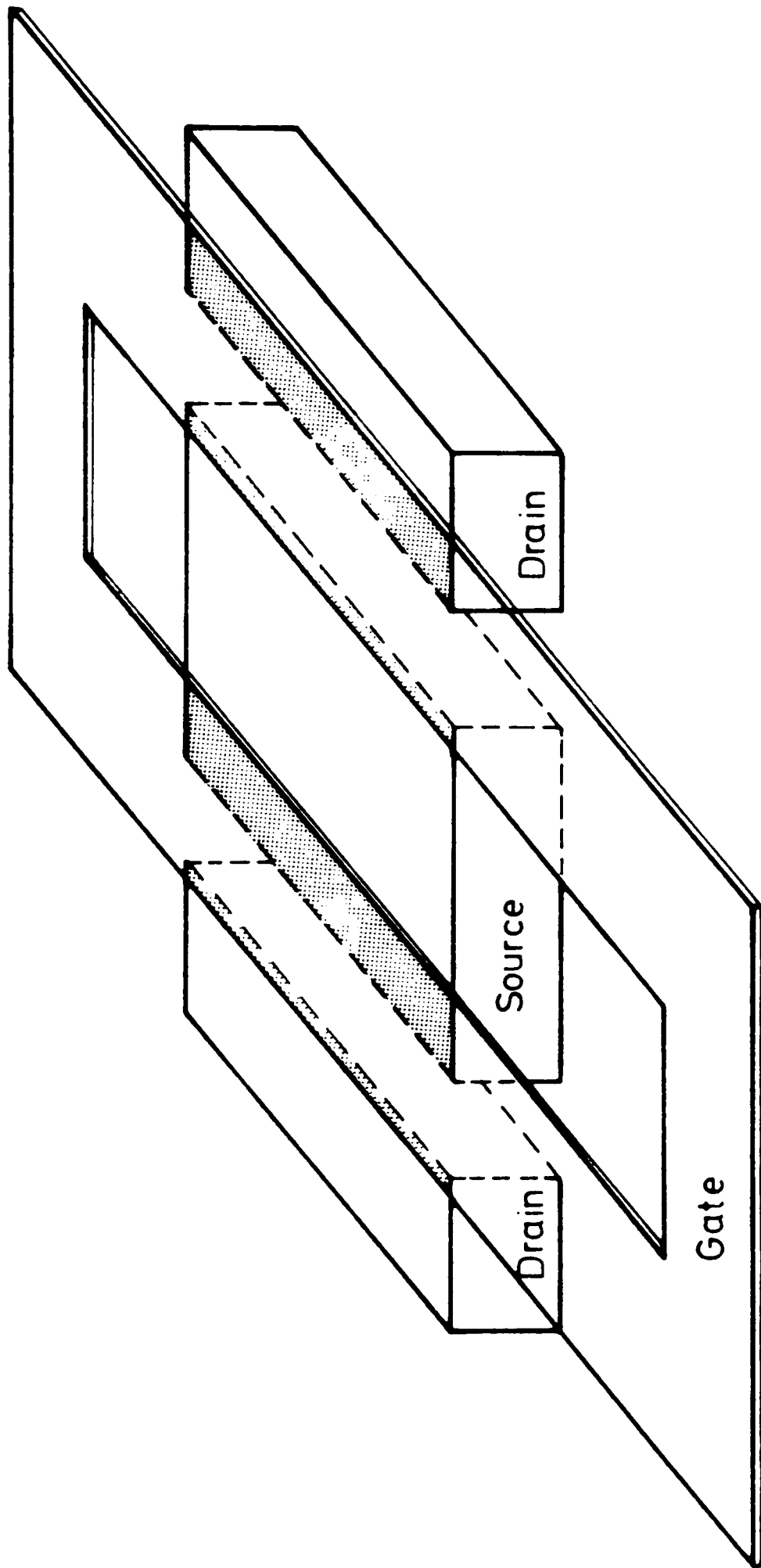
Fig. 7.16 PMOS Device, Heavily Irradiated, OBIC Images

(a)  $V_G = 0V$ ,  $V_J = 0V$

(b)  $V_G = 0V$ ,  $V_J = -1.0V$

(c)  $V_G = 28V$ ,  $V_J = 0V$

$\text{—} = 20\mu\text{m}$



**Fig.7.17**  
Misalignment of the gate. The overlap of the gate with the source and drain is not symmetrical

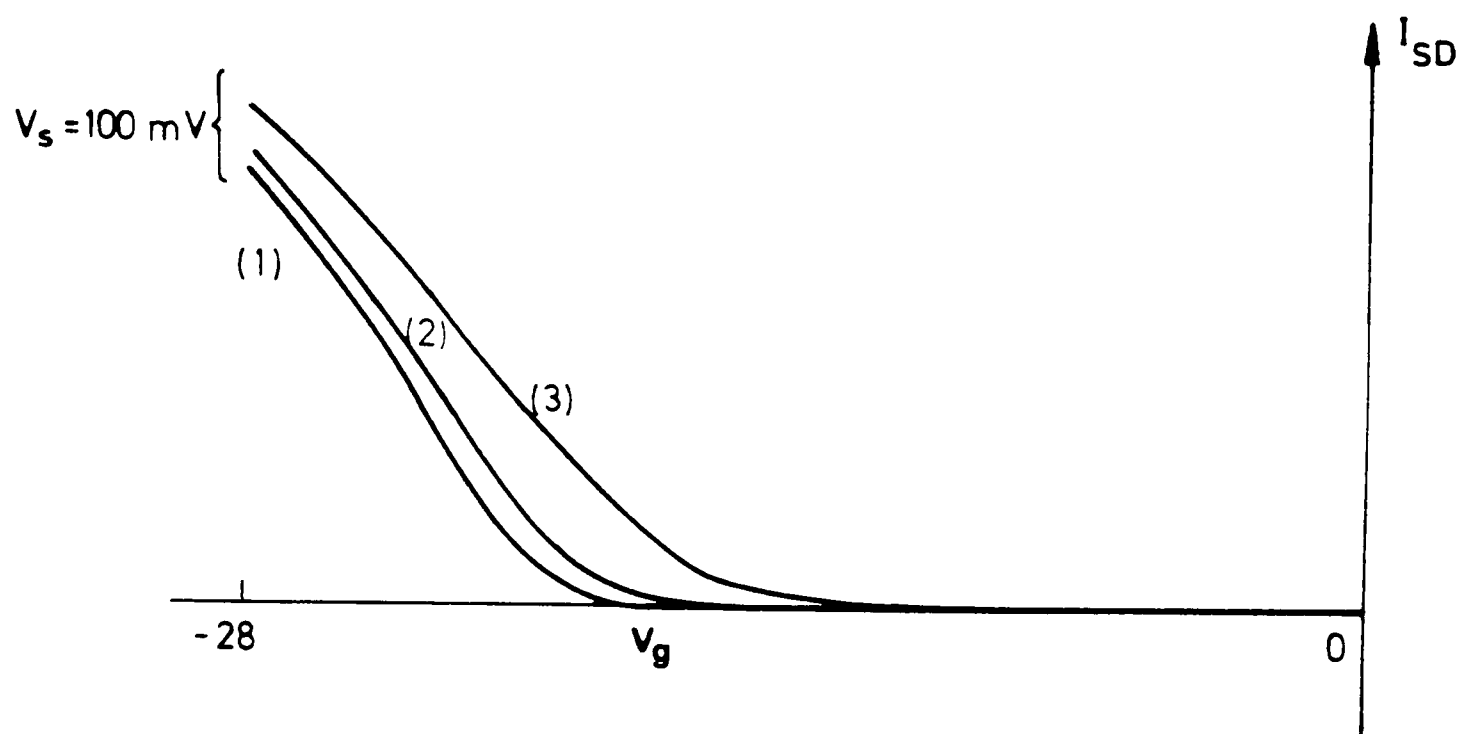


Fig.7.18

Plot of source - drain currents against gate voltage for the heavily irradiated pMOS device of Fig.7.10 with the laser beam focused on just one area of the gate

- (1) No laser light
- (2) Laser attenuated by a factor of 10
- (3) Full laser intensity

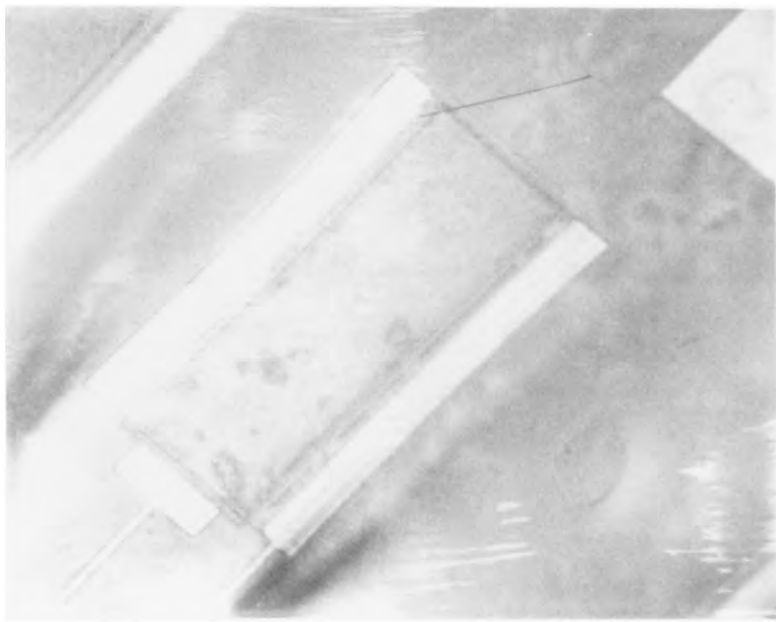
to be expected, since a greater light intensity means that more photoinduced charge carriers give rise to charge in the inversion layer.

### **7.3(e). An unirradiated polysilicon gate device**

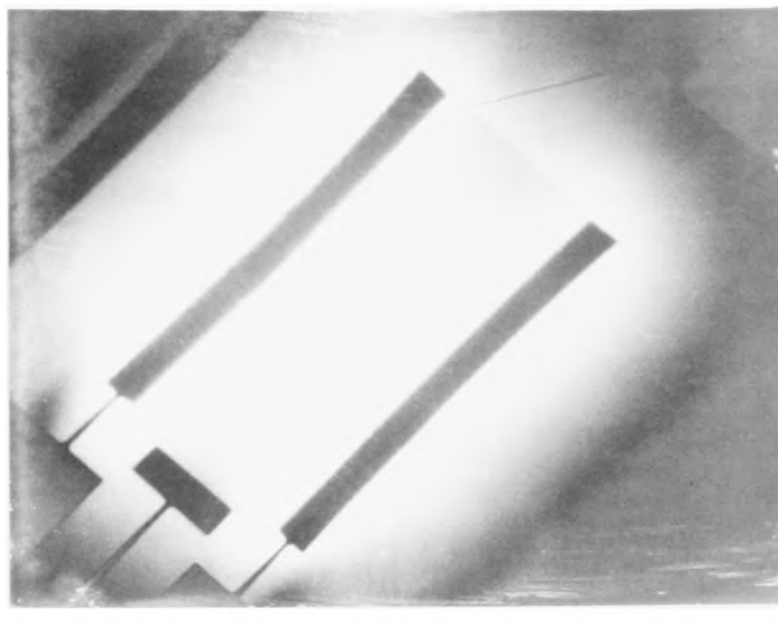
The reason why polysilicon gate devices are used is that these devices have some important advantages over aluminium gate devices. Impurities such as sodium are found in aluminium. Polysilicon may be used in a purer form. Also the use of polysilicon gate devices allows a self-aligned gate process to be used. This means that implantation to create the source and drain of a MOS device may be performed with the polysilicon gate already on the device. Uniform bombardment of the device means that the polysilicon gate is also bombarded, thereby increasing its conductivity. This avoids the problems encountered in MOS device fabrication, where the source and drain are doped before the aluminium gate is laid down. Thus gate alignment is an important concern in MOS device manufacture but not for polysilicon gate devices. A disadvantage of using polysilicon gate devices is that it is difficult to make such devices which are not susceptible to radiation damage.

The Type 1 reflection and OBIC images of a pMOS polysilicon gate device are shown in Figs. 7.19(a) and (b). The gate of this device is shown in larger magnification in Figs. 7.19(c) and (d). Again dark patches in reflection correspond to bright spots in the OBIC image. The 'honeycombed' regions on either side of the gate are the aluminium contacts to the source and drain.

