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Czochralski-Type Crystal Growth in Transverse Magnetic Fields

The present communication is a preliminary report on single crystal growth from the melt in the presence of transverse magnetic fields. To our knowledge no experiments on this subject have been reported in the open literature.

The Czochralski type crystal puller used in our previous studies [1] was adopted to a 4 in. pole gap electromagnet (see fig. 1). An infrared heat shield (quartz tube coated on the inside with a 200 Å gold film) was placed outside the furnace to prevent over-heating of the magnet poles. Two stainless steel sheathed and carbon-coated thermocouples (0.020 in. o.d.) were introduced through the hollow pulling shaft and kept at two different positions about $\frac{1}{4}$ in. from the seed; one was immersed $\frac{1}{4}$ in. in the melt (prior to crystal pulling) whereas the other was $\frac{1}{4}$ in. above the melt. All experiments reported here were carried out at 4000 gauss. It was found, however, that

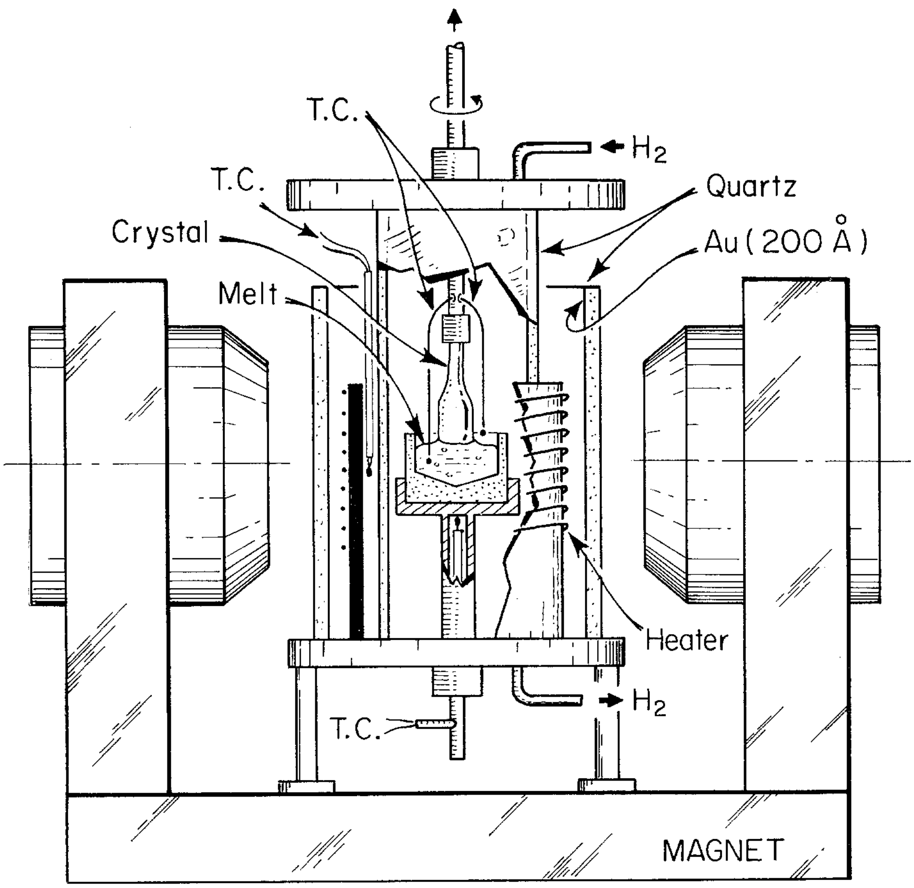

Figure 1 Schematic diagram of the Czochralski crystal puller adapted for the application of a transverse magnetic field.

increasing the magnetic field beyond about 1000 gauss was of no particular consequence. The material used was InSb doped with Te to approximately $10^{18}/cm^3$.

Upon applying the magnetic field the temperature of the InSb melt (in contact with a seed and at thermal steady state) increased by several degrees. This increase reflects the increase in the "effective" viscosity of the melt [2] which leads to diminished thermal convection and thus to decreased heat losses. At the same time the thermal asymmetry [3] in the system (manifested during rotation as a periodic temperature fluctuation as shown in fig. 2) becomes more complex. The increased viscosity apparently decreased convection significantly, so that inherent irregularities in horizontal thermal gradients were preserved during rotation. Such irregular thermal conditions in the melt result from non-uniform heat inputs and heat losses. They are revealed by the immersed rotating thermocouple as seen in fig. 2. This effect of the applied magnetic field on the thermal configuration of the system was unambiguously reflected in the grown crystals of InSb through the corresponding impurity heterogeneities as seen in fig. 3. In the part of the crystal grown without an applied magnetic field (upper part of the figure) the usual rotational striations [3] are clearly present. The increase in temperature upon turning on the magnetic field, is responsible for the extensive remelting seen at about the middle part of fig. 3. Until steady state thermal conditions are established the spacing of the rotational striations increases gradually. At steady state these striations exhibit complex substructures reflecting the irregular thermal conditions "frozen in" by the magnetic field. The pronounced remelting [3] observed (lower part of fig. 3) is due to the fact that a given point at the growth interface encounters faster temperature changes during rotation compared to those in the absence of a magnetic field (see fig. 2). Clearly the presence of a magnetic field during crystal pulling from the melt under rotation adversely affects the homogeneous distribution of impurities in single crystals.

