THE NUCLEATION AND GROWTH OF SOME EUTECTICS

Volume II

M. G. Day, B.A.
St. John's College.

A Thesis submitted for the Degree of Doctor of Philosophy in the University of Oxford

Department of Metallurgy
Trinity Term 1967
For easy reference, the page numbers have been made to correspond with the figure, plate and table numbers.

Where necessary the Growth Direction has been indicated by an arrow and the initials G.D. On longitudinal sections of unidirectionally grown specimens the growth direction is from left to right unless indicated otherwise.
FIG. 1  Binary Eutectic Phase Diagram
FIG. 2. Eutectic Classification Diagram
FIG. 3a  Thall and Chalmers' Al/Si Eutectic Growth Model

FIG. 3b  Chadwick's Al/Si Eutectic Growth Model
FIG. 4 Bell Jar Furnace

(as for vacuum melting and casting)
FIG. 5  Mechanical Pulling Device

Scale 3" to one foot
FIG. 6  Temperature Gradient Measuring Device

(full scale - total length of apparatus = 2')
FIG. 7  A Specimen Temperature Gradient Graph

\[ G = 29.5^\circ\text{C}/\text{cm.} \]

\[ \text{Furnace Maximum Temperature (no water cooling)} = 725^\circ\text{C} \]
FIG. 8a  Temperature Gradient Calibration Curves (Nichrome furnace)

FIG. 8b  Temperature Gradient Calibration Curves (Platinum furnace)
FIG. 9

a. Water Cooling Insert for Nichrome Furnace
   (half scale)

b. Water Cooling Insert for Platinum Furnace
   (half scale)
FIG. 10a  Unicam Specimen Pip with Extracted Particle (x 5)

FIG. 10b  Unicam Specimen Pip with Small Pillar of Eutectic (x 5)
FIG. 11 Block Diagram of Scanning Electron Microscope
FIG. 12 Aluminium/Silicon Phase Diagram
(volume fraction of eutectic silicon = 0.13)
FIG. 13  Silver/silicon Phase Diagram
(volume fraction of eutectic silicon = 0.17)
FIG. 14 Gold/Silicon Phase Diagram

(volume fraction of eutectic silicon = 0.26)
PLATE 15a  Furnace-cooled Al/Si Eutectic

PLATE 15b  Furnace-cooled Al/Si Eutectic
PLATE 16a  Furnace-cooled Al/Si Eutectic

PLATE 16b  Furnace-cooled Al/Si Eutectic
PLATE 17a  Furnace-cooled Ag/Si Eutectic

PLATE 17b  Furnace-cooled Ag/Si Eutectic
PLATE 18a  Furnace-cooled Ag/Si Eutectic

x 460

PLATE 18b  Furnace-cooled Ag/Si Eutectic

x 460
PLATE 19a  Furnace-cooled Au/Si Eutectic

x 460

PLATE 19b  Furnace-cooled Au/Si Eutectic

x 460
<table>
<thead>
<tr>
<th>R cm/sec</th>
<th>G°C/cm</th>
<th>Type</th>
<th>R cm/sec</th>
<th>G°C/cm</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.78 x 10^{-5}</td>
<td>200</td>
<td>•</td>
<td>1.30 x 10^{-4}</td>
<td>29.5</td>
<td>⊙</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>+</td>
<td></td>
<td>16.0</td>
<td>⊙</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>+</td>
<td></td>
<td>3.5</td>
<td>⊙</td>
</tr>
<tr>
<td></td>
<td>29.5</td>
<td>+</td>
<td>2.50 x 10^{-4}</td>
<td>45</td>
<td>⊙</td>
</tr>
<tr>
<td></td>
<td>16.0</td>
<td>+</td>
<td></td>
<td>29.5</td>
<td>⊙</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>⊙</td>
<td></td>
<td>16.0</td>
<td>⊙</td>
</tr>
<tr>
<td>3.70 x 10^{-5}</td>
<td>29.5</td>
<td>+</td>
<td>3.70 x 10^{-4}</td>
<td>120</td>
<td>⊙</td>
</tr>
<tr>
<td>4.63 x 10^{-5}</td>
<td>29.5</td>
<td>+</td>
<td></td>
<td>45</td>
<td>⊙</td>
</tr>
<tr>
<td>6.48 x 10^{-5}</td>
<td>29.5</td>
<td>+</td>
<td></td>
<td>29.5</td>
<td>⊙</td>
</tr>
<tr>
<td>1.30 x 10^{-4}</td>
<td>200</td>
<td>+</td>
<td></td>
<td>16.0</td>
<td>⊙</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>+</td>
<td></td>
<td>3.5</td>
<td>⊙</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>+</td>
<td>5.0 x 10^{-4}</td>
<td>29.5</td>
<td>⊙</td>
</tr>
</tbody>
</table>