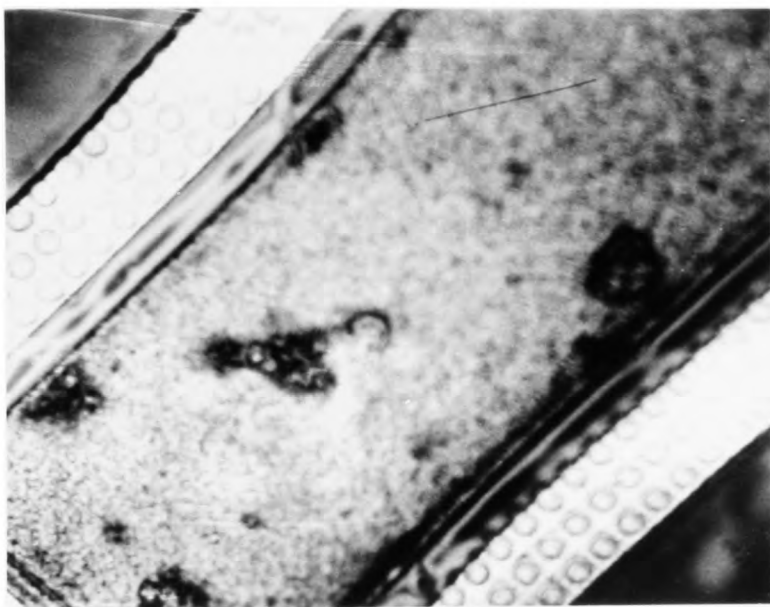
Fig. 7.20 shows the dark current gate voltage characteristic for several positive junction voltages. The very sharp peaks in these plots indicate that the positive charge trapped in the oxide is uniform. The position of the peaks does not occur at the same gate voltage when measurements are repeated. This is due to hysteresis in the device. This hysteresis is illustrated in Fig. 7.21 where the laser is focused on two separate points X1 and X2 on the gate and the  $I - V_g$  plot is repeated for each



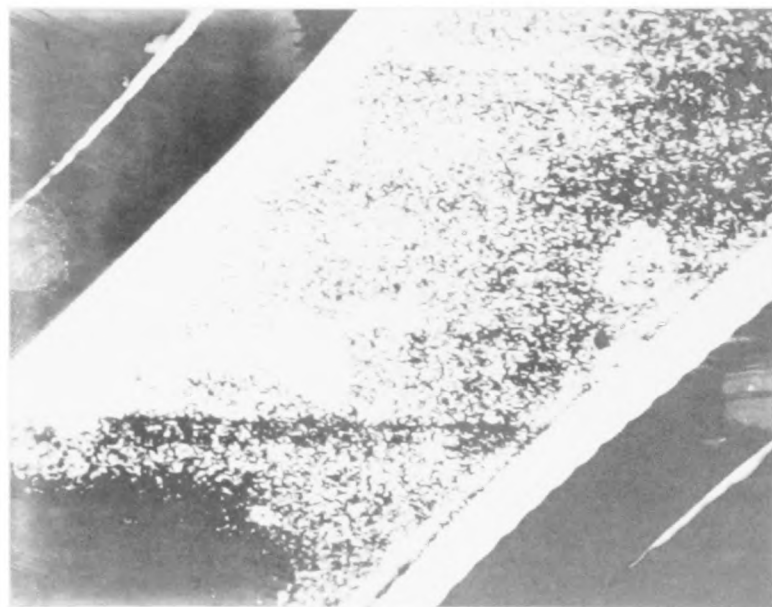
(a)



(b)



(c)



(d)

Fig. 7.19 P Channel Transistor of a LUVCMOS  
Polysilicon Gate Device  
 $V_G = V_D = 0V$

- |                       |   |              |
|-----------------------|---|--------------|
| (a) Type 1 Reflection | } | = 50 $\mu$ m |
| (b) OBIC Image        |   |              |
| (c) Type 1 Reflection | } | = 20 $\mu$ m |
| (d) OBIC Image        |   |              |

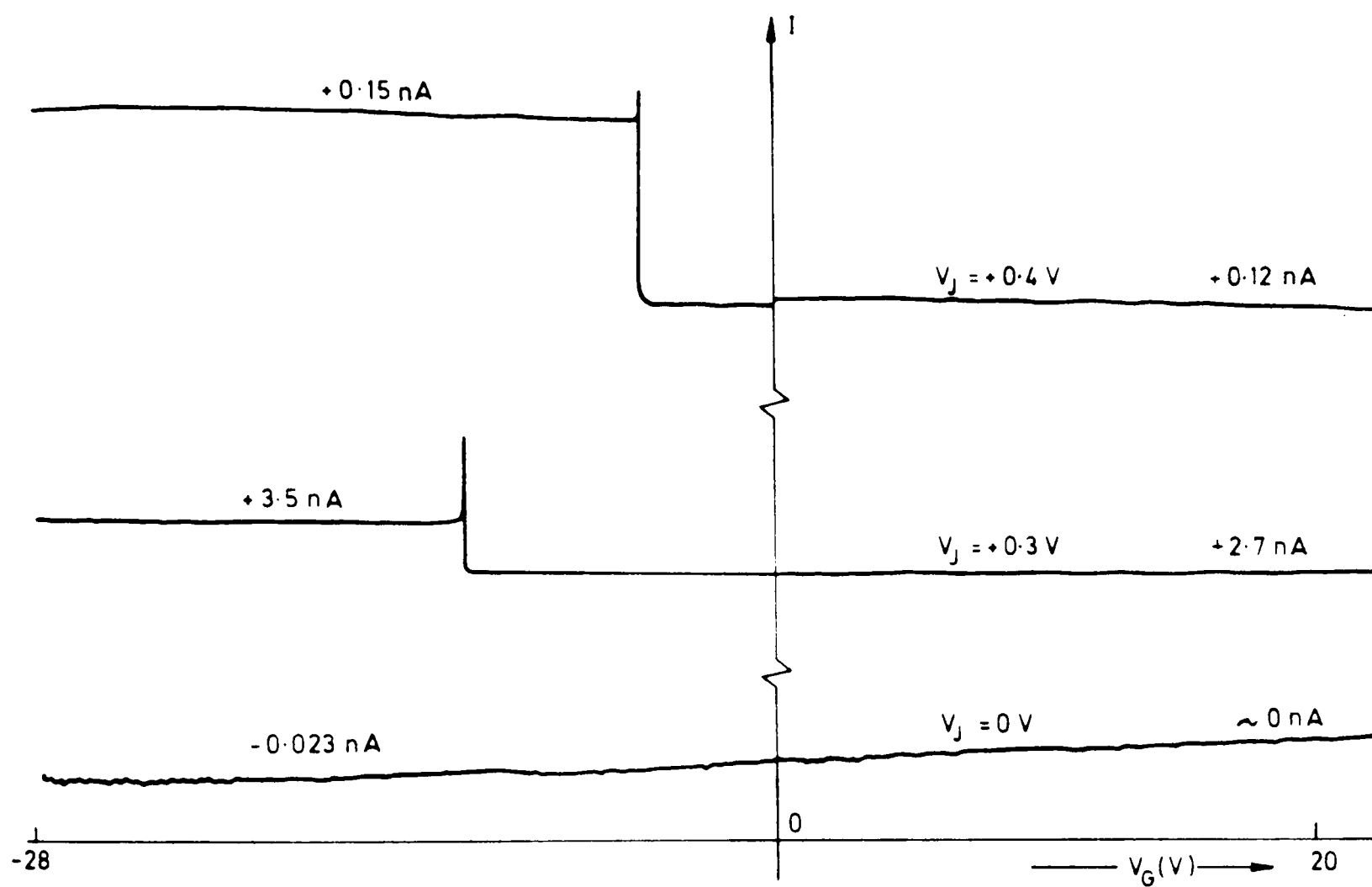


Fig.7.20

Plot of dark substrate current vs. gate voltage for the unirradiated p-channel device with a polysilicon gate

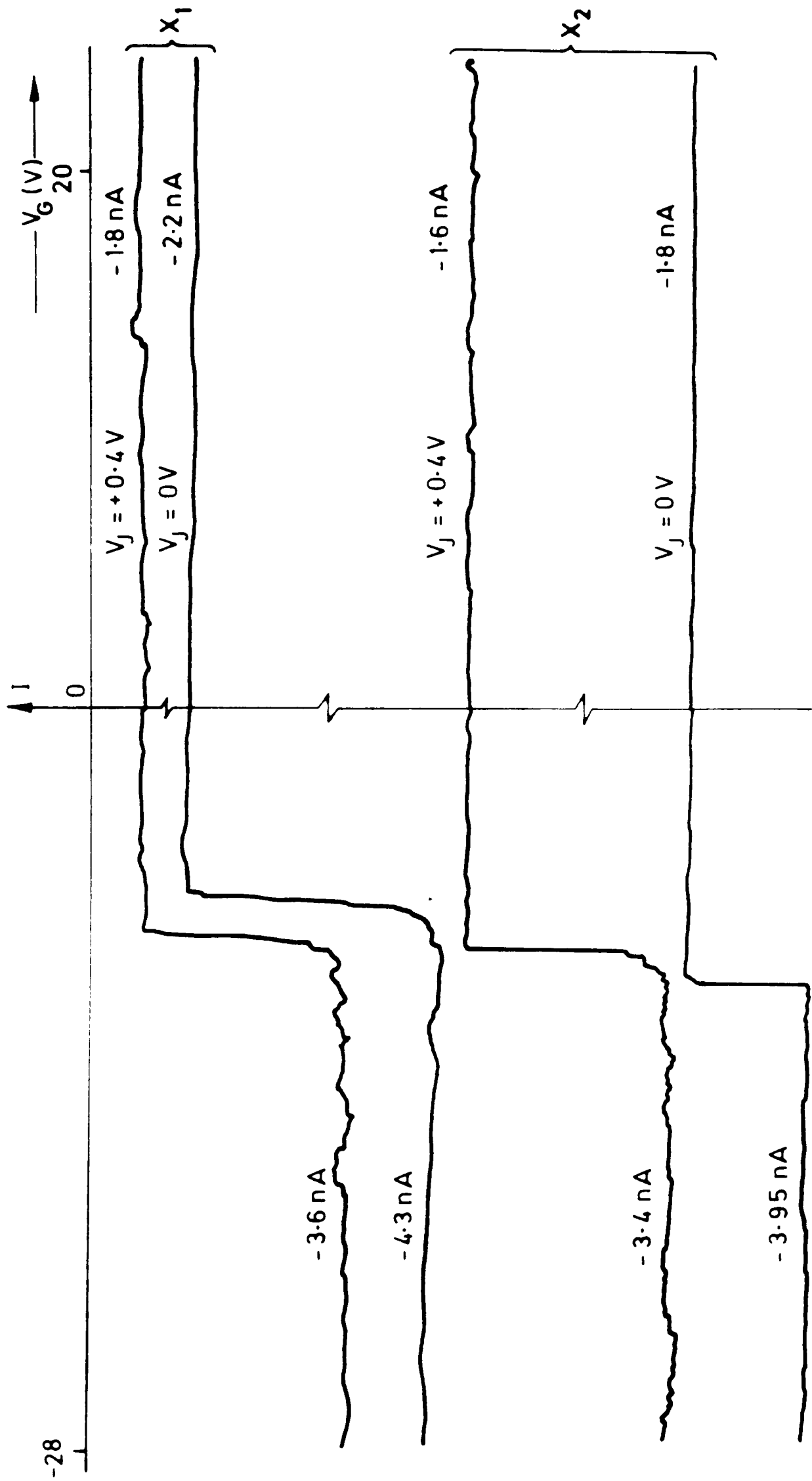


Fig. 7.21

Plot of substrate current vs. gate voltage for the unirradiated

p-channel device with a polysilicon gate using an unattenuated laser.

The laser is focused on two points  $X_1$ ,  $X_2$  of the gate.

point. The fact that these plots are not repeatable means that it is not possible to compare the degree to which positive charge is trapped in the oxide below these regions of the gate. This hysteresis may be due <sup>7.6</sup> to inadequate annealing of the device.

Recombination is not a significant process for the unirradiated polysilicon gate device with the unattenuated laser beam incident on the device since the light generated current swamps the dark current and a current bump is not observed. By attenuating the laser beam by a factor of 1000 and focusing on point X1 of the gate, the light generated current is of the same order of magnitude as the dark recombination current due to recombination at defects. Hence a current bump results as in Fig. 7.22.

## 7.4 CONCLUSIONS

This chapter demonstrates how the scanning optical microscope may be used to obtain qualitative information on the spatial distribution of trapped positive oxide charge and surface state density at the Si-SiO<sub>2</sub> interface of MOS devices. It also shows the increase in the number and spatial inhomogeneity of defects found when a MOS device is heavily irradiated. The problems encountered laying down the metallisation layer of a thin metal gate ( $\approx 0.12\mu\text{m}$ ) are illustrated by the resulting metal pinholes in the gate.

An additional feature of this method to examine the Si-SiO<sub>2</sub> interface is that one can observe any misalignment of the gate relative to the source and drain. The laser beam provides active interaction with the device being examined by causing photocarriers to be generated. Once generated they can recombine again or be separated in a depletion region or diffuse and possibly recombine en route. The doping level in the semiconductor material will affect the number of defects at the interface i.e. the number of recombination centres at which carriers may recombine.

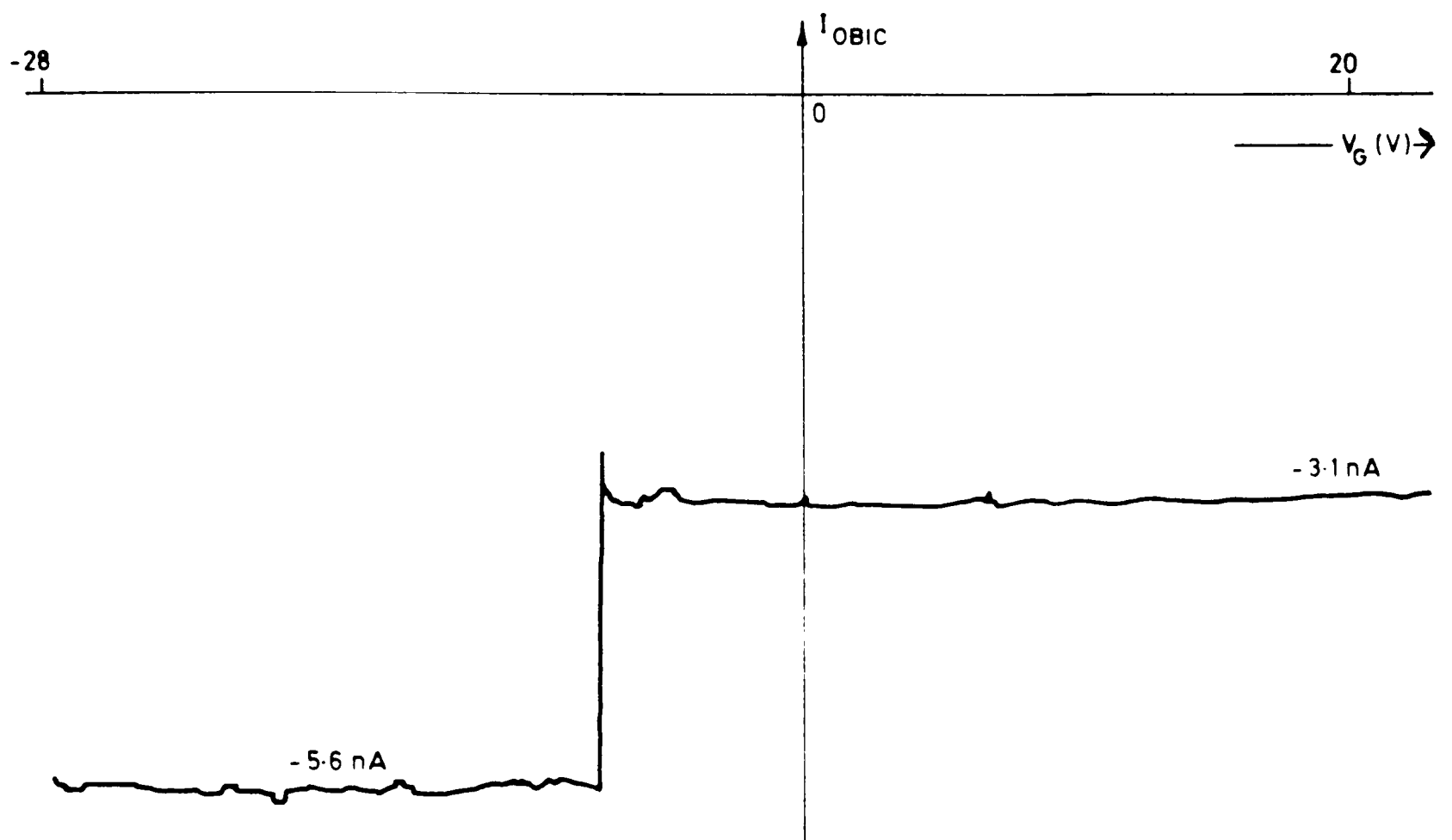


Fig.7.22

Plot of substrate current vs. gate voltage for the unirradiated p-channel device with a polysilicon gate. The laser beam is attenuated by a factor of 1000 and is focused on area  $X_1$  of the gate.

