CHAPTER V
TRANSVERSE STRIATIONS AND GROWTH FEATURES
IN Bi–Sb SINGLE CRYSTALS

This chapter deals with a systematic study of the transverse striations observed on the top free surface and the lamellar dendritic growth features observed on cleavage plane of the crystals grown from melt by zone melting method. The important features of transverse striations are discussed in detail and a possible correlation between the transverse striations, and dendritic growth pattern observed on the cleavage plane is suggested. Only a limited number of photographs has been included in this thesis.
When metal, semiconductor or alloy crystals are grown from the melt it has been observed that the distribution of impurities becomes heterogeneous. For example, crystals grown in \( \langle \text{iii} \rangle \) direction has increased impurity concentration in the central part of the grown crystal, known as 'coring'. Another type of impurity heterogeneity is the periodic variation in impurity concentration along the growth axis. This is exhibited by striations in metal single crystals pulled from the melt by a rotating seed holder, or without rotation (Czochralski method). These striations which appear as bands or lines of increased impurity concentration assume the shape of the growing crystal-melt interface. The striations running normal to the growth direction and parallel to the solid-liquid interface are termed as 'transverse striations'. This is to distinguish them from striations, which run parallel to the growth direction. The transverse striations are the outcome of a periodic growth rate, whereas the longitudinal striations are associated with cellular structures. Such striations were reported by Teghtsoonian and Chalmers. In the present work attention is concentrated only on the study of transverse...
striations and an attempt is made to associate them with the dendritic growth of the crystal.

Several workers have reported the occurrence of transverse striations on the crystals grown by them. Alfred and Bate observed striations on crystals grown by vertical Czochralski technique with rotations. Gatos et al. have reported transverse striations in the selenium doped Indium-Antimonide crystals pulled from the melt.

Morizane et al. have reported striations on single crystals of In-Sb pulled without rotation from the melt in the presence of Tellurium or Selenium impurity employing a Czochralski type apparatus. The formation of pronounced periodic and nonperiodic impurity striations was observed, their appearance and origin were studied as a function of the thermal conditions prevailing in the immediate vicinity of the solid-melt interface. They concluded that the formation of such striations is the result of temperature fluctuations at the interface brought about by convection currents in the melt which in turn are caused primarily by sharp temperature
gradients, in the growing crystal near the interface. Further, it was shown that the formation of impurity striations in nonrotated, pulled crystals, is independent of such parameters as orientation, pulling rate fluctuations, and the amount and type of impurity contents. Consequently they believed that the formation of striations is not directly related to the mechanism of crystal growth. They further expressed considerable doubt on attempts to explain striations exclusively on the basis of supercooling and recovery phenomena as reported by Le May.9

Muller and Wilhelm10 found temperature fluctuations with constant frequency (0.15−1) and nearly constant amplitude of several degrees in molten In-Sb. During crystallization (Unilateral solidifying and zone melting) they found, inhomogeneities like striations normal to the direction of crystallization, caused by temperature fluctuations.

Yim11 observed closely spaced parallel arrays of striations in Bismuth-Antimony alloy crystals prepared by horizontal zone-leveling technique.
Detailed investigation by Yim has shown that irregular growth rate results from thermal fluctuations in the melt during the crystal growth process and hence according to him, transverse striations result from the temperature fluctuations in the melt at the solid-liquid interface.

Resistivity striations arising from the periodic distribution of the impurities are reported by Ueda\textsuperscript{12} in Germanium crystals grown by zone-leveling technique. Transverse striations parallel to the p-n junction were observed after electrolytic etching on the crystal surfaces. It was further observed by them that when crystals containing striations were subjected to heat treatment, striations disappeared. Detailed investigations showed that the striation spacing was proportional to the average growth rate and inversely proportional to the temperature gradient within the crystal near the solid-liquid interface. Even after eliminating the fluctuations in the growing conditions like furnace temperature, jerky motion of the growth rate, they found that the process of development of transverse striations remained unaltered.
Resistivity striations were observed by Camp in polycrystalline and single crystal of Germanium. The striations are believed to result from changes in the rate of advance of the growing interface. He further showed that when the rate is slow the impurity rejected by the solid are largely dispersed throughout the melt by diffusion and mixing. When the rate is fast, a bow wave of impurities forms at the growing interface. This results in an artificially high concentration of impurities in the melt which the interface sees, and consequent increase in the impurity is accepted by the solid.