**KEY:**  • = rodlike, + = angular and ⊙ = irregular type of Al/Si eutectic alloy

**TABLE 20 - A Selection of Results of Unidirectional Solidification Experiments for Hypoeutectic and Eutectic Al/Si Alloys.** (nominal alloy composition of 11.5 wt.% Si, except when R \(> 2.5 \times 10^{-4}\) cm/sec. when 12.5 wt.% Si alloys were used to prevent excessive primary \(\alpha\)-Al dendrite formation)
<table>
<thead>
<tr>
<th>R cm/sec</th>
<th>G°C/cm</th>
<th>Type</th>
<th>R cm/sec</th>
<th>G°C/cm</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.78 x 10^{-5}</td>
<td>600</td>
<td>□</td>
<td>3.70 x 10^{-4}</td>
<td>45</td>
<td>⊗</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>⊗</td>
<td>29.5</td>
<td></td>
<td>⊗</td>
</tr>
<tr>
<td>250</td>
<td></td>
<td>⊗</td>
<td>16.0</td>
<td></td>
<td>⊗</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>⊗</td>
<td>3.5</td>
<td></td>
<td>⊗</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td>⊗</td>
<td>5.0 x 10^{-4}</td>
<td>29.5</td>
<td>⊗</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>⊗</td>
<td>6.3 x 10^{-4}</td>
<td>29.5</td>
<td>⊗</td>
</tr>
<tr>
<td>45</td>
<td></td>
<td>⊗</td>
<td>7.41 x 10^{-4}</td>
<td>120</td>
<td>⊗</td>
</tr>
<tr>
<td>29.5</td>
<td></td>
<td>⊗</td>
<td>45</td>
<td></td>
<td>⊗</td>
</tr>
<tr>
<td>1.30 x 10^{-4}</td>
<td>3.5</td>
<td>⊗</td>
<td>29.5</td>
<td></td>
<td>⊗</td>
</tr>
<tr>
<td>2.50 x 10^{-4}</td>
<td>45</td>
<td>⊗</td>
<td>1.37 x 10^{-4}</td>
<td>120</td>
<td>⊗</td>
</tr>
<tr>
<td>29.5</td>
<td></td>
<td>⊗</td>
<td>29.5</td>
<td></td>
<td>⊗</td>
</tr>
<tr>
<td>3.70 x 10^{-4}</td>
<td>120</td>
<td>⊗</td>
<td>16.0</td>
<td></td>
<td>⊗</td>
</tr>
</tbody>
</table>

**KEY:**
- □ = massive,
- ⊗ = rodlike,
- ⊗ = angular,
- ⊗ = irregular and
- ⊗ = complex regular type of

Al/Si eutectic alloy.

**TABLE 21** - A selection of Results of Unidirectional Solidification Experiments for Hypereutectic Al/Si Alloys.

(nominal alloy composition of 15.0 wt.% Si)
PLATE 22

Massive Al/Si Eutectic – transverse section

\[ R = 2.7 \times 10^{-5} \text{ cm/sec.}, \ G = 600^\circ \text{C/cm.} \]
PLATE 23

Rodlike Al/Si Eutectic - transverse section

\( R = 2.78 \times 10^{-5} \text{cm/sec}, \ G = 200^\circ \text{C/cm}. \)
PLATE 24
Angular Al/Si Eutectic - transverse section

\[ R = 1.54 \times 10^{-5} \text{ cm/sec.}, \theta \approx 30^\circ \text{C/cm.} \]
PLATE 25  Irregular Al/Si Eutectic - transverse section

\[ R = 7.4 \times 10^{-4} \text{ cm/sec}, \quad \alpha = 29.5^\circ \text{C/cm}. \]
PLATE 26

Complex Regular (Web) Al/Si Eutectic
- transverse section

\((R = 3.7 \times 10^{-4} \text{ cm/sec.}, \ G = 29.5^\circ \text{C/cm.})\)
FIG. 27  G/R Morphological Plots

a. Eutectic Al/Si alloys (see table 20)  b. Hypereutectic Al/Si alloys (see table 21)
FIG. 28  Growth Mechanism C/R Plot
(hypereutectic results shown - see tables 20 and 21 for key to symbols used)
X-Ray Rotation Photograph (Cu Kα radiation) about the Growth Axis of an Al/Si Eutectic Specimen with a Primary Al Dendrite.

\[ R = 3.70 \times 10^{-4} \text{ cm/sec}, \quad c = 16.0^\circ \text{C/cm.} \]
PLATE 30  Secondary and Tertiary \{100\} Arms of an \(\alpha\) - Aluminium Dendrite

FIG. 30  Sketch of an Extracted Dendrite (after Tschernoff 1868)
PLATE 31a  
**Al/Si Eutectic - transverse section**  
\( R = 2.78 \times 10^{-5} \text{ cm/sec} \) \( C = 600^\circ \text{C/cm} \).