## **CHAPTER 8**

### **INFRARED AND PHOTOLUMINESCENCE** **IMAGING OF SEMICONDUCTOR DEVICES**

#### **8.1 INTRODUCTION**

Both infrared transmission and photoluminescence are important non-destructive techniques which may be used to image defects in semiconductor devices. Both methods may complement OBIC imaging. In addition these two methods have applications in device examination where OBIC imaging is not possible or convenient. These applications include the use of transmission microscopy to examine semiconductor wafers. Photoluminescence imaging may give very valuable information in the examination of both semiconductor wafers and devices without the need for contacts to be made to the specimen. This chapter considers the use of infrared transmission microscopy to examine gallium arsenide wafers. The theory of imaging using both photoluminescence and OBIC is also developed. This theory is particularly relevant in its application to the detection of defect depth.

#### **8.2 IMAGING WITH THE INFRARED SCANNING** **MICROSCOPE**

##### **8.2(a). Introduction**

Infrared radiation is used in many applications including night vision, astronomy and medicine. Infrared (IR) radiation is also widely used in many techniques useful for semiconductor and semiconductor device investigation. These techniques include investigation of die attach bonds, mask alignment and crystal structure inhomogeneities. IR microscopy instrumentation is limited by the transparency of

conventional optical glasses and the sensitivity of detectors used to wavelengths between about  $0.7\mu\text{m}$  and  $2.0\mu\text{m}$  <sup>8.1</sup>. The use of a scanned laser infrared microscope has been discussed <sup>1.2</sup> which operates at a wavelength longer than the  $1.2\mu\text{m}$  limit of photography. Current production of silicon wafers is so good that such wafers with crystal imperfections are not likely to reach the production line. However IR microscopy of in-process silicon wafers is still useful to detect highly non-uniform doping and surface irregularities. Crystal imperfections and wafer surface non-uniformities pose a much more serious problem for III-V and II-VI materials. A III-V material of particular concern is GaAs. To examine GaAs in transmission it is necessary to use incident radiation of a suitable wavelength such that GaAs transmits at this wavelength. Such a suitable wavelength involves the use of, for example, IR  $1.15\mu\text{m}$  radiation from a Helium-Neon laser. Hence the SOM is a very useful tool to examine IR transmission images of GaAs. In addition sub-band-gap OBIC of GaAs devices is possible at this wavelength. Since IR radiation penetrates deeper into a semiconductor material than visible light IR microscopy is useful to investigate defects which lie physically deep below the semiconductor surface as well as deep defects which lie in the band gap of the material. This chapter presents IR transmission images of liquid encapsulated Czochralski (LEC) GaAs showing the non-uniformity in the absorption of the material. In addition OBIC images of a GaAs device are discussed. The use of IR microscopy to examine die attach bonds is introduced also.

### **8.2(b). Resolution and experimental details**

The experimental work was performed using a transmission scanning microscope such that imaging could be carried out using one of two lasers, both helium-neon, producing radiation of wavelengths  $0.6328\mu\text{m}$  (Energy = 1.95 eV) and  $1.15\mu\text{m}$  (Energy = 1.08 eV). Careful alignment of the system was carried out such that the

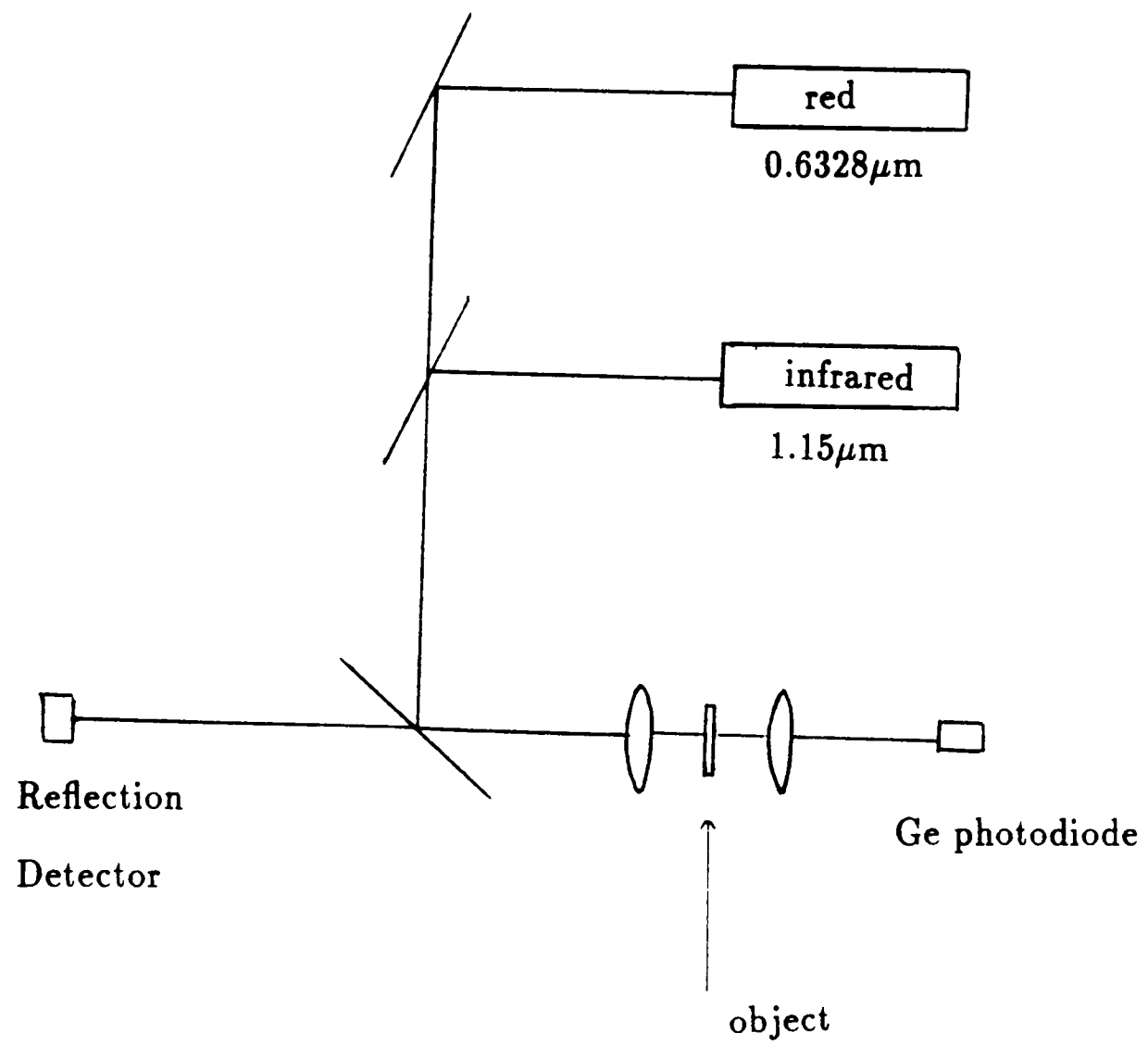


Fig. 8.1 Experimental layout

same area of the specimen was illuminated by each laser. A standard long working distance objective lens with a numerical aperture of 0.6 was used. A schematic of the experimental layout is shown in Fig.8.1. A photograph of this layout is shown in Fig.1.4. It is important that the specimen surface be cleaned and polished before examination. ( $1.15\mu\text{m}$ ) IR images are detected using a germanium photodiode. This is a suitable detector in that it operates at room temperature and detects the longer wavelength IR radiation. Transmission images of an edge are obtained using both beams. The resolution using the IR ( $1.15\mu\text{m}$ ) and red ( $0.6328\mu\text{m}$ ) beams is compared using a transmission electron microscope grid to provide sharp metal edges. Using red light the transmission image of the edge appears approximately  $0.6\mu\text{m}$  wide. On using IR radiation the same edge appears wider in transmission, about  $1\mu\text{m}$  wide. These widths are of the order of the wavelengths being used indicating correct functioning of the microscope.

### 8.2(c). Infrared transmission imaging of GaAs

A limiting factor for the development of GaAs integrated circuit technology is the uniformity and reproducibility of LEC semi-insulating (SI) GaAs material<sup>8.2</sup>. Thus there is intense current interest in the fabrication of this material. The LEC growth method<sup>8.3</sup> involves pulling the crystal from the melt as it grows allowing the GaAs crystal to grow onto a seed crystal which is lowered into the molten GaAs. The liquid encapsulation in the form of a layer of  $B_2O_3$  which floats on the surface of the GaAs melt is used to prevent As evaporation. The nominally undoped GaAs has high resistivity due to the presence of the EL2 deep donor at 0.75eV below the conduction band edge. EL2 is known<sup>8.4</sup> to be an intrinsic point defect of GaAs and to be associated with an excess arsenic stoichiometry. Infrared imaging of GaAs slices may be used to study the inhomogeneity in the absorption of the material. Non-uniformities in IR absorption have been shown to correlate very closely with

non-uniformities observed for dislocations <sup>8.5</sup> as revealed by KOH etching of the surfaces.

Inhomogeneity in the absorption of the material may have severe consequences for the uniformity of parameters of FETs, for example, formed by direct implantation into undoped SI GaAs. IR transmission imaging is non-destructive and may give valuable information on the quality of GaAs substrates. A sample of LEC GaAs is mounted in the SOM. Transmission and reflection images are obtained using radiation from both lasers. Consider focusing on the upper surface of the sample. Fig. 8.2(a) shows an IR reflection image of the GaAs. A similar reflection image is obtained in Fig. 8.2(b) using red light. The dark spots, of course, appear with higher resolution in the red light image. Fig. 8.2(c) gives the corresponding IR transmission image. Surface contamination spots appear dark in both transmission and reflection images. Some spots which are dark in reflection appear bright in transmission. This suggests that these spots are areas where there is non-uniformity in the absorption of the material. The dark lines in the transmission image are not present in reflection and are sharply in focus when focused on the upper rather than the lower surface. This suggests that the cause of these line patterns is not associated with the upper surface but occurs just below this surface.

Now consider focusing on the back surface of the sample. The infrared reflection image of Fig. 8.3(a) shows some of the line detail of Fig. 8.2(c). Fig. 8.3(b) gives the corresponding transmission image. The dark areas in the reflection image of Fig. 8.3(a) appear bright in transmission pointing to inhomogeneity in the absorption of the material. The line pattern evident in Fig. 8.2(c) is possibly due to lattice discontinuities during crystal growth.

It is important to compare reflection and transmission images to understand the later images because a surface defect may easily be mistaken for internal structure. This points to the importance of well polished samples for IR microscopy. IR trans-



**Fig.8.2**

Images of a LEC GaAs sample focused on the upper surface.

(a) Infrared ( $1.15\mu\text{m}$ ) Type 1 reflection image

(b) Red ( $0.6328\mu\text{m}$ ) Type 1 reflection image

(c) Infrared ( $1.15\mu\text{m}$ ) transmission image

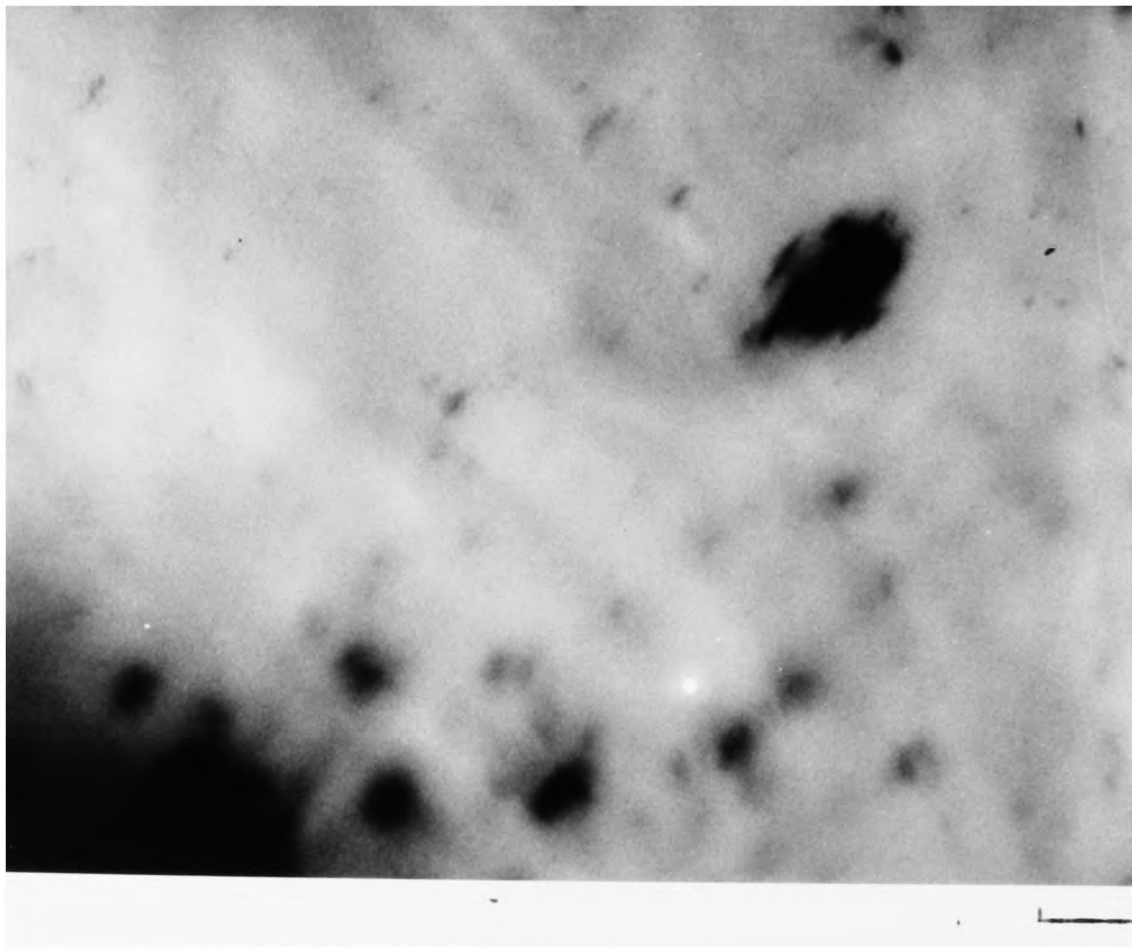


Fig.8.3

Images of a LEC GaAs sample focused on the lower surface.