De Kock et al. observed striations on high resistive floating zone silicon crystals by selective etching of pre-annealed longitudinal Silicon crystal slices. The required pre-annealing treatment was carried out at a temperature between 1000°C and 1200°C in a tubular furnace. A model for the striations revealing is proposed.

Recently experimental and theoretical studies of interface shapes and striation structures were performed by Jindal et al. on Aluminium doped
Silicon single crystals. The interface shapes were observed to be complex, variable and with no evidence of single crystal facet. The striations were of varying length, frequency, intensity and were not parallel to each other. Theoretical calculations of variations of Aluminium concentrations in the crystal as a function of the variation of crystal growth rate showed that, for a few per cent excess Aluminium concentrations to occur over a distance of a few microns along the growth direction, the growth rate should increase by at least an order of magnitude.

From the work reported by the various workers, it can be concluded that the transverse striations on the crystals is a feature common to all crystals grown from melt, irrespective of their material and technique used for their growth. This leads the author to the belief that all the observed striations have a common cause and that this cause must have a close connection with some physical condition which prevails at or near the solid-liquid interface during the actual process of crystal growth. The previous workers have attributed these striations to the periodic
growth rate but the cause for such growth rate fluctuations are not definitely known. Some workers regard the cause to be purely external, such as fluctuations in the furnace temperature, jerky motion of the crystal pulling mechanism or a non-symmetrical temperature distribution in the melt. Others try to find cause in some fundamental property of the growth process itself.

The present author has therefore carried out a systematic study of the development of transverse striations in Bi-Sb alloys single crystals. The results are reported as under:

Homogeneous single crystals of Bi-Sb with Antimony composition from 1 at.% to 12 at.% were grown by zone melting technique described in chapter III. The transverse striations on the top free surface of freshly grown single crystals were studied by optical methods using Vickers Projection Microscope.

Fig.V-1 shows transverse striations observed on the top free surface of the crystal (Bi$_{99}$Sb$_1$)
grown with the velocity 0.4 cm/hr. The temperature gradient in the furnace was 65°C/cm. An array of strictly parallel lines (striations) is clearly visible in the photomicrograph. The striations are running normal to the growth direction and parallel to the solid-liquid interface.

No striations were observed on the underneath surface of the crystal which was in contact with the pyrex glass tube. This was due to the curvature of the solid-liquid interface in that region, resulting from the heat being conducted away through the glass. The mean distance of separation of striations measured by precision comparator was found to be 10 μ.

To understand the mechanism responsible for the formation of transverse striations, crystals were grown at different growth velocities ranging from 0.4 cm/hr to 2.0 cm/hr. The temperature gradient in the furnace was kept constant (65°C/cm) throughout the entire process of crystal growth.

Fig. V-2 shows the striations on the top free surface of Bi_{99}Sb_{1} single crystals grown with the
velocity 0.7 cm/hr. The mean distance of separation of striations was found to be 18 μm.

When the crystals were grown with the velocity 1.0 cm/hr, the mean distance of separation of striations was found to be 23 μm. In addition to the transverse striations, the ridges (grooves) running parallel to the growth axis are also observed. Fig. V-3 is a photomicrograph showing the striations and ridges (grooves) observed on the top free surface. It is interesting to note that the striations are strictly parallel but they get bent as they cross ridges (grooves).

If however, the growth velocity exceeded 1.0 cm/hr, it was found that the striations completely disappeared leaving only ridges on the surface as shown in Fig. V-4.

It can be concluded from the above observations that the mean distance of separation of striations increases with the growth velocity, when the temperature gradient in the furnace is kept constant. Similar results were obtained for crystals containing Antimony composition up to 12 at%. Table V-1 shows the mean
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<th>Alloy composition</th>
<th>Growth velocity (cm/hr)</th>
<th>Mean interstriations spacing (µm)</th>
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<tr>
<td>Bi_{99}Sb_{1}</td>
<td>0.2</td>
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<td></td>
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<td></td>
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<td>18.0</td>
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<tr>
<td></td>
<td>0.8</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Bi_{95}Sb_{5}</td>
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<td>12.0</td>
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<tr>
<td>Bi_{90}Sb_{10}</td>
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<td>Bi_{88}Sb_{12}</td>
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distance of separation of striations at different growth velocities ranging from 0.4 cm/hr to 1.0 cm/hr for alloys of different compositions.