PLATE 31b  
**Al/Si Eutectic - longitudinal section**  
\( R = 2.78 \times 10^{-5} \text{ cm/sec} \) \( C = 600^\circ \text{C/cm} \).
PICTURE 32a  
C.P.4 Etched Al/Si Eutectic - longitudinal  
section  
\( R = 2.78 \times 10^{-5} \text{ cm/sec.}, \ G = 300^\circ \text{C/cm.} \)

PICTURE 32b  
C.P.4 Etched Al/Si Eutectic - longitudinal  
section  
\( R = 2.78 \times 10^{-5} \text{ cm/sec.}, \ G = 300^\circ \text{C/cm.} \)
PLATE 33a

Extracted Massive Silicon Particle

\( R = 2.78 \times 10^{-5} \text{cm/sec.}, \ G = 300^\circ \text{C/cm}. \)

---

PLATE 33b

Extracted Massive Silicon Particle

\( R = 2.78 \times 10^{-5} \text{cm/sec.}, \ G = 300^\circ \text{C/cm}. \)
PLATE 34a
Extracted Massive Silicon Particle
\( R = 2.78 \times 10^{-5} \text{cm/sec.}, \; G = 300^\circ \text{C/cm.} \)

PLATE 34b
Extracted Massive Silicon Particle
\( R \times 2.78 \times 10^{-5} \text{cm/sec.}, \; G = 300^\circ \text{C/cm.} \)
X-Ray Rotation Photograph (Cu Kα X-ray radiation) Showing a Si preferred orientation.
PLATE 36a  
Al/Si Eutectic Quenched Growth Front 
\((R = 2.78 \times 10^{-5}\text{ cm/sec.}, G = 300^\circ\text{C/cm.})\)

PLATE 36b  
\(\alpha\)-Al Cusp on Quenched Growth Front  
(plate 36a)
PLATE 37a  Si leading at Quenched Growth Front  
(plate 36a)

PLATE 37b  Si lagging at Quenched Growth Front  
(plate 36a)
PLATE 38a  Al/Si Eutectic - transverse section
(R = 2.78 x 10^{-5} \, \text{cm/sec.}, \, C = 200^\circ \text{C/cm.})

PLATE 38b  Al/Si Eutectic - longitudinal section
(R = 2.78 x 10^{-5} \, \text{cm/sec.}, \, C = 200^\circ \text{C/cm.})
**PLATE 39a**  
Si Growth Band - longitudinal section  
(R = 2.78 x 10^{-5} \text{cm/sec.}, G = 200^\circ \text{C/cm.})

---

**PLATE 39b**  
Si Growth Band - longitudinal section  
(R = 2.78 x 10^{-5} \text{cm/sec.}, G = 200^\circ \text{C/cm.})
PICTURE 40a

Extracted Si fibres (c.f. plates 38)

\[ R = 2.78 \times 10^{-5} \text{cm/sec.}, \ G = 200^\circ \text{C/cm.} \]

PICTURE 40b

An Extracted Si fibre

\[ R = 2.78 \times 10^{-5} \text{cm/sec.}, \ G = 200^\circ \text{C/cm.} \]
PLATE 41a

A Bifurcated Silicon Fibre

\[ R = 2.78 \times 10^{-5} \text{cm/sec.}, \ G = 200^\circ\text{C/cm.} \]

---

PLATE 41b

Silicon Fibres with Side Plates attached

\[ R = 2.78 \times 10^{-5} \text{cm/sec.}, \ G = 200^\circ\text{C/cm.} \]
X-ray Rotation Photograph (Cu Kα, Kβ radiation) showing preferred orientation for a (1 0 0) Si
FIG. 43  Model of Extracted Angular Silicon Particle
(simplest form)
PLATE 44a  Al/Si Eutectic - transverse section
(R = 2.78 x 10^{-5} cm/sec., C = 16^0 C/cm.)

PLATE 44b  Al/Si Eutectic - longitudinal section
(R = 2.78 x 10^{-5} cm/sec., C = 16^0 C/cm.)
**PLATE 45a**  
Extracted Angular Silicon Particles  
(c.f. plate 60a)  
\[(R = 2.78 \times 10^{-5} \text{ cm/sec.}, \ G = 29.5^\circ \text{C/cm.})\]

**PLATE 45b**  
End View of an Extracted Angular Si Particle  
\[ (R = 1.54 \times 10^{-5} \text{ cm/sec.}, \ G \approx 30^\circ \text{C/cm.}) \]
X-Ray Rotation Photograph (Cu Kα radiation) about the Growth Axis of an Al/Si Lutectic Specimen

\[ R = 2.75 \times 10^{-5} \text{cm/sec.}, \ C = 27.5^\circ\text{C/cm.} \]
PLATE 47  Extracted Smooth Silicon Plate
(R = 1.54 \times 10^{-5} \text{ cm/sec}. G \approx 30^\circ C/cm.)