(a) Infrared ( $1.15\mu\text{m}$ ) Type 1 reflection image

(b) Infrared ( $1.15\mu\text{m}$ ) transmission image

mission images may be useful in determining whether substrate inhomogeneities or device processing stages are responsible for rejection of the final device.

IR transmission images may also be an excellent guide in the comparison of wafer quality taken from different sections of the ingot under examination. Such images taken of a range of wafers taken from adjacent sites in the ingot could yield useful information on the growth behaviour of the crystal.

#### 8.2(d). Infrared sub-band-gap photocurrent images of a GaAs device

Conventional OBIC imaging involves injecting carriers into the semiconductor material using a laser whose wavelength is such that its quantum energy is greater than the material's band gap. Sub-band-gap OBIC involves the use of a source whose quantum energy is less than the band gap of the semiconductor. Now there is insufficient energy to excite carriers directly from the valence to conduction bands without a two-stage excitation process via an intermediate energy level. This level could be due to a defect or contaminant in the material. Thus an OBIC signal is obtained only if such defects are present in the material. Clearly sub-band-gap light is not absorbed until it reaches a defect. In the absence of defects it is transmitted. Thus sub-band-gap OBIC may be used to image defects or contaminants deep below the surface of a device which would not be imaged in above-band-gap conventional OBIC.

Previous work <sup>8.6</sup> has shown images of a GaAs light-emitting diode (LED) where such defects are imaged and their effect on the light emitted from the device is investigated. This work shows conventional and sub-band-gap images. There are bright spots in the sub-band-gap image. This detail does not appear in either reflection or above-band-gap OBIC images. This suggests that the defects responsible for these spots occur below the surface of the material and below the absorption

depth of red light in GaAs. This work also gives an emitted light image of the LED. This image shows a region of low emissivity which corresponds directly with the bright spots seen in the sub-band-gap OBIC image. This highlights the significance of sub-band-gap OBIC imaging in that conventional OBIC or reflection imaging would not have imaged these defects.

### **8.3 PHOTOLUMINESCENCE OF DEFECTS**

#### **8.3(a). Introduction**

Fast, non-destructive means for evaluating semiconductor wafers and wafer processing can allow rapid progress to be made in both wafer and device development. A photoluminescence measurement is particularly appropriate for this purpose. Photoluminescence may be used to examine unprocessed wafers. No contacts to the sample are required. Also information is obtained from the top few microns of the wafer where the devices will be built.

Photoluminescence can give information on sample purity. Impurities can reduce the efficiency of a luminescent process by providing unwanted radiative (or nonradiative) paths for recombination. Photoluminescence is particularly useful in the determination of the material characteristics most important for light-emitting diodes e.g. relative external quantum efficiency and spectral energy distribution. This technique may also be useful in detecting defects in other semiconductor devices such as semiconductor lasers.

Cathodoluminescence (CL) studies using the scanning electron microscope are frequently used to image and study electrically active defects in semiconductors. CL imaging has an advantage over the electron beam induced current method (EBIC) in that the only sample preparation required for CL work is polishing of the surface. EBIC requires the fabrication of a Schottky contact or a p-n junction <sup>8.7-8.9</sup>. The

development of the scanning optical microscope has allowed the optical analogue of CL i.e. the scanning photoluminescence technique to be developed.

One of the beauties of photoluminescence imaging of a device is that no external contacts to the device are necessary. This should allow examination of the device at many stages during production and give a means of evaluating each processing stage. However photoluminescence may not be used to examine all semiconductor materials in that not all materials are photoluminescent or their luminescence efficiency may be low.

Photoluminescence may be stimulated by a focused laser beam which is scanned over the sample in a scanning optical microscope arrangement. Previous work <sup>1,10</sup> has examined a GaAsP sample using photoluminescence in a scanned-laser microscope. The luminescence is detected by a photomultiplier tube which collects all the photoluminescence wavelengths and whose amplified output is used to modulate the electron beam of a display oscilloscope which is scanned in synchronism with the focused laser beam. Thus the spatial information on a given luminescent feature may be found. This spatial information may give information on wafer crystal perfection and impurity distribution. For example H.J. Hovel and D. Guidotti <sup>8,10</sup> have made correlations of photoluminescence with defect densities in semi-insulating GaAs.

Previous work <sup>8,11</sup> has introduced the theory of photoluminescence imaging of a point defect which lies below the surface of a semiconductor. This chapter considers this theory in more detail as the light beam of a SOM is scanned over the point defect. The factors affecting the resolution are investigated. In addition the photoluminescence and OBIC images of the same defect in a Schottky barrier or shallow p-n junction device will be considered. The surface in this case is modelled as having an infinite surface recombination velocity. It will be shown that from the photoluminescence and OBIC contrast information it is possible to deduce the depth of a point defect given a value of the bulk diffusion length of the semiconductor.

### **8.3.(b). The photoluminescence image of a defect**

Consider a point defect at depth,  $a$ , below the surface of a semi-infinite n-type semiconductor with surface recombination velocity,  $s$ . On scanning a light spot across the semiconductor surface there is an excess free carrier distribution,  $p(r)$ . The photoluminescence signal is given by

$$PL = \int_V A(z) \left( \frac{\tau}{\tau_r} \right) p(r, z) dV \quad (8.1)$$

where  $V$  is the semi-infinite volume of the material and a constant of proportionality has been omitted which takes surface reflection losses and the light collection efficiency into account. The internal quantum efficiency of the material is given by the ratio of the total recombination rate,  $\tau$ , to the radiative recombination rate,  $\tau_r$ .

The total recombination rate is given by

$$\tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}} \quad (8.2)$$

where  $\tau_{nr}$  is the non-radiative recombination rate and it is assumed that radiative and non-radiative processes occur simultaneously. Löhnert and Kubalek<sup>8,8</sup> have already discussed the two reasons for contrast in cathodoluminescence studies. These are equally applicable in the photoluminescence case. In the first the photoluminescence contrast is due to variations in  $\tau_r$  at essentially constant  $\tau$ , ( $\tau_r \gg \tau_{nr}$ ). In this case we would not expect any OBIC contrast if a suitable junction could be made. The second mechanism concerns spatial variation in  $\tau_{nr}$  and hence also in  $\tau$ . This is the more usual situation which gives contrast on both photoluminescence and OBIC studies. We shall restrict ourselves to this case in the following discussions.

The factor  $A(z)$  in Eq.8.1 represents the attenuation of the luminescence light as it reaches the surface of the material. This factor may be calculated as <sup>8.12</sup>

$$A(z) = \int_0^{\theta_c} \exp - \left( \frac{\alpha_l z}{\cos \theta} \right) \sin \theta d\theta \quad (8.3)$$

where  $\alpha_l$  is the attenuation coefficient of the luminescence radiation and  $\theta_c$  is the critical angle at the semiconductor-air interface. Jakubowicz<sup>8,9</sup> has mentioned that the critical angle is often sufficiently small to allow  $A(z)$  to be accurately described by  $\exp -\alpha_l z$ . This absorption is neglected altogether by some authors<sup>8,13</sup>.

The symmetry of the problem suggests finding the solution in a cylindrical coordinate system<sup>4,8</sup>. This allows the photoluminescence signal to be written as

$$PL \sim \int_0^\infty A(z) \bar{p}(0, z) dz \quad (8.4)$$

where  $\bar{p}$  is the Fourier-Bessel transform of  $p$  as introduced in Chapter 4. The problem now reduces to finding an expression for  $\bar{p}(0, z)$  in the presence of a point defect. In the absence of any defect the excess minority carrier distribution is, under low injection conditions, the solution of the steady state diffusion and continuity equations as introduced in Chapter 4. The boundary conditions for  $p(r, z)$  are

$$\frac{\partial p}{\partial z} = sp \quad \text{at } z = 0 \quad ; \quad p = 0 \quad \text{at } z \rightarrow \infty \quad (8.5)$$

where  $s = v_s/D$ .  $D$  is the minority carrier diffusion coefficient,  $v_s$  is the surface recombination velocity and  $z=0$  corresponds to the semiconductor surface.

A solution for  $\bar{p}_0$  in the absence of a defect has been found<sup>4,8</sup> as

$$\bar{p}_0(\nu, z) = \int_0^\infty G(\nu, z|z') \bar{g}(\nu, z') dz' \quad (8.6)$$

where  $g$  is the generation term as used in Chapters 4 and 5,

$$g(r, z) = g_0 \frac{\alpha}{\pi c^2} \exp - \left( \frac{r^2}{c^2} \right) \cdot \exp -\alpha z \quad (8.7)$$

$G$  is the Green's function<sup>4,8</sup> given by

$$G(\nu, z|z') = \frac{1}{\beta} \left\{ \exp -\beta|z - z'| + \left( \frac{\beta - s}{\beta + s} \right) \exp -\beta(z + z') \right\} \quad (8.8)$$

and  $\beta^2 = \nu^2 + 1/L^2$  where  $L$  is the minority carrier diffusion length.

Now consider the case of a point defect located at  $(r_0, a)$ . Consider the modified generation function,  $g'$ , due to the defect given by substitution of Eq.5.9 into Eq.5.1. We may now write an expression for the photoluminescence signal in the presence of a defect by substituting Eq.8.6 into Eq.8.4 with  $\bar{g}$  replaced by the Fourier-Bessel transform of the modified generation function. This gives

$$PL \sim \int_0^\infty f(z') \bar{g}'(0, z') dz' \quad (8.9)$$

where

$$f(z') = \int_0^\infty A(z) G(0, z|z') dz \quad (8.10)$$

If we now substitute the appropriate expression for  $\bar{g}'(0, z')$  one may write the photoluminescence signal in the presence of a defect located at  $(r_0, a)$  as

$$PL(r_0) \sim \int_0^\infty f(z') \bar{g}(0, z') dz' - \gamma f(a) p_0(r_0, a) \quad (8.11)$$

where the first term represents the luminescence in the absence of the defect and the second the reduction in signal due to the presence of the defect. We may now introduce a contrast function,  $C_{PL}(r_0)$ , in an entirely analogous fashion to OBIC and EBIC studies as

$$C_{PL}(r_0) = \left\{ \frac{\gamma f(a)}{\int_0^\infty f(z') \bar{g}(0, z') dz'} \right\} p_0(r_0, a) \quad (8.12)$$

Thus the resolution in photoluminescence is determined by the shape of the function  $p_0(r, z)$  evaluated at  $z = a$  multiplied by the term in brackets. The function  $p_0(r, z)$  is easily obtained by taking the inverse Fourier-Bessel transform of Eq. 8.6.

This gives <sup>4,8</sup>

$$p(r, z) = \frac{g_0 \alpha}{2 \pi D} \cdot \int_0^\infty \left\{ \exp -\alpha z - \left( \frac{\alpha + s}{\beta + s} \right) \exp -\beta z \right\} \frac{\exp(-\nu^2 c^2/4)}{\beta^2 - \alpha^2} J_0(\nu r) \nu d\nu \quad (8.13)$$

In particular Fig. 8.4 gives the form of the free carrier distribution for the cases of zero and infinite surface recombination velocities. The boundary conditions of the problem mean that the carrier distribution and hence the contrast will peak below the semiconductor surface for non-zero surface recombination velocity. The parameters chosen for these plots correspond to the absorption of 752 nm radiation from a krypton laser in GaAs <sup>8.14</sup>.