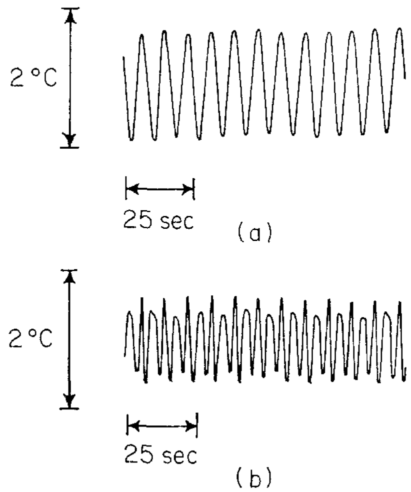

Figure 2 Temperature variations (thermal asymmetry) as recorded by a rotating thermocouple immersed in the melt, (a) in the absence of a magnetic field, (b) in the presence of a 4000 gauss transverse magnetic field.

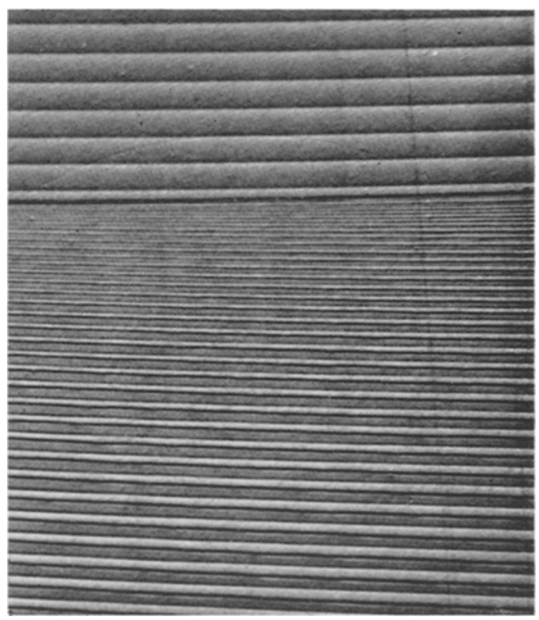

Figure 3 An etched (211) surface of InSb single crystal (doped with Te) cut along the growth axis exhibiting rotational impurity heterogeneities. The upper part was pulled with rotation in the absence of a magnetic field; the lower part was pulled in a transverse magnetic field of 4000 gauss. Note the adverse effects of the applied field on the homogeneity of dopant distribution (× 200).

In the absence of seed rotation, thermal asymmetry no longer leads to periodic fluctuations of dopant concentration (rotational striations); however, random fluctuations of varying intensity still form (non-rotational striations). Mechanical vibrations, pulling rate variations due to mechanical friction as well as thermal effects contribute to the formation of non-rotational striations [4]. However, the contribution from thermal convection is very small provided only shallow vertical thermal gradients are present. Consistent with these findings the presence of a magnetic field was found to have no appreciable effect on the homogeneity of the resulting crystals. Fig. 4 shows a cross-section of an InSb crystal grown in a magnetic field. The upper part grown under rotation shows the complex rotational striations pointed out above. The lower part was grown in the same magnetic field but without seed rotation. The faint striations present in this part are apparently of mechanical origin and thus cannot be eliminated by the presence of the magnetic field. The type

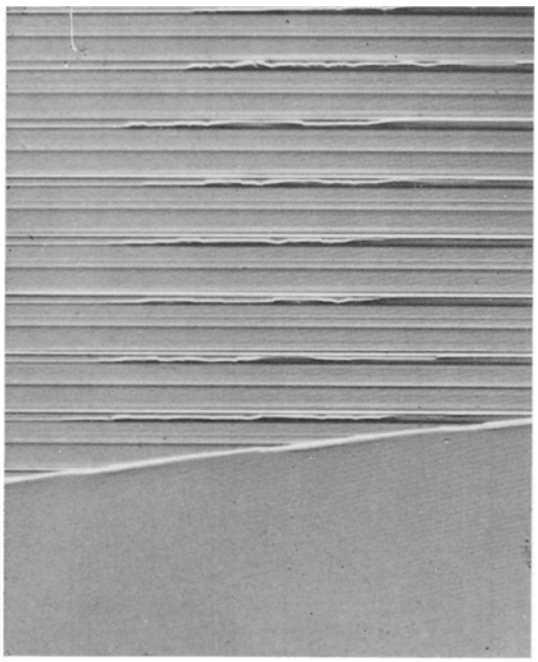

Figure 4 A (211) surface of InSb cut along the growth axis; the upper part reveals complex rotational impurity striations characteristic for growth in a magnetic field. The lower portion was grown without seed rotation in a magnetic field and exhibits faint impurity striations (see text). Note the extensive remelting in the central portion and the pronounced change in interface morphology (× 400).

of sharp thermal fluctuations which were suppressed by magnetic fields [5] during horizontal solidification are not encountered in the systems commonly employed for crystal growth. Thus, magnetic fields are of no significant advantage regarding impurity homogeneity during crystal growth in the absence of rotation. Actually they tend to enhance the onset of local interface instabilities because of increased accumulation of rejected impurities in the growth boundary region.

We believe that magnetic fields can be used advantageously in crystal growth from the melt or solidification processes in general: increasing the "effective" viscosity of the melt allows the detailed mapping of thermal gradients (horizontal and vertical) within the melt without appreciable interference from convection currents. Such mapping should prove very valuable in improving the thermal characteristics of crystal growth systems. More important the "increased" viscosity brought about by a magnetic field could be exploited in making possible the use of increased vertical thermal gradients at the solid-melt interface, without causing extensive mass convection currents. Under such conditions (sharp thermal gradients at the interface) one could avoid the interference of constitutional supercooling to give significantly more favourable solidification conditions for multicomponent systems. Furthermore, at very slow growth rates, it could be possible to achieve conditions whereby the concentration of impurities at the interface is completely diffusion controlled and thus near equilibrium solidification studies become feasible.

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