FIG. 47  Crystallography of Smooth Silicon Side Plates
PLATE 48a

Surface-marked Si side plate (reflected light)
\( R = 2.78 \times 10^{-5} \text{ cm/sec.}, \ G = 3.5^\circ \text{C/cm.} \)

PLATE 48b

Surface-marked Si side plate
(transmitted light)
\( R = 2.78 \times 10^{-5} \text{ cm/sec.}, \ G = 3.5^\circ \text{C/cm.} \)
PLATE 49a

Extracted Smooth Silicon Side Plate
(R = 2.78 x 10^{-5} \text{cm/sec.}, \ G = 3.5^\circ \text{C/cm.})

x 60

PLATE 49b

Extracted Smooth Silicon Side Plate
(R = 2.78 x 10^{-5} \text{cm/sec.}, \ G = 3.5^\circ \text{C/cm.})

x 225
PLATE 50  X-Ray Laue Photograph taken normal to a \{100\} Smooth Side Plate of a \{210\} Spinel Twinned Extracted Silicon Particle
Extracted Corrugated Silicon Plate
\( R = 1.54 \times 10^{-5} \, \text{cm/sec.} \quad G = 30^\circ \text{C/cm.} \)

Crystallography of Corrugated Silicon Side Plates
X-Ray Laue Photograph taken normal to a {110} Corrugated Side Plate of a {210} Spinel Twinned Extracted Angular Silicon Particle
Angular Silicon Particles - Nodal Angle Histogram (transverse sections)
<table>
<thead>
<tr>
<th>Corrugated Plates</th>
<th>90° based all smooth or all corrugated plates.</th>
</tr>
</thead>
<tbody>
<tr>
<td>53°</td>
<td>53° and 90° based all smooth or all corrugated plates.</td>
</tr>
<tr>
<td>127°</td>
<td>127° and 53° based all smooth or all corrugated plates.</td>
</tr>
<tr>
<td>135°</td>
<td>135° and 90° based mixed smooth and corrugated plates</td>
</tr>
<tr>
<td>98°</td>
<td>45°, 53° and 90° based mixed smooth and corrugated plates.</td>
</tr>
</tbody>
</table>

**FIG. 55** Angular Silicon Particles - Nodal Types (transverse sections)
FIG. 56  [001] Stereographic Projection

(Growth direction of angular silicon particle = [001] and the thick line traces represent the side plates of the particle, see figs. 55 and 119)
FIG. 57 [001] Stereographic Projection with a (210) Spinel Twin
(Growth direction of angular silicon particle = [001] and the thick line traces represent the side plates of the particle, see fig. 55)
PLATE 58  Al/Si Quenched Growth Front

\[ R = 2.78 \times 10^{-5} \text{ cm/sec.}, \ G = 29.5^\circ \text{C/cm.} \]

FIG. 58  Line Diagram of Angular Eutectic Growth Front showing the Relation of Projected Free Edge Distance \((d)\) to the Silicon Morphology
PLATE 59a
Al/Si Eutectic - transverse section
\( R = 2.78 \times 10^{-5} \text{cm/sec.}, \quad C = 200^\circ \text{C/cm.} \)

PLATE 59b
Al/Si Eutectic - transverse section
\( R = 2.78 \times 10^{-5} \text{cm/sec.}, \quad C = 120^\circ \text{C/cm.} \)
PLATE 60a
Al/Si Eutectic - transverse section
(R = 2.78 \times 10^{-5} \text{cm/sec.}, C = 29.5^0 \text{C/cm.})

PLATE 60b
Al/Si Eutectic - transverse section
(R = 2.78 \times 10^{-5} \text{cm/sec.}, C = 3.5^0 \text{C/cm.})
TABLE 61 - showing the Variation of the Projected Free Edge Distance (d) and the Internodal Separation (λ) with Specimen Temperature Gradient (G) in Angular (⟨100⟩ Si-type) Al/Si Eutectic Alloys.

(μ was constant and equal to 2.78 x 10^{-5} cm/sec)

<table>
<thead>
<tr>
<th>G°C/cm</th>
<th>d (μ)</th>
<th>λ (μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>75</td>
<td>32</td>
<td>62</td>
</tr>
<tr>
<td>45</td>
<td>55</td>
<td>85</td>
</tr>
<tr>
<td>29.5</td>
<td>83</td>
<td>100</td>
</tr>
<tr>
<td>16.0</td>
<td>150</td>
<td>160</td>
</tr>
<tr>
<td>3.5</td>
<td>420</td>
<td>300</td>
</tr>
</tbody>
</table>
FIG. 62  A Graph showing the Dependence of the Projected Free Edge Distance (d) and the Internodal Separation ($\lambda$) on Specimen Temperature Gradient ($G$) in Angular ($<100>$ Si-type) Al/Si Eutectic Alloys (see table 61)
PLATE 63a
Al/Si Eutectic - transverse section
(\( R = 2.70 \times 10^{-5} \text{cm/sec.}, \quad \alpha = 29.5^\circ \text{C/cm.} \))

PLATE 63b
Al/Si Eutectic - transverse section
(\( R = 6.48 \times 10^{-5} \text{cm/sec.}, \quad \alpha = 29.5^\circ \text{C/cm.} \))
PLATE 64a  Al/Si Eutectic - transverse section
(R = 1.30 \times 10^{-4}\text{cm/sec.}, \theta = 29.5^\circ\text{C/cm.})