### 8.3(c). OBIC imaging of a point defect

If one restricts one's attention to the case of infinite surface recombination velocity one may consider the surface to be a charge collecting Schottky barrier allowing an OBIC image to be formed. The signal detected in this case may be written

$$I = 2 \pi q D \int_0^\infty \frac{\partial p}{\partial z}(r, z) \Big|_{z=0} r dr \quad (8.14)$$

where  $q$  is the electronic charge, or alternatively in terms of the Fourier-Bessel transform we can write this equation as

$$I = 2 \pi q D \frac{\partial \bar{p}}{\partial z}(0, z) \Big|_{z=0} \quad (8.15)$$

Using the expression for  $\bar{p}$  of Eq.8.6 and considering a point defect one may obtain an expression for the OBIC current in the presence of the defect as

$$I(r_0) = 2 \pi q D \left[ \int_0^\infty m(z') \bar{g}(0, z') dz' - \gamma m(a) p_0(r_0, a) \right] \quad (8.16)$$

with

$$m(z') = \frac{\partial G}{\partial z}(0, z|z') \Big|_{z=0} \quad (8.17)$$

where the second term represents the decrease in collected current due to the increased recombination at the defect. The contrast function in this case may be written as

$$C_{OBIC}(r_0) = \left\{ \frac{\gamma m(a)}{\int_0^\infty h(z') \bar{g}(0, z') dz'} \right\} p_0(r_0, a) \quad (8.18)$$

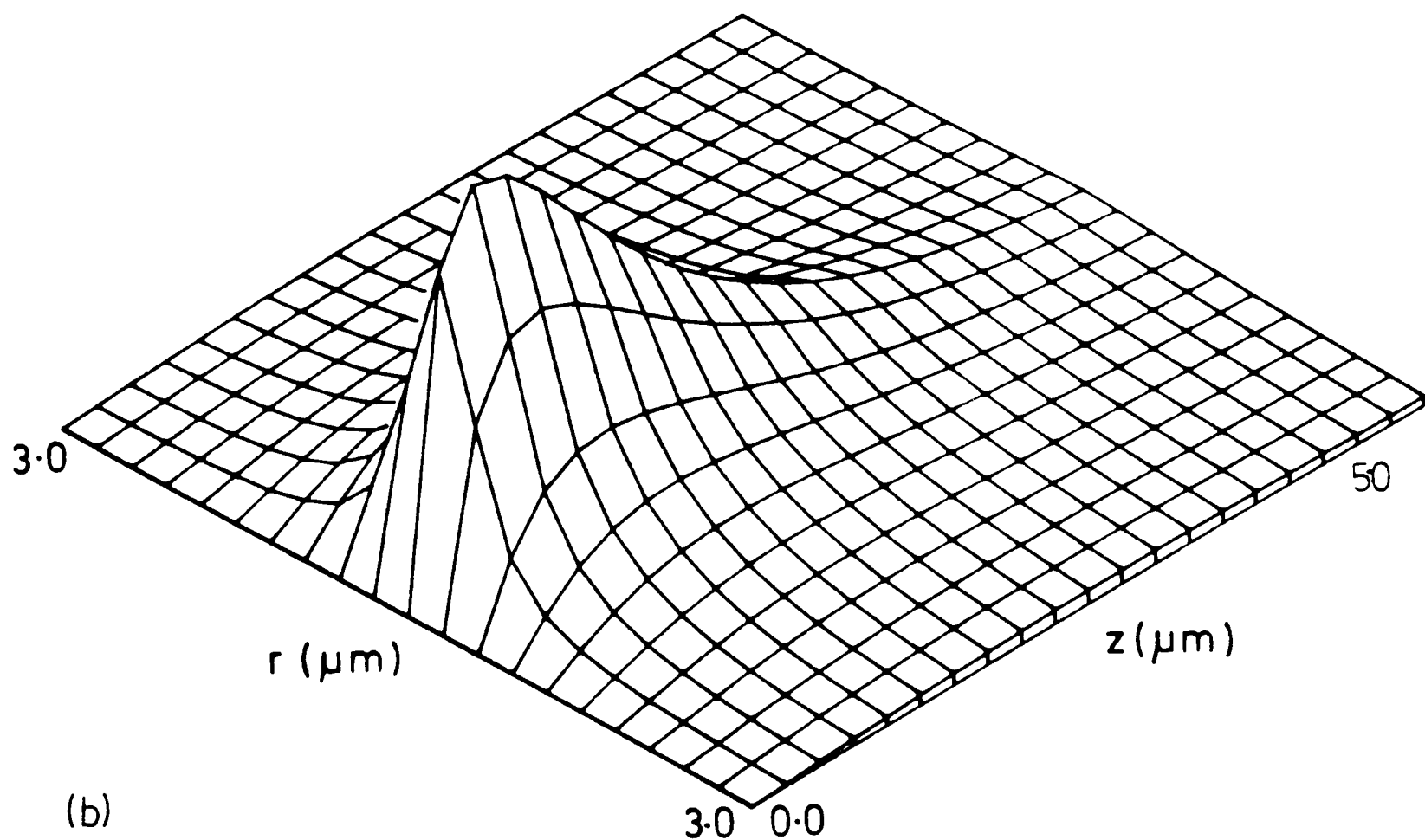
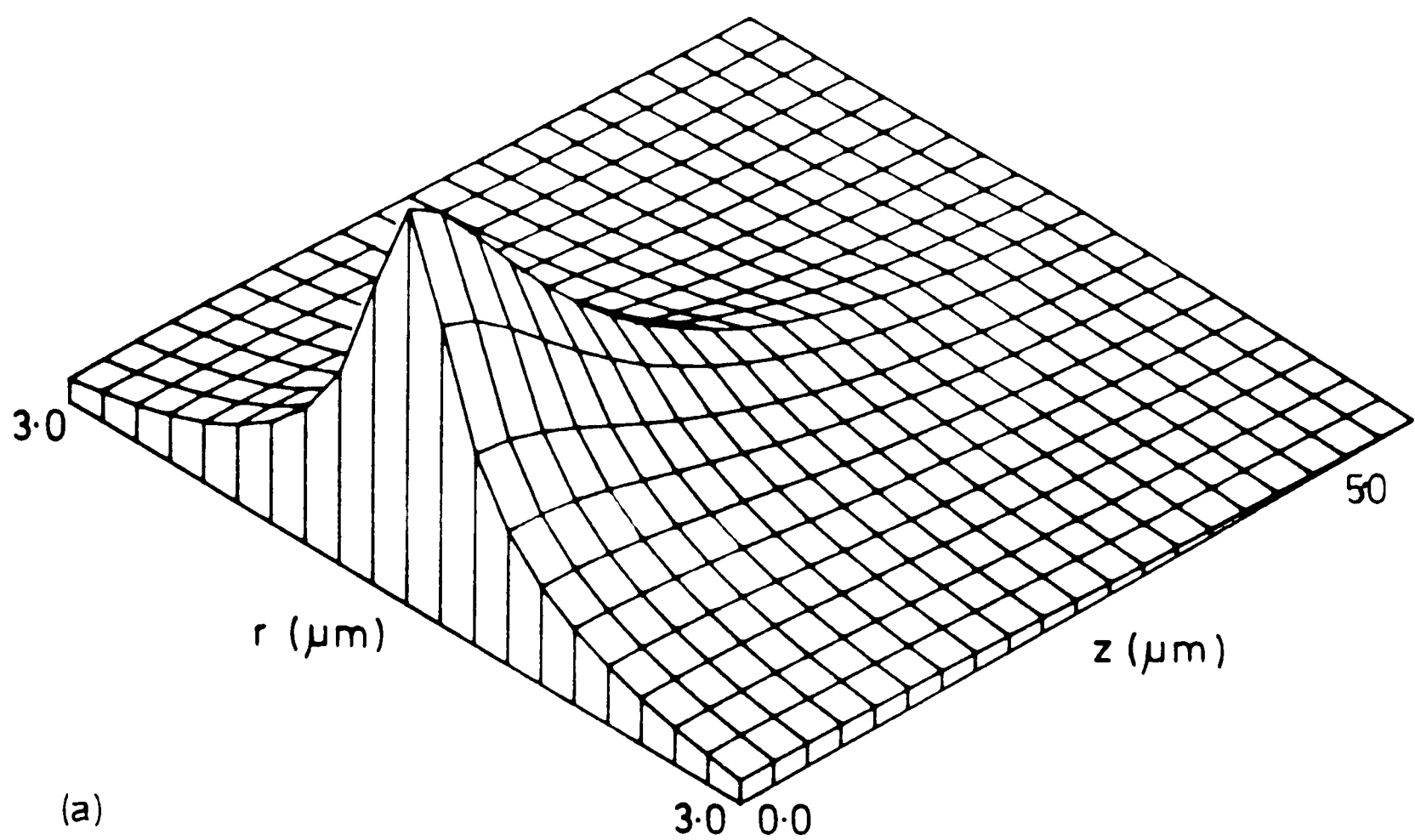


Fig.8.4

The distribution of free carriers for the case of (a) zero and (b) infinite surface recombination velocity. The curves are for the case of  $c = 0.25\mu\text{m}$ ,  $\alpha = 1\mu\text{m}^{-1}$  and  $L = 5\mu\text{m}$

Note that the OBIC contrast is primarily determined by  $p_0(r_0, a)$  in exactly the same way as for the photoluminescence contrast.

### **8.3(d). Comparison of contrast curves for photoluminescence and OBIC imaging**

If one follows 't Hooft et al <sup>8.13</sup> in neglecting the absorption term,  $A(z)$ , of Eq.8.3 for photoluminescence imaging one may obtain an expression for  $f(z)$  as

$$f(z) = 2L^2 \left[ 1 - \frac{sL}{1 + sL} \exp - \frac{z}{L} \right] \quad (8.19)$$

Using the expression for  $p(r, z)$  of Eq.8.13 and substituting into Eq.8.12 we obtain an expression for the photoluminescence contrast for a point defect.

$$C_{PL}(r_0) = \frac{\gamma\alpha}{D} \left\{ \frac{(1 + A_1)(1 + S(1 - \exp - B_1))}{(1 + A_1 + S_1)} \right\} Q(r_0) \quad (8.20)$$

where

$$Q(R_0) = \int_0^\infty \left( \exp - A_1 B_1 - \frac{A_1 + S_1}{n + S_1} \exp - n B_1 \right) \frac{\exp - \nu^2 C_1^2 / 4}{n^2 - A_1^2} J_0(\nu R_0) \nu d\nu \quad (8.21)$$

with  $A_1 = \alpha L$

$$S_1 = sL$$

$$C_1 = c/L$$

$$B_1 = a/L$$

$$n = (1 + \nu^2 L^2)^{1/2}$$

$$R_0 = r_0/L$$

Chapter 4 has already considered an expression for the OBIC contrast for a point defect in a Schottky Barrier device. Fig. 8.5 (a) shows the photoluminescence contrast as a function of radial scan coordinate,  $\xi$ , for infinite surface recombination velocity. Fig. 8.5(b) shows the corresponding OBIC plot. Again absorption of 752 nm radiation in GaAs is considered. Clearly both plots have the same shape as predicted by Eq.8.12 and Eq.8.18.

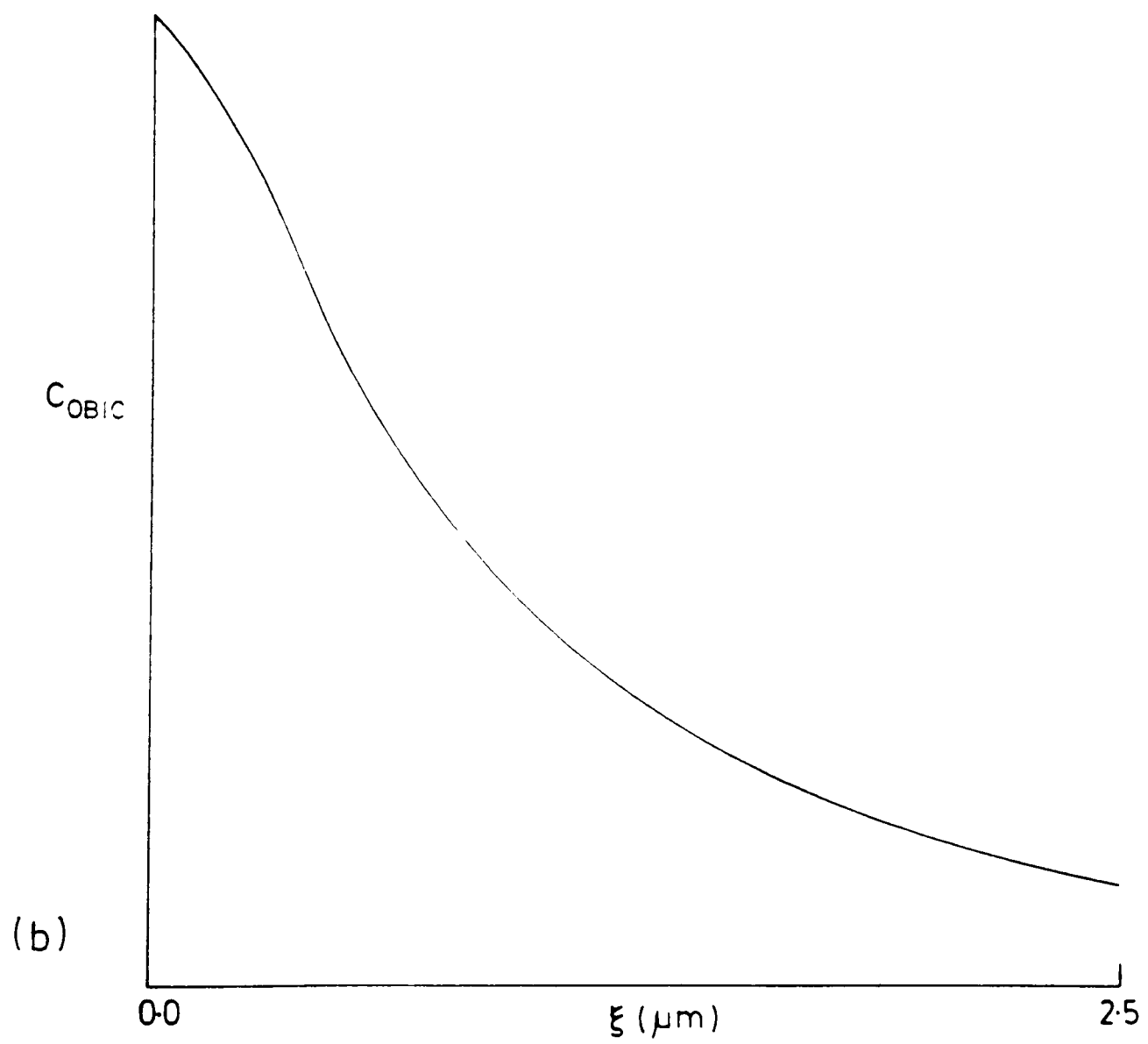
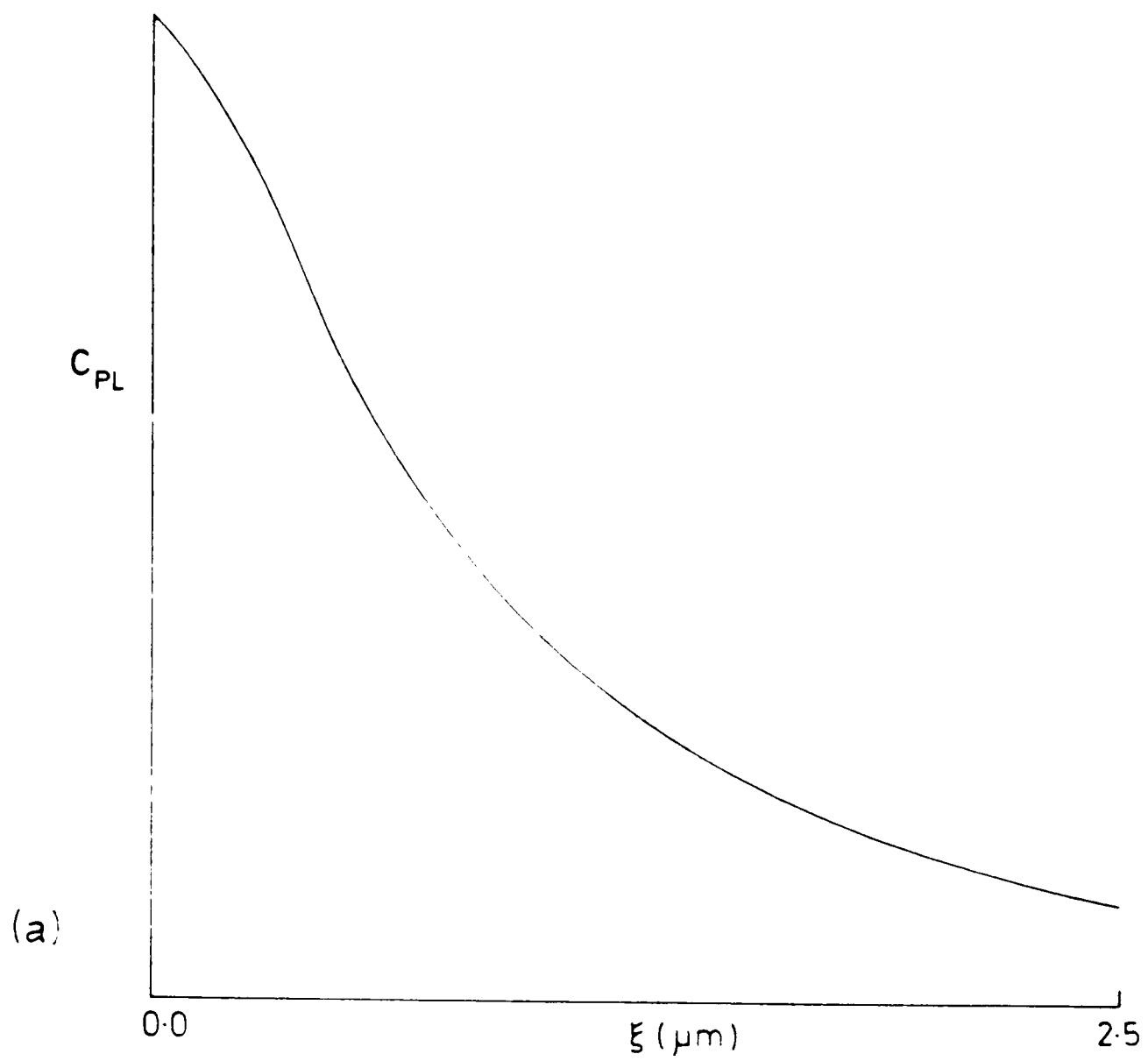