This led us to investigate the factors responsible for the development of ridges and for the bending of striations as they cross these ridges.

To understand this phenomena, a study of the solid-liquid interface by decanting technique was undertaken. It was observed that when the growth velocity was very low (upto 0.6 cm/hr) the solid-liquid interface was either plane or step like. But when the growth velocity reached 0.7 cm/hr, the solid-liquid interface exhibited cellular structure as shown in Fig.V-5. The development of a cellular structure was first described by Smialowski\textsuperscript{16} and also observed by Graf\textsuperscript{17}, Chalmers and Cahn\textsuperscript{18} and Goss and Weintraub\textsuperscript{19}. It has been shown however (Rutter and Chalmers\textsuperscript{20}) that the interface of the crystal solidifying under the condition leading to the formation of cellular structure is not plane, but is composed of convex regions at the cell ends, separated by grooves. These grooves are the terminations of the
cell boundaries at the interface. In the present case the ridges (grooves) observed (Fig.V-4) on the top free surface and running parallel to the growth axis are associated with the cellular substructure, developed on account of constitutional supercooling. The ridges obstruct the movement of planes during crystal growth which results in the bending of striations.

Modrzejewski\textsuperscript{21} has reported the study of the interface by thermal growth conditions on striation formation in Aluminium and Lead single crystals, grown by Bridgman's method. It was shown that in crystals where striations did not appear, the cellular structure was well developed, while the appearance of striations was accompanied by the disappearance of the cellular substructure. Contrary to this the present author has observed both, the striations and the ridges (grooves), as shown in Fig.V-3.

When the growth velocity exceeds 1.0 cm/hr, the striations completely disappear leaving only ridges on the top free surface. It seems that, as the growth velocity increases, the degree of
supercooling also increases, and the motion of solid-liquid interface becomes irregular, which results in the disappearance of striations.

The effect of impurity on the formation of striations was also studied. When the crystals were grown using Bismuth 99.9% purity, keeping other parameters as before, no striations were observed even at low growth velocities. This probably shows that the macro-segregation inhibitates the development of striations.

When crystals were grown, using high purity zone-refined Bismuth and Antimony, it was found that the striations were not observed in the absence of proper zone-leveling i.e., when the ratio of zone length to charge length was not precisely maintained and the number of passes were not sufficient to get homogeneous charge. This probably indicates that the homogeneity of the charge plays an important role in the development of striations.

In addition to the above mentioned observations it was found that in some crystals, on scanning the
top free surface, the direction of striations was different in different regions, indicating thereby that the growth had not proceeded strictly only in one direction. To check whether the striations are surface phenomena or body phenomena, crystals exhibiting striations were deeply polished either chemically or electrolytically. Fig. V-6(a) and 6(b) show the striations before and after polishing. The photomicrographs clearly show that there is no apparent change in the appearance of striations. This suggests that the striations are not mere surface structures but are the outcome of some body phenomena.

In general the salient noteworthy features of striations may be summarized as follows:

(1) For low growth velocity, the mean distance of separation of striations increases with the growth velocity (temperature gradient is kept constant).

(2) When the growth velocity reaches about 0.7 cm/hr ridges are observed in addition to the usual striations. The ridges (grooves) run perpendicular to striations, and at their crossings the striations become curvilinear.
(3) If however, the growth velocity exceeded 1.0 cm/hr, the striations completely disappeared leaving only ridges on the surface.

(4) No striations were observed unless the constituent metals were high purity zone refined. This probably shows that macro-segregation inhibitates the development of striations.

(5) Even in the case of high purity constituent metals, if proper zone-leveling was not done, the striations were not observed, indicating thereby, that the homogeneity of the crystal plays an important role in the development of striations.

(6) The striations remain parallel throughout the top free surface only when the growth proceeded strictly in one direction. If there is a variation in growth direction, the striations have different directions in different regions.
(7) Striations continue to appear even when the top free surface was repeatedly polished. This suggests that striations are not mere surface structures but are the outcome of some body phenomena.