PLATE 64b  Al/Si Eutectic - transverse section
(R = 2.5 \times 10^{-4}\text{cm/sec.}, \theta = 29.5^\circ\text{C/cm.})
<table>
<thead>
<tr>
<th>$R$ cm/sec</th>
<th>$d$ (µ)</th>
<th>$\lambda$ (µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.78 \times 10^{-5}$</td>
<td>83</td>
<td>100</td>
</tr>
<tr>
<td>$6.48 \times 10^{-5}$</td>
<td>80</td>
<td>98</td>
</tr>
<tr>
<td>$1.30 \times 10^{-4}$</td>
<td>74</td>
<td>86</td>
</tr>
<tr>
<td>$2.5 \times 10^{-4}$</td>
<td>46</td>
<td>62</td>
</tr>
</tbody>
</table>

**Table 65** - showing the Variation of the Projected Free Edge Distance ($d$) and the Internodal Separation ($\lambda$) with Specimen Growth Rate ($R$) in Angular ($\langle 100\rangle$ Si type) Al/Si Eutectic Alloys.

($G$ was constant and equal to $29.5^\circ$C/cm)
FIG. 66 A Graph showing the Dependence of the Projected Free Edge Distance (d) and the Internodal Separation (λ) on Specimen Growth Rate (R) in Angular (\(<100>\) Si-type) Al/Si Eutectic Alloys (see table 65)
PLATE 67a  
Al/Si Eutectic - longitudinal section  
\( R = 3.7 \times 10^{-4} \text{cm/sec.}, \ G = 16 \text{ C/cm.} \)

PLATE 67b  
Al/Si Eutectic - Quenched Growth  
Front (after Chadwick, 1965 - growth conditions similar to Plate 57a)
**PLATE 60a**  
Extracted Fibrous and Platelike Irregular Silicon  
\( R = 3.7 \times 10^{-4} \text{cm/sec.}, \quad \alpha = 16.0^\circ \text{C/cm.} \)

**PLATE 60b**  
Extracted Fibrous and Platelike Irregular Silicon  
\( R = 3.7 \times 10^{-4} \text{cm/sec.}, \quad \alpha = 16.0^\circ \text{C/cm.} \)
PLATE 69a  An extracted Idiomorphic Silicon Plate
($R = 3.7 \times 10^{-4}\text{cm/sec.}, G = 16^\circ\text{C/cm.}$)

PLATE 69b  An Extracted Idiomorphic Silicon Plate
($R = 3.7 \times 10^{-4}\text{cm/sec.}, G = 16^\circ\text{C/cm.}$)
**PLATE 70a**

An Extracted Triangular Silicon Plate  
(see fig. 74a)  
($R = 3.7 \times 10^{-4} \text{cm/sec.}, C = 16^\circ \text{C/cm.}$)

**PLATE 70b**

An Extracted Triangular Silicon Plate  
(see fig. 74a)  
($R = 3.7 \times 10^{-4} \text{cm/sec.}, C = 16^\circ \text{C/cm.}$)
An Extracted Silicon Lath (see fig. 74b)

\[ R = 3.7 \times 10^{-4} \text{ cm/sec., } G = 16^\circ \text{C/cm.} \]
X-Ray Laue Photograph taken normal to an extreced (111) Irregular particle containing a (111) Spine Twin
A Back Reflection Oscillation Photograph (Cu Kα X (3))

about the Growth Direction of a Silicon Lath

Crystal in Al/Si Eutectic Alloy

(R = 3.7 \times 10^{-4} \text{cm/sec}, \ C = 16.0^\circ/\text{cm})
FIG. 74a  Triangular Silicon Plate

FIG. 74b  Lath-shaped Silicon Plate
PLATE 75a
Side View of Fractured Silicon Lath
\[ R = 3.7 \times 10^{-4} \text{ cm/sec}, \ G = 16^\circ \text{C/cm.} \]

PLATE 75b
Silicon Lath Fractograph
\[ R = 3.7 \times 10^{-4} \text{ cm/sec}, \ G = 16^\circ \text{C/cm.} \]
C.P.4 Etched Al/Si Eutectic - longitudinal section

(R = 3.7 x 10^{-4} cm/sec., C = 3.5^0C/cm.)
PLATE 77a  C.P.4 Etched Al/Si Eutectic - longitudinal section  
\( R = 3.7 \times 10^{-4} \text{ cm/sec.}, \; G = 3.5^\circ C/\text{cm} \)

PLATE 77b  C.P.4 Etched Al/Si Eutectic - longitudinal section  
\( R = 3.7 \times 10^{-4} \text{ cm/sec.}, \; G = 3.5^\circ C/\text{cm} \)
**PLATE 76a**

Heavily Etched Al/Si Eutectic - growth direction 45° to normal of paper

\[ R = 3.7 \times 10^{-4} \text{cm/sec.}, \; C = 16^\circ \text{C/cm.} \]