Fig.85

Contrast as a function of radial scan coordinate,  $\xi$

(a) Photoluminescence contrast

(b) OBIC contrast

### **8.3(e). Determination of defect depth**

The similarity in contrast curves for OBIC and photoluminescence suggests a method to determine the defect depth in situations where both OBIC and photoluminescence imaging are possible. In such a case the ratio of the two contrasts yields

$$R = \frac{C_{PL}(r_0)}{C_{OBIC}(r_0)} = \left\{ \frac{f(a)}{m(a)} \right\} \cdot \left\{ \frac{\int m(z') \bar{g}(0, z') dz'}{\int f(z') \bar{g}(0, z') dz'} \right\} \quad (8.22)$$

This equation may be solved to yield the defect depth,  $a$ . As a specific example of this method we neglect the internal absorption of the luminescence radiation ie.  $A(z) = 1$ . Under these circumstances one may solve Eq. 8.22 for the defect depth as

$$a = L \ln \left\{ 1 + \frac{R}{\alpha L} \right\} \quad (8.23)$$

which for the case of large  $L$  becomes simply

$$a \sim R/\alpha \quad (8.24)$$

Here, knowing the diffusion length, the defect depth may be calculated. A similar technique is possible in the scanning electron microscope by comparing the EBIC contrast with the cathodoluminescence contrast<sup>8,15</sup>. However a disadvantage of this approach is the uncertainty in the electron case of the form of the generation function. The use of a point generation source or a uniform generation sphere tangential to the surface is only an approximation. An advantage of the optical case is that the behaviour of the carrier generating probe is well known analytically.

## **8.4 CONCLUSIONS**

Infrared microscopy is useful to investigate defects which lie physically deep below the semiconductor surface. It is also useful to investigate deep defects which lie in the band-gap of the material. Both IR transmission and photoluminescence imaging are valuable techniques in the examination of substrate quality and for evaluating growth processes. OBIC imaging is useful in the examination of semiconductor devices to which external connections have been made. Sub-band-gap OBIC may give information on defects below the device surface which are detrimental to device performance. These defects may not necessarily be evident in the conventional OBIC image. Photoluminescence imaging has an advantage over OBIC in the imaging of defects in semiconductor devices in that it does not require that electrical contacts be made to the device. However not all materials are photoluminescent or their luminescence efficiency may be low. By obtaining the contrast of a sub-surface defect in both photoluminescence and photocurrent methods the depth of the defect below the surface may be estimated.

## CHAPTER 9

### CONCLUSIONS

#### 9.1 DISCUSSION

This thesis has investigated novel ways in which semiconductor devices may be examined non-destructively using the light probe of a scanning optical microscope. Theory is developed which forms the basis of an understanding of how excess minority carriers are distributed in a semiconductor when probed with a focused light beam. This is the first time the theory has been developed using a light beam as a probe. Initially the theory is developed for a Schottky Barrier. It is then extended to the planar junction case. In both cases the resolution of defects in the devices is investigated.

An exciting novel method to obtain spatial information on the distribution of defects at the silicon/silicon-dioxide interface in Metal Oxide Semiconductor devices has been found. The OBIC technique is used for this purpose. Defects at this interface can cause serious problems for device manufacturers. This method also allows misalignment of the metal gate to be detected. In addition defects in MOS devices due to radiation damage may be examined using this technique. This information could be very important for devices used in space applications.

A new method has been found to highlight dislocations in transistors. This method involves the rectification and differentiation of the optical beam induced current signal with the result that such defects are immediately evident. The beauty of this approach is that it is a one-knob technique which requires much less skill and time than the detection of dislocations using normal OBIC imaging. In addition, this technique is much less sensitive to laser fluctuations and inhomogeneties in reflection over the sample surface.

A comparison of OBIC and the well known EBIC technique is made which points to OBIC as the superior technique in semiconductor device examination. Two other non-destructive techniques which can complement OBIC imaging are investigated. These methods include transmission imaging of Gallium Arsenide and photoluminescence imaging. A theory has been presented to consider the imaging of defects in semiconductors using photoluminescence. This method can give similar information to the OBIC technique. It has the advantage of being a non-contact method and may be used to examine semiconductor wafers as well as semiconductor devices. However not all materials are photoluminescent. For these materials OBIC is a very powerful technique.

The importance of developing the theories to understand OBIC and photoluminescence imaging has been highlighted by my visits to outstanding research centres in the USA and Japan. This was a unique opportunity which highlighted the need for non-destructive techniques in semiconductor device examination. It also highlighted the need to understand the theory underlying such non-destructive techniques to allow meaningful interpretation of the images they show.

## **9.2 PROPOSED RESEARCH FOR THE FUTURE**

### **9.2(a). Metal Oxide Semiconductor devices :**

By observing the currents obtained from the source and drain separately as the laser beam is scanned over the metal oxide semiconductor device, one should be able to obtain information about the efficiency of current paths in the device. A model based on the diffusion equation could be found to account for the observed current profile. Also avalanching, which is a real problem occurring locally in p-n junctions could be induced at one junction of a MOS device. Current profiles could be obtained from the source and drain separately. There should be a much reduced current observed from the avalanched junction once avalanching has occurred.

The methods used to examine the Si-SiO<sub>2</sub> interface could be used to examine interfaces in other materials and other devices such as photodiodes and semiconductor lasers. In the latter devices lasing occurs near interfaces and this is where problems arise. Also OBIC images could be obtained using different laser wavelengths. Scanned ultra violet light could also be used to selectively anneal regions of radiation-induced positive charge to create specific  $I_{SD} - V_g$  characteristics. In this way characteristics of the device could be selectively modified.

### **9.2(b). Detection of pinholes in the insulator of MIS structures :**

Pinholes in thin oxide or insulator are of crucial concern to semiconductor device manufacturers. Consider a pinhole in a MIS structure. As a laser scans over a semi-transparent metal surface, hole-electron pairs are generated in the semiconductor. A Schottky Barrier may be formed where metal has penetrated the pinhole and is in contact with the underlying semiconductor. OBIC connections to the metal plate and semiconductor substrate allow the OBIC signal to be detected as the laser scans the metal surface. Carriers generated by the light beam in the region of the Schottky Barrier are swept out by the electric field at this junction. Hence the pinhole in the oxide would be detected as a bright region in the OBIC signal.

Since polysilicon-semiconductor contacts can also be rectifying contacts, the same method could be used to detect insulator pinholes in polysilicon gate devices. If the pinhole is such that metal does not penetrate it, we may have a metal-air-semiconductor structure at the pinhole. If one considers a thin oxide or insulator structure of thickness about  $1\mu m$ , then the application of a voltage of approximately 1V to the metal surface could cause breakdown in air causing device failure. Thus the above method using OBIC may be used to obtain a spatial map of pinholes in the insulator where the metal makes contact with the semiconductor.

### **9.2(c). Photoluminescence :**

The theory of defect imaging using photoluminescence has been developed in this thesis. It would be very valuable to compare experimental photoluminescence images with the transmission images of Chapter 8 for a compound such as Gallium Arsenide. In addition, it would be very interesting to compare successive slices of GaAs from the same ingot in this way to obtain information on the growth of the crystal. Photoluminescence would also be extremely useful in the examination of laser diodes. Consider light incident on an area of a semiconductor laser which contains defects. Light of longer wavelength may be re-emitted by this region. In this way the SOM could be used to examine non-radiative recombination competing with radiative recombination in the device. This method is not only novel, it should also give useful insight into the operation of semiconductor lasers.

### **9.2(d). Electrooptic sampling in GaAs integrated circuits :**

With increasing numbers of medium and large scale integrated logic circuits that operate at gigahertz frequencies an urgent need has arisen for measurements of digital waveforms at various points in such circuits. Conventional sampling oscilloscopes can resolve risetimes approaching 25 ps. However, novel transistors fabricated in GaAs may have very short risetimes of the order of 10 ps. Electrooptic sampling can take advantage of the very short light pulses, in the femtosecond range available today and allow non-invasive probing of circuits integrated in electrooptic semiconductors.

This electrooptic sampling technique uses the optical birefringence induced in GaAs in the presence of an applied electric field. When an optical pulse is passed through the material the polarisation of the beam is altered in direct proportion to the electric field along the beam path. The change in polarisation is converted into

a change in amplitude that is proportional to the circuit voltage. Use of the raster of a scanning optical microscope would allow the voltage waveforms throughout the integrated circuit to be probed.

#### **9.2(e). The integrity of metal-semiconductor connections :**

Consider probing the back of the semiconductor device with infrared light . Silicon and GaAs, for example, are transparent to infrared radiation. This would allow metal contacts at the surface of the device to be imaged in reflection. This method has the potential of highlighting poor electrical contacts in the device.

#### **9.2(f). Minimum device separations in integrated optics**

##### **Applications :**

Consider a group of semiconductor devices which are to be probed with a light beam in integrated optics applications. The minimum spacing of these devices to allow correct functioning of the circuit is critical to device manufacturers. This minimum spacing is determined by several factors, including the generation volume of light generated carriers in the semiconductor, diffusion in the semiconductor and surface recombination velocity. This points to the very important application of the theory developed in this thesis, estimating the volume in which the light beam generates carriers and considering the excess minority carrier distribution below the surface of the material.

## APPENDIX 1

### THE EXPONENTIALLY DECAYING GAUSSIAN BEAM

#### APPROXIMATION

Chapter 2 predicts the light intensity profile for a convergent light beam focused in a semiconductor material. To estimate the OBIC resolution of a point defect, in a Schottky barrier device for example, Eq.4.33 shows that it is necessary to find an expression for the excess minority carrier distribution in the semiconductor,  $p(r)$ . This is given by the solution of Eq.4.9 where the light intensity profile,  $g$ , acts as a pump term. The solution of this equation is given by the integral equation of Eq.4.11. This integral solution may not be solved easily analytically. Its numerical solution may be made substantially easier by using an approximate expression for the generation term.

The approximate expression used is

$$g(r, z) = \frac{g_0 \alpha}{\pi c^2} \exp - \frac{r^2}{c^2} \exp - \alpha z \quad (A1.1)$$

One reason for using the Gaussian term in (A1.1) is that a laser produces a gaussian beam so that a gaussian approximation to the intensity profile in the focal plane is not unrealistic. This approximation allows great computational ease.

It is important to remember that the shape of the light intensity distribution in the semiconductor material is only one of a number of factors affecting the OBIC resolution of a defect. Diffusion, beam attenuation, defect depth and the boundary conditions of the problem also affect the resolution.

Figs. A1.1 (a) and (b) show the three dimensional intensity distributions for the 'real' and approximate beams respectively. Their shapes are very similar.

