was introduced by applying an averaging or weighting technique in the calculation of Δy, so that $(\Delta y_{i-1} + 2\Delta y_i + \Delta y_{i+1})/4$ was used instead of Δy_i. This correction is based upon the premise that the sputtering process is dictated by a collision cascade of finite dimensions and the target atoms are not always sputtered away one by one, so that the progress of the apical point, which is a discontinuity in $(\partial\theta/\partial x)$ in Equation 1, should be considered in relation to the motion of the surroundings. The necessity of the later correction has been already suggested by Carter *et al* [3].

Following Carter *et al* [3], the development of sinusoidal surfaces represented by $y = a \sin x$ are simulated in the present study by employing $S(\theta) = A \cos\theta + B\cos^2\theta + C\cos^4\theta$ as shown in Fig. 1. Figs. 5a and b show the changes of the typical surfaces of $a = 1$ and $a = 2$, respectively, under the same sputtering yield of $A = 3.4142$, $B = 12.7574$ and $C = -15.1716$, the curve of which has a maximum of $m = 5$ at $\theta_m = \pi/4$. Each figure shows that the triangle is formed in the early stage of sputtering, but at some points in the surface its development differs from that predicted by Carter *et al* [3]. One difference is that the sharp craters are not observed at the foot of the triangle. Another is that the slope of the triangular sections of the surface is nearly equal to θ_m, not θ_0 (the angle for which $S(\theta_0) = S(0)$) [3].

Consequently, these correction procedures mentioned above are considered to be necessary for the simulation of the development of real surfaces under ion bombardment.

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On the directional solidification of eutectic systems from the melt

A crystal growth method, allowing the growth from the melt of crystals having predetermined profiles, has recently been described in the literature [1, 2]. This technique has been called "edge-defined, film-fed, growth" (EFG) and involves the withdrawal of crystals from a thin liquid pool formed on the top planar surface of a shaping die. The liquid pool is fed by capillaries which extend down through the die into a liquid reservoir. The edge definition or crystal shaping is the result of the fulfilment of a contact angle requirement between the liquid and the die surface [3]. EFG has been investigated extensively by the growth of $\langle 0001 \rangle$ growth axis filamentary sapphire [2, 4, 5].

In recent years there has been a surge of interest in the field of directional solidification of eutectics with a view to their possible use in structural, electronic and optical applications. The present communication reports that EFG has been used to directionally solidify some ionic salt eutectic systems. The interphase relationship with growth speed has been determined, and several advantages which the method may offer over traditional directional solidification processes are suggested.

Details of the ribbon shaping die and crucible set-up, fabricated from nickel, have been described previously [6]. The eutectics chosen, LiF-CaF_2 and LiF-NaCl, were grown in an argon atmosphere. When the crucible and melt are heated to above the melting temperature of the eutectic mixture (prepared from 99.9% pure constituents), liquid rises to fill the feed slot of the die by capillary action. A small cleaved seed crystal of LiF, oriented so that $\langle 001 \rangle$ is along the growth axis, is lowered into contact with the melt in the capillary slot. After adjustment of melt temperature and seed withdrawal rate, the molten eutectic spreads across the top surface of the die and growth of a ribbon 0.6 cm wide × 0.15 cm thick is established.

Using this method several crystals were grown from each eutectic system at rates up to 40 cm h^{-1}. Withdrawal rate changes, together with melt temperature adjustments, were carried

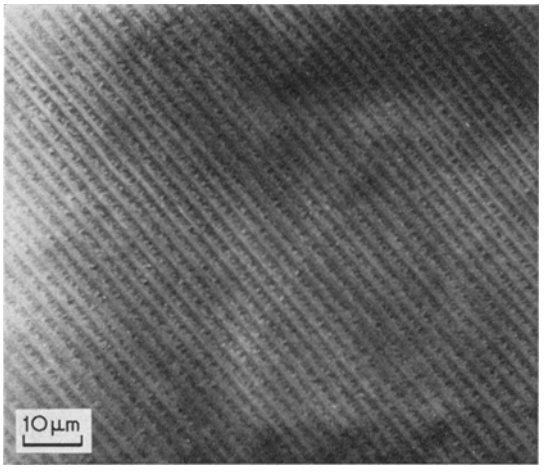

Figure 1 Longitudinal transmission photomicrograph of the Lif-CaF_2 eutectic directionally solidified at 2.5 cm h^{-1}.

out during growth enabling the relationship between interphase spacing and growth rate to be determined along a single ribbon. The ribbons were examined metallographically in transmitted light.

A representative longitudinal photomicrograph of the LiF-CaF_2 eutectic is shown in Fig. 1. A transverse photomicrograph of the LiF-NaCl eutectic is presented in Fig. 2. In agreement with previously reported studies [7], alternate lamellar of LiF and CaF_2 are noted in Fig. 1, whereas rods of LiF in a NaCl matrix are observed in Fig. 2. Careful measurement of a series of micrographs made possible a determination of the relationship between interlaminar spacing, λ, and growth rate, R, for both systems. The data are plotted in Fig. 3 where it is evident that the measurements from both systems are consistent with the dependence $\lambda \propto R^{(-0.55)}$. This is close to the relationship $\lambda \propto R^{(-0.5)}$ predicted by theory [8].