**PLATE 76b**

Heavily Etched Al/Si Eutectic - growth direction 45° to normal of paper

\[ R = 3.7 \times 10^{-4} \text{cm/sec.}, \; C = 16^\circ \text{C/cm.} \]
Heavily Etched Al/Si Eutectic - growth direction 60° to normal of paper

\[ R = 3.7 \times 10^{-4} \text{cm/sec.}, \ g = 16^\circ C/cm. \]
PIATE 80a

Al/Si Eutectic - transverse section

($R = 3.7 \times 10^{-4} \text{cm/sec.}$, $G = 29.5^\circ \text{C/cm.}$)

PIATE 80b

Al/Si Eutectic - transverse section

($R = 6.3 \times 10^{-4} \text{cm/sec.}$, $G = 29.5^\circ \text{C/cm.}$)
PLATE 81a  Al/Si Eutectic - transverse section

\( R = 7.41 \times 10^{-4} \text{ cm/sec.}, C = 29.5^\circ \text{C/cm.} \)

PLATE 81b  Al/Si Eutectic - transverse section

\( R = 1.37 \times 10^{-3} \text{ cm/sec.}, C = 29.5^\circ \text{C/cm.} \)
<table>
<thead>
<tr>
<th>$R$ cm/sec</th>
<th>$\lambda$ irregular ((\mu))</th>
<th>$\lambda$ webs ((\mu))</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.70 \times 10^{-4}$</td>
<td>11.54</td>
<td>4.31</td>
</tr>
<tr>
<td>$5.0 \times 10^{-4}$</td>
<td>9.92</td>
<td>3.77</td>
</tr>
<tr>
<td>$6.3 \times 10^{-4}$</td>
<td>8.63</td>
<td>3.38</td>
</tr>
<tr>
<td>$7.41 \times 10^{-4}$</td>
<td>7.69</td>
<td>3.15</td>
</tr>
<tr>
<td>$1.37 \times 10^{-3}$</td>
<td>5.77</td>
<td>2.46</td>
</tr>
</tbody>
</table>

**TABLE 82** - showing the Variation of the Interparticle Spacing (\(\lambda\)) with Specimen Growth Rate (\(R\)) for both Irregular and Complex Regular Al/Si Eutectic Alloys.

(C was constant and equal to 29.5°C/cm)
FIG. 83 A Graph showing the Dependence of the Interparticle Spacing \( (\lambda) \) on the Specimen Growth Rate \( (R) \) for both Irregular and Complex Regular Al/Si Eutectic Alloys (see table 82)
PLATE 84a  Rapidly Quenched Al/Si Eutectic

PLATE 84b  Heavily Etched Rapidly Quenched Al/Si Eutectic
PLATE 85a  Heavily Etched Rapidly Quenched Al/Si Eutectic

x 7,500

PLATE 85b  Heavily Etched Rapidly Quenched Al/Si Eutectic

x 15,000
PLATE 86a  
**Al/Si Eutectic - transverse section**  
($R = 3.7 \times 10^{-4} \text{cm/sec.}, G = 29.5^\circ \text{C/cm.}$)

PLATE 86b  
**Al/Si Eutectic - transverse section**  
($R = 3.7 \times 10^{-4} \text{cm/sec.}, G = 29.5^\circ \text{C/cm.}$)
PLATE 87a

Al/Si Eutectic - transverse section

\( R = 3.7 \times 10^{-4} \text{cm/sec}, \ G = 29.5^\circ \text{C/cm} \)

---

PLATE 87b

Al/Si Eutectic - transverse section

\( R = 3.7 \times 10^{-4} \text{cm/sec}, \ G = 29.5^\circ \text{C/cm} \)
FIG. 88 Complex Regular Silicon Particles - Platelet/Spine Angle Histogram
PLATE 89a
Al/Si Eutectic - longitudinal section
(R = 3.7 x 10^{-4} cm/sec., G = 29.5°C/cm.)

PLATE 89b
Al/Si Eutectic - longitudinal section
(R = 3.7 x 10^{-4} cm/sec., G = 29.5°C/cm.)
PLATE 90a

Extracted Complex Regular Si Particle

\( R = 3.7 \times 10^{-4} \text{ cm/sec.}, \ G = 29.5^\circ \text{C/cm.} \)

x 125

PLATE 90b

Extracted Complex Regular Si Platelets

\( R = 3.7 \times 10^{-4} \text{ cm/sec.}, \ G = 29.5^\circ \text{C/cm.} \)
Plate 21

X-Ray Rotation Photograph (Cu Kα X-ray radiation) showing the \( <110> \) preferred growth direction of an Extracted Complex Regular Silicon Particle
FIG. 92 [011] Stereographic Projection showing the Spine/Platelet Relationship of a Simple Web (see fig. 93a)
FIG. 93a  A Simple Web (see fig. 92)

FIG. 93b  A 1st Order \{111\} Spinel Twinned Web (see fig. 94)
A non-axial (ill) (white) is axially twinned across a (ill) twin boundary to give the observed (ill) (black) platelets
FIG. 95 [011] Stereographic Projection with a Non-axial (111) Spinel Twin
FIG. 96 Some Transverse Sections of Silicon Web Forms. (simple and 1st order twin spine/platelet relationships only) Red is related to black via an axial \( \{111\} \) spinel twin. The numbers indicate the number of inclined platelet systems. (see figs. 93)
FIG. 97a  A 2nd Order \{111\} Spinel Twinned Web
(see fig. 98)