The author agrees with the previous workers that periodic distribution of impurities resulting from thermal fluctuations are responsible for the development of transverse striations. The very fact that the striations are body phenomena and that they are associated with some growth process, it is likely that the striations should be reflected as some features on an interior crystal plane inclined to the top free surface. As Bi-Sb crystals have perfect (111) cleavage plane, the author felt that the study of microtopography of cleavage surfaces may throw some light on the origin of transverse striations.

Single crystals containing 12 at.% Antimony and exhibiting striations on the top free surface were therefore cleaved along the (111) plane. The freshly cleaved specimens were examined, using Vickers Projection
Microscope. No unusual features, except the cleavage lines and twin bands were observed. However, when the cleavage surface of a few grown crystals was etched in the solution, containing

\[ \text{22} \]

- 4 parts nitric acid (A.R. Quality, 70%),
- 7 parts tartaric acid (saturated solution), and
- 1 part water.

Characteristic concentric triangular features were observed as shown in Fig. V-7. The scattered small triangles are random etch pits having orientation exactly opposite to the observed triangular features. It seems that these triangular features are due to the lateral growth of dendrites and due to different etch rate the pattern is visible only after etching. No such characteristic concentric triangular features were observed on the crystals containing Antimony up to 11 at.%

Skvortsov\textsuperscript{23} has observed almost similar lateral dendritic growth pattern in germanium crystals. Etching technique was used to reveal the lateral growth pattern of Germanium dendrites of twin layer thickness over 7 \( \mu \). It was further reported that the character of the
lateral growth is very much dependant on the thickness of the twin layer and unidirectional growth is characteristic of dendrites with thick twin layers.

Smith, and Faust and John were first to examine the lateral growth of the dendritic Germanium. Smith concluded from the pattern formed by Copper deposited on the principal face that the growth in width occurs by propagation of \( [111] \) layers from the zig-zag side surface of the trunk, with infilling of some re-entrant angles and the reproduction of coarser dentate relief at the edges. Faust and John used etching technique to examine the growth mechanism. It was shown that the etch rate of crystals heavily doped with As, Sb and Bi in certain reagents is dependant on the dope concentration. The dope is unevenly trapped and rejected as the dendritic strip grows, etching reveals concentration differences, and hence the growth pattern.

Fig. V-8 shows a parallel dendritic growth pattern in the region far away from the centre of the triangular features. One straight edge of the triangular features is clearly visible in the photomicrograph.
It is known that when a solid-liquid interface is below the equilibrium temperature, solidification begins. The latent heat evolved tends to decrease the degree of supercooling and suppress the solidification process. The rate of removal of latent heat therefore controls the rate at which solidification can continue and the interface temperature adjusts itself so that it corresponds to the rate of solidification determined by the externally imposed thermal conditions. Now the thermal conditions and the orientation of the surface govern the local rate of growth, which results in a complicated morphology that may occur during solidification. It was shown by Weinberg and Chalmers that for a slow rate of supercooling in 'pure' liquid metal, the interface is smooth on a microscopic but not on atomic scale. If however, the supercooling takes place at a faster rate either due to changes in external conditions or due to the presence of impurities in the melt, dendritic solidification takes place. Weinberg and Chalmers have also shown that the arm of dendrites always grow in the crystallographically determined directions.
Several workers have reported dendritic growth of metal and alloy crystals.

Ludwing Grof\(^{28}\) reported the growth mechanism of metal and salt crystals. It was shown that the high growth rates lead to dendritic form with purely defined faces which can be considered as kinetic equilibrium forms. Growth of low indexed planes (tetragonal) takes place only due to the phase equilibrium, whereas other phenomena prevail away from it.

Liaw and Faust\(^{29}\) reported habits, morphology and internal structure of Lead dendrites grown from gels. Growth was found to proceed in three stages. The first stage showed mainly single crystal dendrites growing in the \(\langle 100\rangle\) direction, while the second and third stages gave dendrites growing in the \(\langle 211\rangle\) direction. All the dendrites were faceted by \(\{111\}\) family planes. The second and third stage of the dendrites were shown by the twin plane re-entrant edge mechanism.

Sugiyama and Umeda\(^{30}\) have reported the study of dendritically grown Cu-Sn alloy with different growth conditions.
Ahearn and Flemings\textsuperscript{31} showed dendritic morphology of the unidirectionally solidified Sn-Bi alloy with the aid of X-ray and macroetch techniques. Columnar growth direction (growth direction of the primary arm) in this alloy is \([110]\), the secondary arm grows in the \([1\bar{1}1]\), \([\bar{1}11]\) and \([112]\) directions. Interstices between \([112]\) dendrite arms fill in during early stage of solidification, so that well-defined \([\bar{1}10]\) planes are seen in the final structure.