In both systems, ribbons exhibiting a considerable degree of directional uniformity have been obtained at rates up to 25 cm h^{-1}. At faster growth rates non-linear phase distributions are observed. These phase distributions are similar to those reported in other systems [7] and are associated with cellular interface growth conditions resulting from constitutional supercooling.

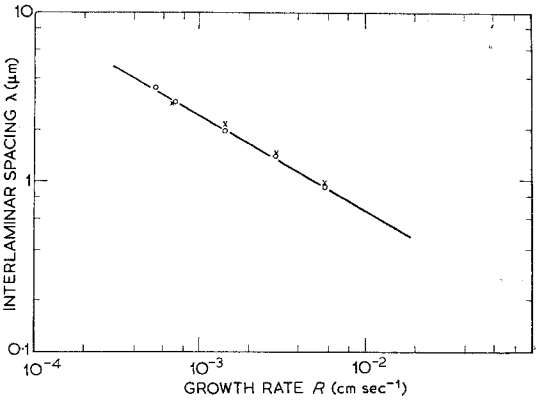

Figure 3 Log-log plot of the interlaminar spacing, λ, as a function of growth speed, R, for the LiF-CaF_2 (○) and LiF-NaCl (×) eutectic systems.

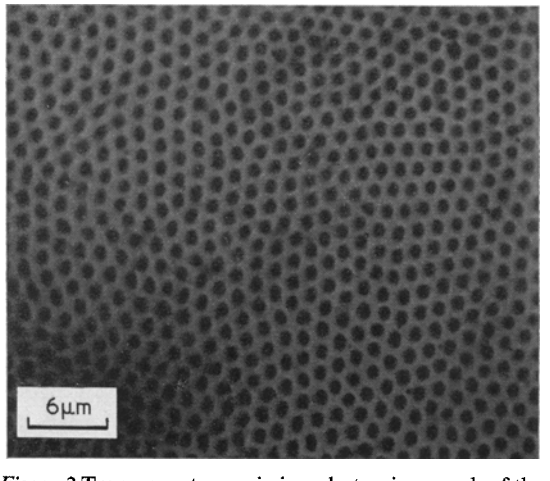

Figure 2 Transverse transmission photomicrograph of the LiF-NaCl eutectic directionally solidified at 5.0 cm h^{-1}.

Although the present studies are of a preliminary nature, EFG appears to offer several advantages, other than shape profiling, over traditional directional solidification techniques. The primary advantage is associated with the temperature gradient at the growth interface. Unlike directional solidification in containers or crucibles, EFG always produces the same conditions at the growth interface after a few centimeters of growth at a constant withdrawal rate and melt temperature. That is, the heat sink is not modified by the distance solidified or heat transfer through a container wall. Thus, eutectic composites having uniform microstructures over their entire length are guaranteed. Also, since solidification occurs from a thin liquid pool separated from the melt reservoir by

a capillary, the composition of the solidifying crystal is constrained to be identical with that of the melt, all of the liquid constituents passing upwards through the capillary being incorporated into the solid. Thus, if planar interface growth is achieved under selected growth conditions, this interface will not be modified as solidification continues by impurity rejection, resulting in constitutional supercooling and breakdown into a cellular growth front. Other possible advantages associated with this separation of growth area and melt reservoir are deliberate variation of composition during growth and continuous replenishment of the reservoir.

It is probable that the theoretically highest planar growth rates may be achieved in many eutectic systems using EFG. Ignoring heat losses by radiation from the meniscus surface, Chalmers *et al* [3] showed that, for sapphire, growth by means of a planar interface depended on the crystal being the sole means of extracting heat from the growth region. That is, at the maximum growth rate consistent with planar growth, the thermal conductivity of the solid sapphire and heat loss by means of an optical light pipe effect were the controlling parameters. Assuming zero heat transfer across the liquid growth film from the die surface, they calculated a maximum growth rate of 2.4 cm min^{-1}. One of the present authors [4] obtained an experimentally measured maximum growth rate for light pipe quality sapphire of 3.0 cm min^{-1}. The achievement of this growth rate was made possible by careful control of the growth conditions and the selection of tungsten (which has a substantial thermal conductivity at 2000°C) as die material. If similarly beneficial growth environments can be arranged for the directional solidification of eutectic systems, there is no obvious reason why near maximum planar growth rates should not be achieved over the entire length of the shape grown.

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Fracture strength in tension of a-axis filamentary sapphire grown by EFG

The tensile fracture strength of *c*-axis filamentary sapphire grown by the "edge-defined, film-fed growth" technique (EFG) has been extensively investigated and reported in the literature [1-3]. Average room temperature fracture strengths in the range 2.4 to 2.9 GN m^{-2} (350 to 425 $\times$ 10^3 lb f $in.^{-2}$) are commonly measured for filament grown at rates up to 6 cm min^{-1} and having a nominal 0.025 cm diameter. This *c*-axis filamentary sapphire retains over 30% of its room temperature tensile strength when tested at 1325°C [4].

Compressive strength data obtained from 3 mm diameter rod samples having growth and loading axes parallel to the *a* and *c* directions, respectively, have shown that despite similar room temperature strengths, the *a*-axis rods exhibit only a slight fall in strength with increasing temperature up to 1300°C [5]. At 1300°C *a*-axis samples had retained 80% of their room temperature compressive strength, com-