FIG. 97b  Another 2nd Order \{111\} Spinel Twinned Web
(see fig. 100)
FIG. 98  [011] Stereographic Projection Showing the Spine/Platelet Relationship of a 2nd Order Twinned Web (see fig. 97a)

An axial (111) (white) is non-axially twinned across a 1st order (111) twin boundary and then non-axially twinned across a 2nd order (111) twin boundary to give the observed (111) (red) platelets
FIG. 99  [011] Stereographic Projection Showing the Spine/Platelet Relationship of a 2nd Order Twinned Web

A non-axial (001) (white) is axially twinned across a 1st order (111) twin boundary and then non-axially twinned across a 2nd order (111) twin boundary to give the observed (001) (red) spine
FIG. 100  [011] Stereographic Projection Showing the Spine/Platelet Relationship of a 2nd Order Twinned Web (see fig. 97b)

A non-axial (\{11\} white) is axially twinned across a 1st order (\{11\} twin boundary and then non-axially twinned across a 2nd order (\{11\} twin boundary to give the observed (\{11\}) (red) platelets
PLATE 101a  Al/Si Eutectic - transverse section
\( R = 3.7 \times 10^{-4} \text{cm/sec.}, G = 29.5^\circ \text{C/cm.} \)

PLATE 101b  Al/Si Eutectic - transverse section
\( R = 3.7 \times 10^{-4} \text{cm/sec.}, G = 120^\circ \text{C/cm.} \)
PLATE 102a  
Al/Si Eutectic - transverse section  
\((R = 1.30 \times 10^{-4}\text{ cm/sec.}, G = 16.0^\circ\text{C/cm.})\)

PLATE 102b  
Al/Si Eutectic - longitudinal section  
\((R = 1.30 \times 10^{-4}\text{ cm/sec.}, G = 16.0^\circ\text{C/cm.})\)
X-Ray Rotation Photograph (Cu Kα radiation) about the growth axis of an Al/Si Eutectic Specimen

(R = 1.30 x 10^-4 cm/sec, \theta = 20.5°/cm.)
FIG. 104 Line Drawing of an Observed (100) Smooth Plate with an Irregular (111) Plate attached
PLATE 105a

Extracted Angular/Irregular Silicon
$(R = 1.30 \times 10^{-4} \text{cm/ sec.}, \quad \alpha = 16.0^\circ \text{C/cm.})$

PLATE 105b

Extracted Angular/Irregular Silicon
$(R = 1.30 \times 10^{-4} \text{cm/sec.}, \quad \alpha = 16.0^\circ \text{C/cm.})$
Heavily Etched Al/Si Eutectic - growth direction normal to paper

\( R = 1.30 \times 10^{-4} \text{cm/sec.}, \ G = 16.0^\circ \text{C/cm.} \)

Heavily Etched Al/Si Eutectic - growth direction 40° to normal of paper

\( R = 1.30 \times 10^{-4} \text{cm/sec.}, \ G = 16.0^\circ \text{C/cm.} \)
Heavily Etched Al/Si Eutectic - growth direction 60° to normal of paper

\[ R = 1.30 \times 10^{-4} \text{ cm/sec.}, \ G = 16^\circ \text{C/cm.} \]
PLATE 108a  C.P.4. Etched Al/Si Eutectic - longitudinal section  
\( R = 2.78 \times 10^{-5} \text{cm/sec.}, C = 3.5^\circ \text{C/cm.} \)

PLATE 108b  C.P.4. Etched Al/Si Eutectic - longitudinal section  
\( R = 2.78 \times 10^{-5} \text{cm/sec.}, C = 3.5^\circ \text{C/cm.} \)
PLATE 109a  Anodised Al/Si Eutectic - transverse section
(R = 1.54 x 10^{-5} cm/sec., C = 300°C/cm.)

x 125

PLATE 109b  Anodised Al/Si Eutectic - transverse section
(R = 1.54 x 10^{-5} cm/sec., C = 300°C/cm.)

x 125
PLATE 110a  Ag/Si Eutectic - transverse section
(R = 2.78 x 10^-5 cm/sec., C = 30°C/cm.)

PLATE 110b  Ag/Si Eutectic - longitudinal section
(R = 2.78 x 10^-5 cm/sec., C = 30°C/cm.)
PLATE IIIa  Extracted Silicon Particles
\( R = 2.78 \times 10^{-5} \text{cm/sec.}, \quad C \approx 30^\circ \text{C/cm.} \)

PLATE IIIb  Extracted Silicon Particle
\( R = 2.78 \times 10^{-5} \text{cm/sec.}, \quad C \approx 30^\circ \text{C/cm.} \)
PLATE 112a  
Extracted Silicon Particles  
\((R = 2.78 \times 10^{-5}\text{cm/sec.}, G \approx 30^\circ\text{C/cm.})\)

PLATE 112b  
Extracted Silicon Particles  
\((R = 2.78 \times 10^{-5}\text{cm/sec.}, G \approx 30^\circ\text{C/cm.})\)
PLATE 113

X-Ray Rotation Photograph (Cu Kα radiation) about the Growth Axis of a Ag/Si Epitaxic Specimen

$R = 2.76 \times 10^{-5}$ cm/sec., $c \approx 30^\circ$/cm.