Atwater and Chalmers\textsuperscript{32} observed surface markings on Lead dendrites withdrawn from the melt and identified them as traces of \([1\bar{1}1]\) and \([100]\) planes, and showed that the surface of the dendrite, as examined, were terraced, and terraces corresponded to the 'cropping out' of all four sets of \([1\bar{1}1]\) planes and one set of \([100]\) planes. However, they were not satisfied because these traces were presented as features of interface during growth because the traces could have been formed during separation from melt.

Bolling and Tiller\textsuperscript{33} have reported terraced structure on Lead dendrites and identified the traces as close packed i.e. \((111)\) planes and showed that
these terraces were present during the growth of the dendrite.

Tiller has considered theoretically the operations of the platelet system and has proposed an explanation of the process which occurs in the three cases of a pure metal and metal with solute but of insufficient amount to produce constitutional supercooling, and a metal with sufficient solute to give rise to constitutional supercooling. The theory is generally applicable to the f.c.c. crystals only. Tiller has grown single crystals of Lead by thermal valve technique under dendritic condition. The necessary supercooling of the melt was achieved by means of an air jet which was gently played onto liquid just ahead of the interface. The liquid was rapidly decanted during growth and dendrites were examined under microscope. Four conjugate \{111\} platelet systems extended from the tip of a dendrite and each platelet system had a \langle211\rangle axis pointing towards the tip of the dendrite. It was therefore concluded by him, that a dendrite grows from a single platelet system interface into a supercooled melt by the successive operation of two, three and finally four conjugate platelet systems.
It has been shown by the present author that the concentric triangular features observed in Fig. V-8 are due to the lateral growth of dendrites and the pattern is visible only after etching.

It is important to know whether the triangular features are merely surface features or body phenomena, following experiments were undertaken:

(1) Study of the triangular features after successive polishing of the cleavage plane.

(2) Study of the growth pattern on the oppositely matched cleavage faces.

(3) Study of the growth pattern on the top and bottom faces of a thin wafer of a freshly cleaved specimen.

The cleaved surface exhibiting these features was repeatedly polished electrolytically (using the electrolyte reported by Yim et al.\textsuperscript{35}). Figures V-9(a) and 9(b) are the photomicrographs of the pattern before and after deep polishing. There is almost one to one correspondence of the growth pattern before and after polishing, showing that the pattern remains unaltered on deep polishing.
The oppositely matched cleavage faces were etched in a chemical etchant. Figures V-10(a) and 10(b) are the photomicrographs of the growth pattern on the oppositely matched cleavage faces. The photomicrographs clearly show, one to one correspondence of the growth pattern.

The phase contrast photograph of the lateral growth of dendrites in \( \langle 112 \rangle \) direction is shown in Fig. V-11(a). Fig. 11(b) shows the pattern on the oppositely matched cleavage face. There is almost one to one correspondence of the pattern.

When a thin wafer of a freshly cleaved specimen having cleavage faces at its top, and bottom was etched, identical triangular growth pattern was observed in the corresponding regions as shown in Figs. V-12(a) and 12(b).

All these observations confirm that the triangular growth features observed on the cleavage plane are not merely surface features but are outcome of some body phenomena.

Light profile was adjusted on the region of Fig.V-9. The profile shift observed is shown in Fig.V-13. Fig.V-14 shows the multiple beam interferogram taken over the area
of Fig.V-7. The light profile and multiple beam interferogram clearly reveal that the growth pattern has a step like structure.

Fig.V-15 shows triangular dendritic growth pattern on the specimen obtained from the end which was first solidified. The photomicrograph shows the triangular patterns originating from different nuclei (A, B and C). It is interesting to note that the edges of the triangular growth patterns are strictly parallel to one another.

It has been pointed out that the triangular features observed on the cleavage plane are the outcome of some body phenomena and the pattern has a step like structure.

Now, it is important to determine the direction of the edges of the triangular pattern and the indices of the planes responsible for these edges. Stereographic method based on the three trace analysis suggested by Reed-Hill was employed to determine the direction of the edges of the triangular pattern and the indices of the planes responsible for these edges. It was found that
the edges had the directions $[\overline{1}10]$, $[10\overline{1}]$ and $[0\overline{1}1]$
and the planes were of $\{111\}$ family.