Consider the intensities along the optic axis,  $I(u, 0)$ , for the real and approximate beams. Eq.A1.1 gives an expression for the intensity for the approximate beam

$$I(u, 0)_{\text{approx}} \propto \exp - \alpha z \quad (A1.2)$$

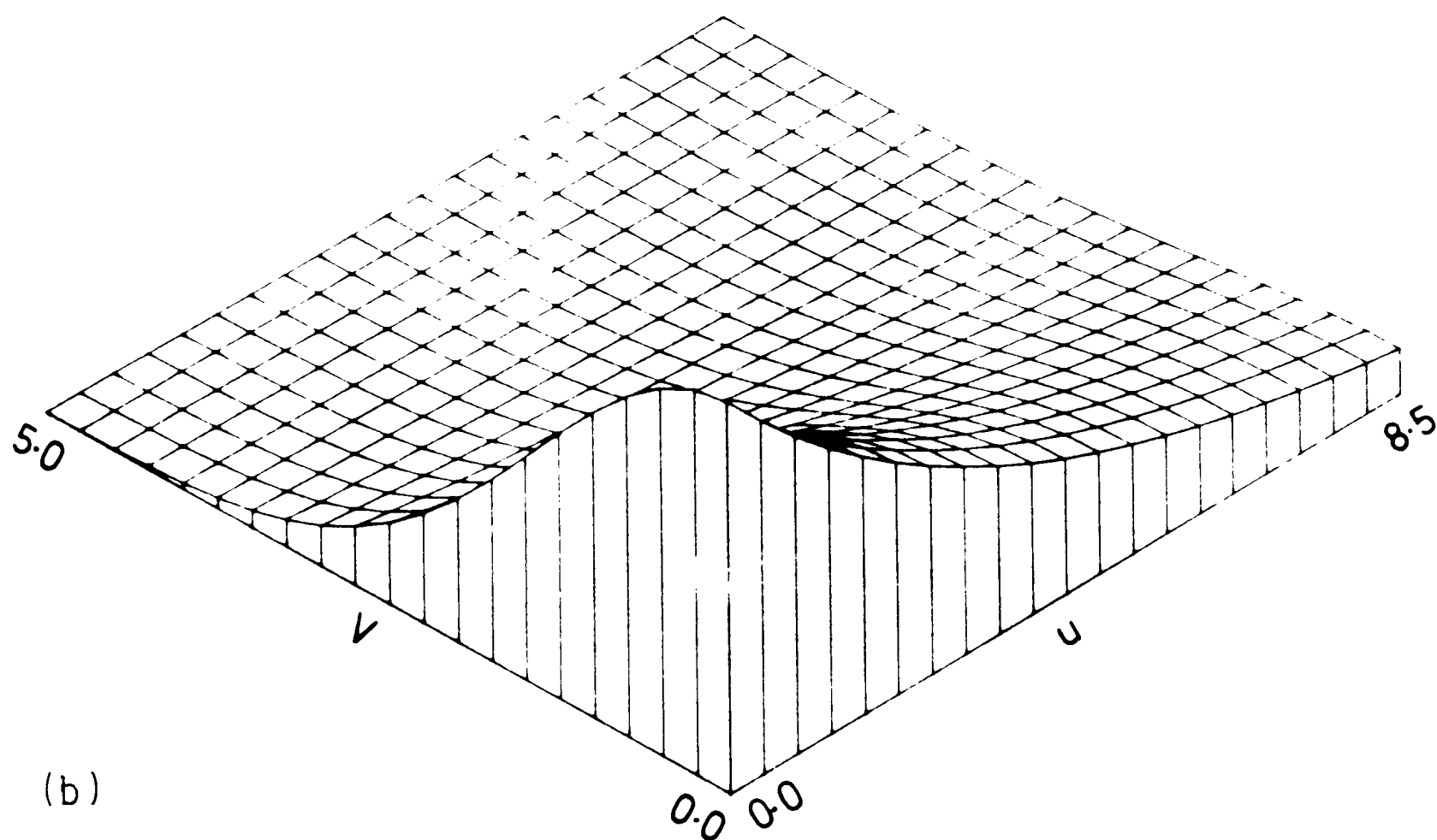
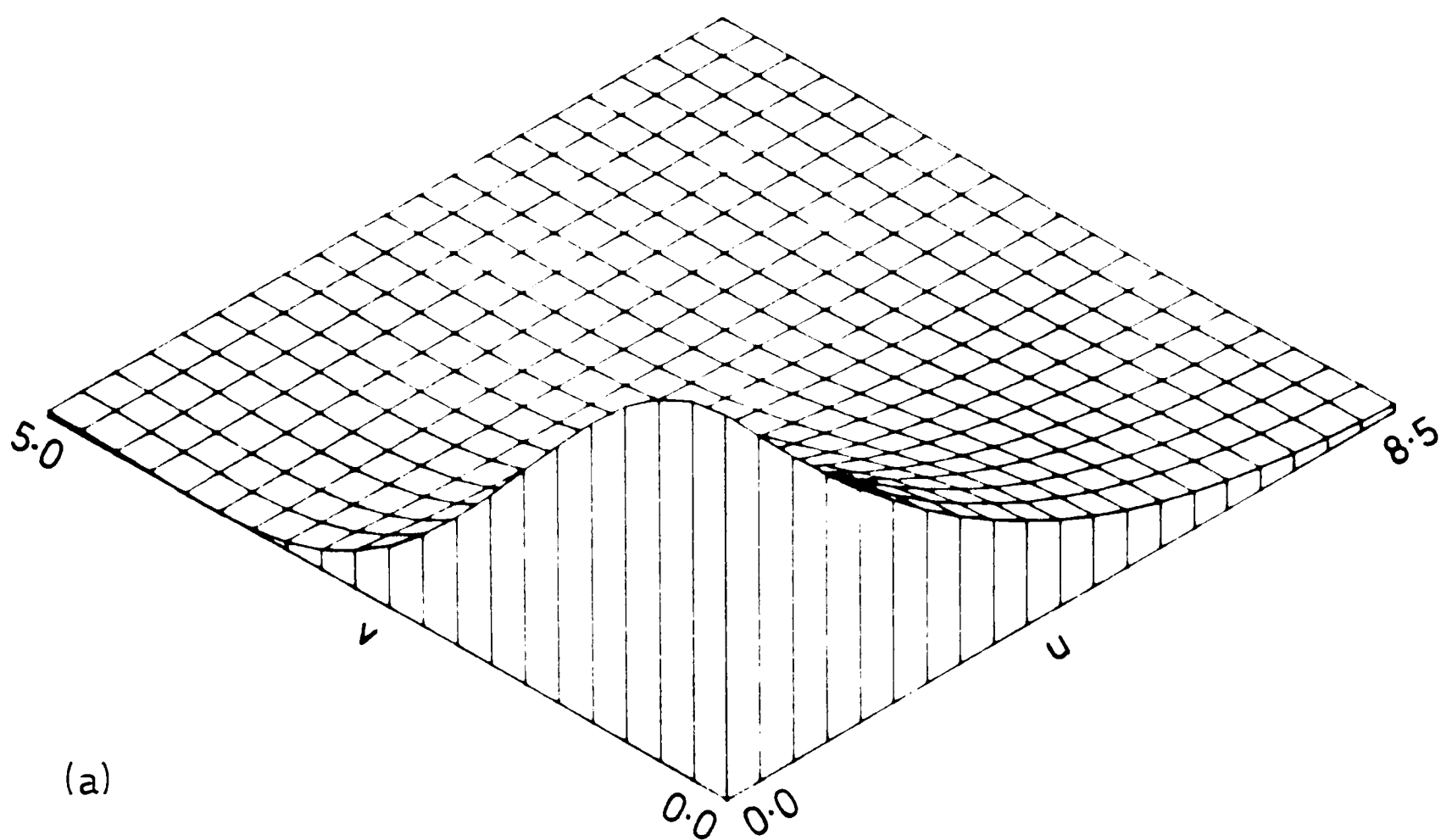


Fig.A1.1

Three dimensional intensity distributions for

(a) The real beam

(b) The approximate beam

From Eq. 2.7 one gets

$$I(u, 0)_{real} \Big|_{u_0=0} = \frac{\exp -a\beta u}{(u/4)^2 + (\beta u/4)^2} \left[ \sin^2 u/4 + \sinh^2 \beta u/4 \right] \quad (A1.3)$$

with

$$a = \frac{4 + \sin^2 \alpha}{2 \sin^2 \alpha} \quad (A1.4)$$

for a beam focused on the semiconductor surface.

Now consider the intensities in the focal plane,  $I(0, v)$ .

$$I(0, v)_{approx} \propto \exp -\frac{r^2}{c^2} \quad (A1.5)$$

$$I(0, v)_{real} \propto \left( \frac{2J_1(v)}{v} \right)^2 \quad (A1.6)$$

Note that  $u$  and  $v$  have already been defined in chapter 2. Figs. A1.2 and A1.3 compare the intensities along the optic axis and in the focal plane, respectively, for the two beams using the same value of numerical aperture, 0.4. There is quite good agreement in these plots. Expressions for the integrated intensity, integrated over a plane at depth  $z$  for real and approximate beams are given by

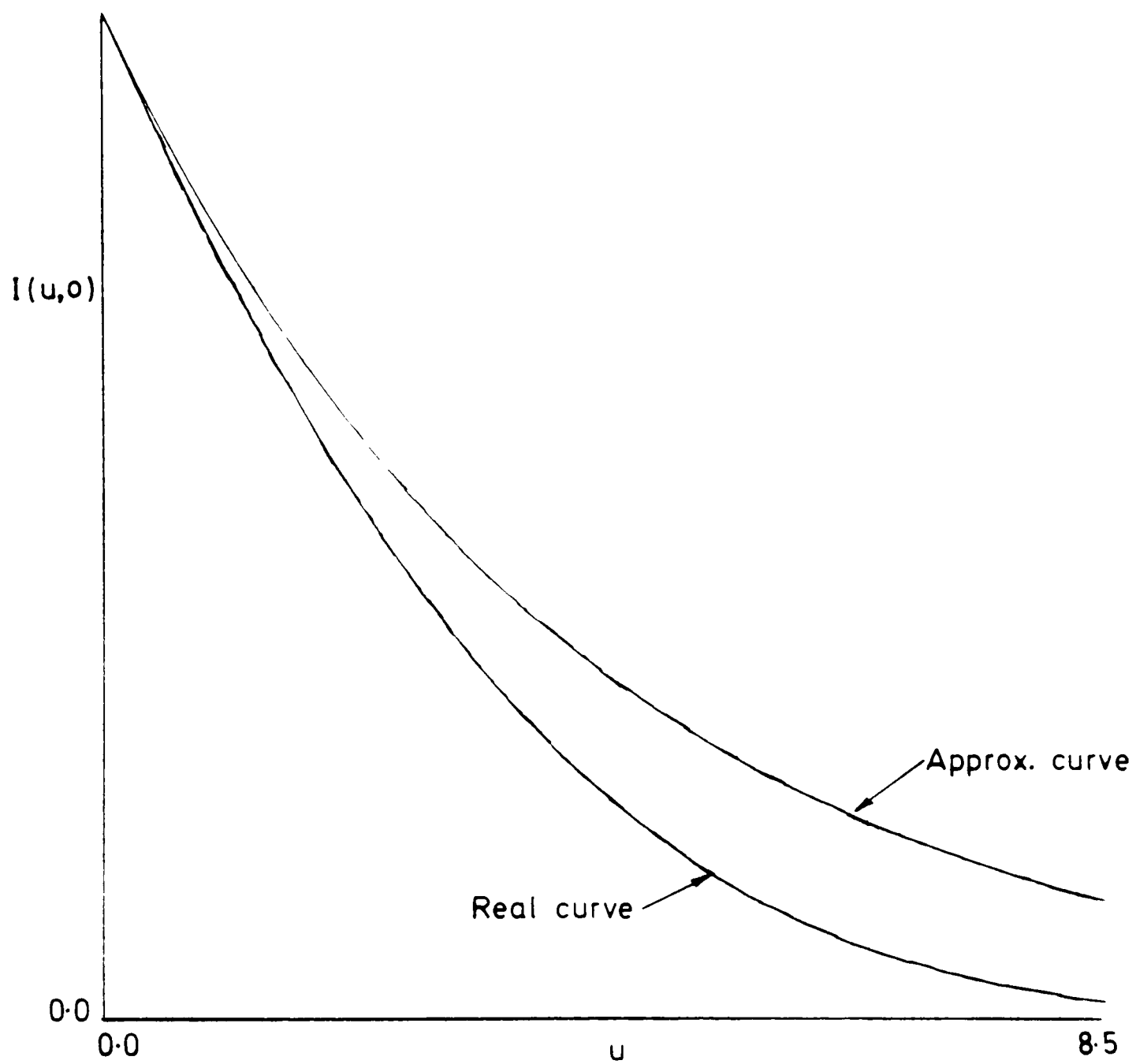
$$L(u)_{approx} \propto \exp -\alpha z \quad (A1.7)$$

and

$$L(u)_{real} = \exp -a\beta u \frac{\sinh \beta u/2}{\beta u/2} \quad (A1.8)$$

for a beam focused on the surface.

Fig. A1.4 compares the integrated intensity expressions for the two beams. Clearly this integrated intensity is a very important factor in determining the background diffusion current in the absence of a defect,  $I_0$ . The close agreement of the real and approximate curves of Fig. A1.4 suggests that using the approximate generation expression of Eq.A1.1 will not have any significant effect on this background current.