**PICTURE 114a**

_Ag/Si Eutectic - transverse section_

\[(R = 2.78 \times 10^{-5} \text{cm/sec.}, G \approx 30^\circ\text{C/cm.})\]

**PICTURE 114b**

_Ag/Si Eutectic - transverse section_

\[(R = 7.41 \times 10^{-4} \text{cm/sec.}, G \approx 30^\circ\text{C/cm.})\]
PLATE 115a  Au/Si Eutectic - transverse section
(R = 2.78 \times 10^{-5} \text{cm/sec.}, \sigma \approx 30^\circ \text{C/cm.})

PLATE 115b  Au/Si Eutectic - longitudinal section
(R = 2.78 \times 10^{-5} \text{cm/sec.}, \sigma \approx 30^\circ \text{C/cm.})
Solute Distribution Curves for Al/Si Eutectic Alloy growing with a Planar Aluminium Growth Front
FIG. 117a  A Silicon Particle containing One
Twin Plane (c.f. fig. 74a)

FIG. 117b  A Silicon Particle containing Two
Twin Planes (c.f. fig. 74b)
FIG. 118a  A Model of a $\frac{1}{3} a \langle 110 \rangle$ Screw Dislocation in A Diamond Cubic Material. (after Hornstra 1958)

FIG. 118b  A Model of the Proposed Growth Front for Angular Eutectic Silicon Particles
FIG. 119 Model showing the Proposed Growth Front for Angular Eutectic Silicon Particles containing a Corrugated Side Plate
FIG. 120  A Graph showing a Possible Relationship between the Undercooling (ΔT) and the Imposed Growth Rate (R) for Screw Dislocation and Spinel Twin based Mechanisms
PLATE 121a  
**Al/Ge Eutectic - longitudinal section**  
\( R = 2.5 \times 10^{-6} \text{ cm/sec.}, \theta \approx 30^\circ \text{C/cm.} \)  
(after Hellawell 1967a)

PLATE 121b  
**Al/Ge Eutectic - transverse section**  
\( R = 3 \times 10^{-5} \text{ cm/sec.}, \theta \approx 30^\circ \text{C/cm.} \)  
(after Hellawell 1967a)
FIG. 122 Model of the Proposed Growth Front for a Complex Regular Eutectic Silicon Particle

PLATE 122 A Quenched Al/Ge Web Interface
\[ R = 3 \times 10^{-7} \text{ cm/sec.}, \ G = \sim 30^\circ \text{C/cm.} \]
(after Hellawell 1967a)
<table>
<thead>
<tr>
<th>Eutectic alloy and growth conditions</th>
<th>Na concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace cooled Al/Si eutectic</td>
<td>0.011 wt.%</td>
</tr>
<tr>
<td>&quot;            &quot;   Au/Si eutectic</td>
<td>0.016 wt.%</td>
</tr>
<tr>
<td>&quot;            &quot;   Au/Si eutectic</td>
<td>0.092 wt.%</td>
</tr>
<tr>
<td>R = 2.76 x 10^{-5} cm/sec</td>
<td></td>
</tr>
<tr>
<td>Al/Si eutectic</td>
<td>0.014 wt.%</td>
</tr>
<tr>
<td>G = 29.5°C/cm</td>
<td></td>
</tr>
<tr>
<td>R = 1.37 x 10^{-3} cm/sec</td>
<td>0.009 wt.%</td>
</tr>
<tr>
<td>Al/Si eutectic</td>
<td></td>
</tr>
<tr>
<td>G = 29.5°C/cm</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 123** - Sodium Concentration of Various Doped F.C.C. Metal/Silicon Eutectic Alloys.
PLATE 124a  Sodium Modified Furnace-cooled Al/Si Eutectic

PLATE 124b  Furnace-cooled Al/Si Eutectic
PLATE 125a  Sodium Modified Furnace-cooled
Al/Si Eutectic
(heavily etched)

PLATE 125b  Sodium Modified Furnace-cooled
Al/Si Eutectic
(heavily etched)
PLATE 126a  Sodium Modified Furnace-cooled Ag/Si Eutectic

PLATE 126b  Furnace-cooled Ag/Si Eutectic
PLATE 127a  Sodium Modified Furnace-cooled Au/Si Eutectic

PLATE 127b  Furnace-cooled Au/Si Eutectic
PLATE 128a  Sodium Modified Al/Si Eutectic - transverse section

\( R = 1.37 \times 10^{-3}\text{cm/sec.}, \ C = 29.5^\circ\text{C/cm.} \)

PLATE 128b  Al/Si Eutectic - transverse section

\( R = 1.37 \times 10^{-3}\text{cm/sec.}, \ C = 29.5^\circ\text{C/cm.} \)