The triangular dendritic growth features observed on the cleavage plane may be explained as follows:

It seems that in the present case, when the crystal is grown from the melt, the growth proceeds readily by the extension of the four sets of closed packed, $\{11\}$ planes available in the crystal and hence the necessity of nucleation of fresh lattice plane does not arise. In fact the extension of one or more sets of planes having highest atomic packing leads to the dendrite growth, preferably in $\langle112\rangle$ direction. The observed triangular features on the cleavage plane are due to traces resulting from the intersection of three inclined faces of the tetrahedral pyramid, with the cleavage face. The vertex of the tetrahedral pyramid is the nucleus of the dendrite formed by the addition of layers of $\{111\}$ planes proceeding in $\langle112\rangle$ direction.

Billing\textsuperscript{37} has reported the growth of Germanium crystals from an undercooled melt. He has shown that the dendritic growth in these materials proceeds from
the seed crystal into the melt mainly by extension of one or more sets of the \{111\} family of lattice planes, i.e. along the planes of the highest atomic packing and is especially favoured along \{112\} direction in these planes. Dendritic growth is thus intimately connected with the low co-ordination number of these materials.

Bhide et al.\(^{38}\) have reported the surface studies of the dendritic growth of Germanium crystals. They have observed triangular growth features aligned along the central lines of dendrites and on the opposite faces of the platelet. The results of the present author are thus in agreement with those reported by Billing and Bhide on the dendritic growth of Germanium crystals.

It has been shown that the transverse striations on the top free surface of the single crystals are the outcome of some body phenomena. The lamellar dendritic growth pattern observed on the cleavage plane are also due to some body phenomena.

It seems that there is some connection between the transverse striations observed on the top free surface and the dendritic growth pattern observed on the cleavage plane.
The direction of striations and the indices of the top free surface of those crystals exhibiting triangular pattern were determined by stereographic as well as X-ray methods. The plane of the top free surface was found to belong to \{110\} family and the transverse striation on it were in \langle T10 \rangle direction. The cleavage plane \langle 111 \rangle would then make an angle of 36° with the top free surface. The growth axis had \langle 112 \rangle direction. These directions are schematically shown in Fig. V-16.

Above observations led the present author to believe that the striations on the top free surface are produced by the intersection of one set of \{111\} family planes with it as dendritic growth proceeds. During the growth it is expected that the movement of the advancing plane would be discontinuous (on account of periodic temperature changes, arising probably from convection current near the interface), leaving traces which would appear as a transverse striations. Periodic freezing and remelting at the solid-liquid interface was observed by Komarov and Regel\textsuperscript{39}, even in a stationary Bismuth melt if temperature gradient was greater than about 40°C/cm.
An excellent experimental verification of the above belief is provided by the following observations:

To confirm this parallelism between the direction of striations and one of the edges of the triangular features on the cleavage plane, the edges of the triangular features running in \( [\bar{1}10] \) direction were focused in the microscope. The stage of the microscope was moved in the direction normal to \( [\bar{1}10] \) direction till it reached the common section of the cleavage plane and the top free surface. On shifting it a little further the striation on the top free surface were observed to run in the same \( [\bar{1}10] \) direction. Fig.V-17 is a schematic diagram showing this parallelism.

Conclusions:

(1) High purity of constituent metals (Bismuth and Antimony) and the homogeneity of the alloy formed by them are the two governing factors in the development of transverse striations.

(2) When the impurity content is large or when inhomogeneity exists in the crystal, the movement of the growing set of planes becomes irregular and may
probably terminate before reaching the top free surface which explains the absence of striations.

(3) The absence of striations at high velocity can be attributed to the irregular motion of \{\{111\}\} family planes.

(4) The observed triangular features on the cleavage plane are due to the traces resulting from the intersection of three inclined faces of the tetrahedral pyramid with the cleavage face. The vertex of the tetrahedral pyramid is the nucleus of the dendrite formed by the addition of layers of \{\{111\}\} planes proceeding in \langle{112}\rangle direction.

(5) The striations on the top free surface are produced by the intersection of one set of \{\{111\}\} family planes with it as dendritic growth proceeds.
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