**Fig.A1.2**

Intensity along the optic axis

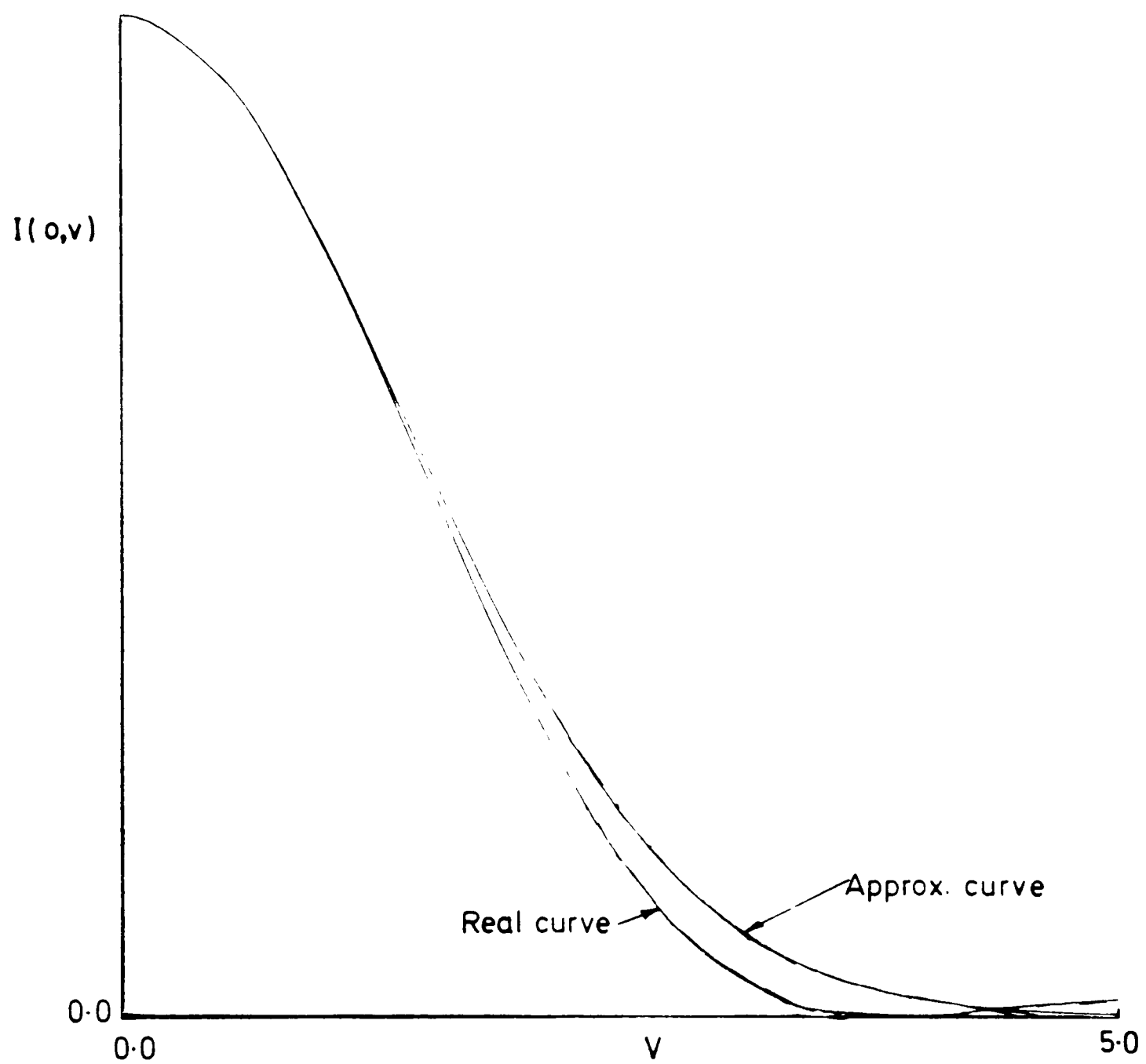


Fig.A1.3

Intensity in the focal plane

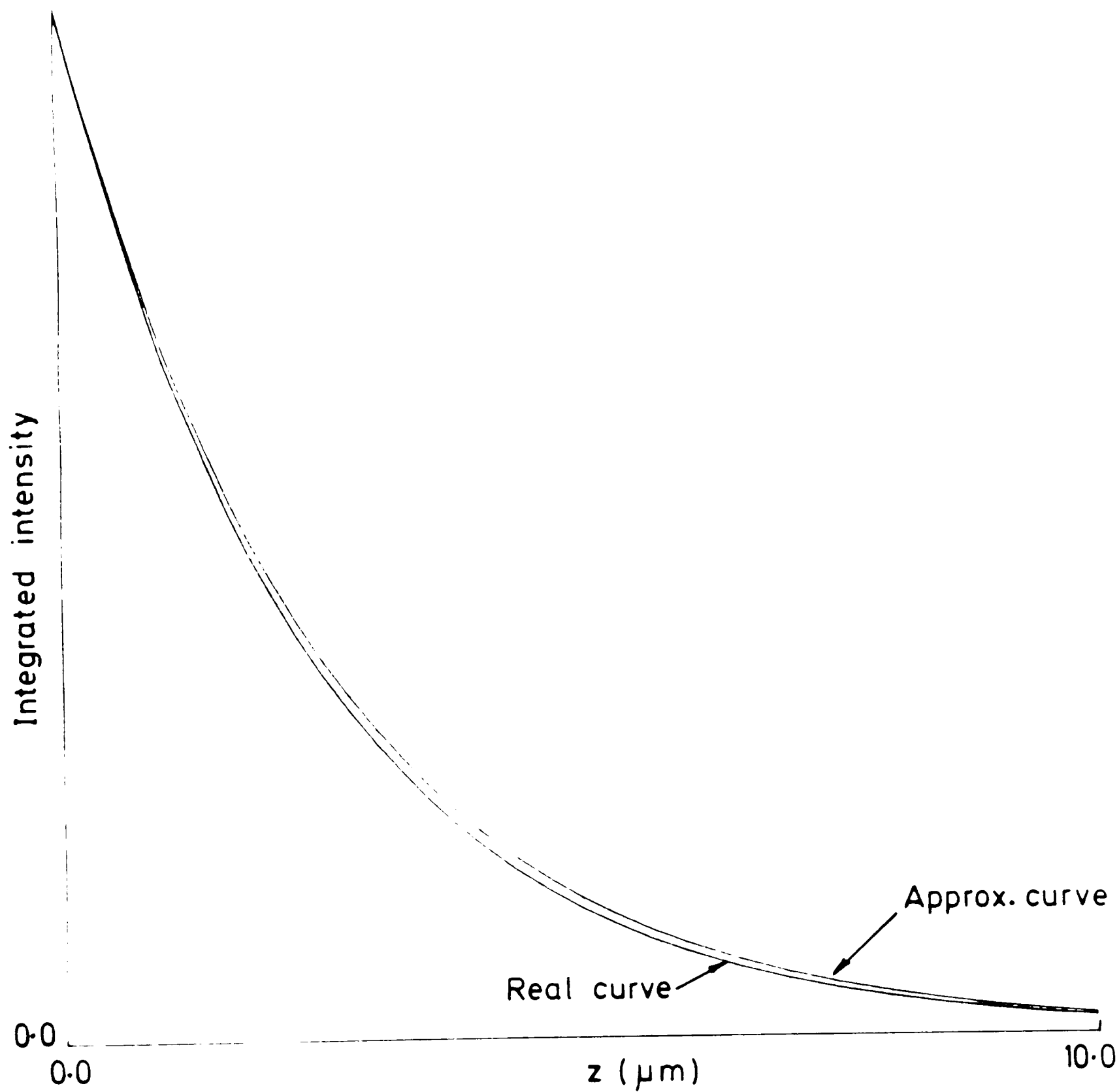


Fig.A1.4

Integrated intensity as a function of depth, z

It has already been shown in the imaging of dislocations in Schottky barriers discussed in Chapter 4 that the resolution is relatively insensitive to the Gaussian beam width parameter,  $c$ . Similarly it is reasonable to expect that the diffusion of generated carriers and the attenuation of the input beam mean that the value of numerical aperture chosen, provided it has a reasonable value, is not critical in determining resolution.

It is interesting to note that in the extreme case of an annular lens with pupil function

$$\begin{aligned} P(\rho) &= 1 & \rho &= 1 \\ &= 0 & \text{otherwise} \end{aligned} \quad (A1.9)$$

that the intensity  $I(u, v)$  from Eq.2.5 simplifies to

$$I(u, v) = A^2 \exp - \left( k\beta(2 + \sin^2 \alpha)(h + z) \right) J_0^2(v) \quad (A1.10)$$

This means that the intensity may be written as a product of two functions, one of which is a function of  $v$  only,  $|J_0(v)|^2$ . The other function depends only on  $u$  and the dependence is exponential. This gives an intensity distribution of the same form as the approximate expression of Eq.A1.1. Another interesting case is that of low numerical aperture where the expression for intensity given by Eq.2.5 resembles a product of two functions, one which is essentially a function of  $u$  and the other which is essentially a function of  $v$ , giving an expression of approximately the same form as Eq.A1.1.

## APPENDIX 2

### THE RECOMBINATION-GENERATION RATE

Chapter 7 considers the detection of defects at the silicon/silicon-dioxide interface in MOS devices. This appendix gives a derivation of the expression for the recombination-generation rate of charge carriers in semiconductors used in chapter 7. The recombination and generation of electrons and holes in semiconductors may take place at some type of recombination-generation centres or traps. These sites may be crystal lattice dislocations, impurity atoms located interstitially or substitutionally in the crystal lattice or surface defects. Under steady state conditions a single energy level recombination centre is characterized by three numbers: the capture cross-section for electrons, the capture cross-section for holes and the energy involved in these transitions. The cross-sections are inversely proportional to the lifetimes of holes and electrons respectively and the transition energy may be measured from one of the edges of the energy gap of the semiconductor.

There are four basic processes involved in the carrier generation and recombination through traps. If a trap is occupied by a hole an electron may drop into the trap from the conduction band and recombine with the hole or the trap may emit a hole to the valence band. If the trap is initially filled with an electron, the trapped electron may be emitted to the conduction band or a valence band hole may move into the trap and recombine with the trapped electron. Consider the electron capture process. The rate that the electron in the conduction band will drop into an empty trap is given<sup>A2.1</sup> as

$$\frac{n f_{tp}}{\tau_{no}} \quad (A2.1)$$

where  $n$  is the density of electrons in the conduction band,  $f_{tp}$  is the fraction of traps occupied by holes and  $\tau_{no}$  is the lifetime for electrons injected into a highly  $p$ -type specimen.

The electron emission rate from the conduction band may be written as

$$af_t \quad (A2.2)$$

where  $a$  is a proportionality factor which includes trap density, total number of electronic states in the conduction band and the probability of electron emission from traps.  $f_t$  is the fraction of traps occupied by electrons; i.e.  $f_t = 1 - f_{tp}$ .

The expression for  $a$  can be obtained by considering the system under thermal equilibrium conditions. Under these conditions the electron emission rate of Eq.A2.2 must equal the electron capture rate of Eq.A2.1.

If the occupancy of traps is expressed in terms of a quasi Fermi level for traps,  $F_t$ , and using

$$f_t = \left(1 + \exp(E_t - F_t)/kT\right)^{-1} \quad (A2.3)$$

where  $E_t$  is the trap energy,  $k$  is Boltzman's constant,  $T$  denotes temperature, then equating Eqs.A2.1 and A2.2 one may obtain

$$a = \frac{n_1}{\tau_{n0}} \quad (A2.4)$$

$n_1$  is the density of electrons in the conduction band when the Fermi level falls at  $E_t$ , and equals  $n_i \exp(E_t - E_i)/kT$ . (The subscript  $i$  indicates intrinsic values).

The net capture rate for electrons by the traps under non-equilibrium conditions may be written as

$$U_{cn} = \frac{n f_{tp} - n_1 f_t}{\tau_{n0}} \quad (A2.5)$$

An entirely similar treatment can be carried out for holes leading to the following equation for the net rate of capture for holes under non-equilibrium conditions.

$$U_{cp} = \frac{p f_t - p_1 f_{tp}}{\tau_{p0}} \quad (A2.6)$$

where  $p$  is the density of holes in the valence band.

$p_1$  is the density of holes in the valence band when the Fermi level falls at  $E_t$ ,  $n_i \exp(E_i - E_t)/kT$ .  $\tau_p$  is the lifetime for holes injected into a highly n-type specimen.

The rate of recombination for non-equilibrium but steady state conditions is obtained by requiring that the net rate of capture of holes equal that of electrons.

This leads to

$$\begin{aligned} U &= U_{cp} = U_{cn} \\ &= \frac{pn - n_i^2}{(n + n_1) \tau_{p0} + (p + p_1) \tau_{n0}} \end{aligned} \quad (A2.7)$$

for the steady state recombination rate for electrons or holes.

If  $\tau_{p0} = \tau_{n0} = \tau$  this reduces to an equation of the form of Eq.7.2 when also considering the rate contribution due to incident laser light (photogeneration).

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## **Appendix 2**

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## **PUBLICATIONS RESULTING FROM THIS RESEARCH**

1. A new method for displaying low-contrast optical beam induced contrast images in the scanning optical microscope. (with T.Wilson)  
J.Appl.Phys., (1986), **59**, 3,702.
2. Distribution of charge carriers generated in a semiconductor by a focused convergent light beam. (with T.Wilson)  
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3. Optical beam induced current imaging of dislocations in semiconductors. (with T.Wilson)  
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4. Theory of optical beam induced current images of defects in semiconductors. (with T.Wilson)  
J.Appl.Phys., (1986), **61**, 1,191.
5. Optical beam induced current imaging in scanning optical microscopy. (with P.D.Pester and T.Wilson)  
Presented at the Fourth International symposium on Optical and Optoelectronic Applied Science and Engineering, The Hague, The Netherlands, April 1987.
6. Optical beam induced current imaging of defects using scanning optical microscopy. (with T.Wilson)  
Presented at the International Symposium on Defect Recognition and Image Processing in III-V Compounds, Monterey, California, April 1987.
7. Royal Television Society report on the Baird Travelling Scholarship  
To be published in the journal of the Royal Television Society, August 1987.
8. Photoluminescence and optical beam induced current images of defects

in semiconductors. (with T.Wilson)

Submitted for publication, 1987.

9. The effect of bias on optical beam induced current imaging of defects in planar and Schottky junction devices. (with T.Wilson)

Submitted for publication, 1987.

10. The imaging of interface states and trapped oxide charge in MOS structures. (with T. Wilson)

Submitted for publication, 1987.