Simulation of the eddy current sensing of gallium arsenide Czochralski crystal growth

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The feasibility of eddy current sensing of (1) the melt surface position and (2) the liquid-solid interface shape of 3-inch gallium arsenide crystals being grown by the Czochralski technique has been investigated using an axisymmetric finite element method. The results show clearly that differential sensor designs operating at high frequency (~1 MHz) are very sensitive to the distance between the sensor and the surface of the melt providing the opportunity to precisely monitor and control this important variable of the growth process. The calculations also show a weaker effect of interface shape upon the imaginary impedance component at lower frequencies (1–10 kHz). Its physical basis is due to the different skin depths of solid and liquid GaAs. We show that a sensor's response to this interface effect can be enhanced by appropriate design of the differential sensor's pick-up coils.

1. Introduction

Emerging monolithic microwave integrated circuits and low power, high speed computation is creating a demand for semi-insulating GaAs wafers. Presently, these materials are 40–50 times the cost of silicon, and suffer wide variations in their electrical and physical properties. While there is likely to always be some additional costs associated with the processing of compound semiconductors, it can be significantly lessened by increasing yield, eliminating wafer to wafer variability and reducing the degree of human supervision of the slow crystal growth process.

Yield losses for crystals grown by the high pressure, liquid encapsulated Czochralski (HPLEC) process are principally due to the loss of single crystal orientation during growth, uncontrolled variation of crystal diameter, and handling damage during subsequent post solidification processing. For instance it is not unusual to observe a transition to polycrystallinity half-way (or even less) through the growth of a boule with a subsequent halving of yield. This loss of single crystal growth has been linked to a change of liquid-solid interface shape. Provided the growing crystal is convex, single crystal growth occurs. However, because of changes in the heat transport of the liquid during growth, it is not unusual for the crystal to develop a concave curvature at the edge of the crystal. This results in the nucleation of new orientation grains and the loss of useful material.

Researchers have been pursuing intelligent processing of materials (IPM) approaches to address these issues [1]. In the IPM approach, a suite of advanced sensors are employed to directly measure critical parameters of the growth process. This new information is combined with process understanding (in the form of predictive mathematical models and process heuristics) in a supervisory controller. The controller combines multivariable real-time control algorithms with an artificial intelligence-based supervisor to facilitate growth of material with a goal state combination of electrical properties and ideally near theoretical yield. Ultimately, such a supervisor promises to lessen or eliminate the need for human participation in the growth process provided suitable sensors are available. In particular, a need exists...
for sensing the melt height with respect to the furnace and the liquid–solid interface shape.

There are many physical differences between solid and liquid gallium arsenide near its melting temperature that could be considered a basis for sensing melt position and interface shape. They include (together with their measurement methodologies):
- refractive index (optical scattering);
- density (X- or γ-ray tomography);
- elastic moduli (ultrasonic imaging);
- emissivity (infra-red imaging);
- electrical conductivity (eddy current measurements).

The optical and infrared techniques suffer from a high optical attenuation in crystalline material near the melt temperature and the difficulty of seeing through the boric oxide melt overlayer of the LEC process. Of the remainder, the use of uncooled encircling eddy current sensors appears to be the most promising because of the large difference in electrical properties of solid and liquid gallium arsenide. It can also be implemented noninvasively.

We report on feasibility studies of eddy current methods for sensing interface shape and the melt height during GaAs crystal growth. It extends the previously reported experimental eddy current responses of an encircling sensor during Czochralski silicon crystal growth [2–6]. In this earlier work, the sensor data were primarily used to calculate the axial and radial thermal profiles within the growing crystal. Here, we seek to evaluate other potential uses of such sensor approaches, and in particular, the determination of the interface shape. Similar concepts have been proposed for controlling the interface of HgCdTe during solidification, though in that case the geometry was different to the one studied here [7].

The eddy current method relies upon the large difference in electrical conductivity of solid and liquid gallium arsenide at the melting point [8,9].

![Graph of temperature dependence of electrical conductivity for gallium arsenide](image)

Fig. 1. Temperature dependence of electrical conductivity for gallium arsenide [8,9].
height is known, the results show that the interface shape can then be inferred from differential sensor measurements at lower frequency (in the 2–10 kHz region) provided one’s instrumentation can measure the complex impedance to order 1 part in $10^2$.

2. The model system

We have conducted our calculations on a model system that is suited for experimental validation [10]. We note in fig. 1 that the conductivity of solid gallium arsenide is close to that of graphite while the conductivity of the liquid is similar to mercury. This suggests a laboratory bench system for experimental study that consists of a mercury bath (representing the melt) and a graphite cylinder (representing the crystal). By machining the graphite, it is possible to reproduce the interface shapes of interest during the Czochralski growth of GaAs (fig. 2), and by vertically translating the sensor, the effect on melt height. Normally, one seeks interfaces such as

![Fig. 2. Interface shapes chosen for study of sensing concepts.](image-url)
that shown in fig. 2b. As the radius of curvature increases (fig. 2a), better crystal quality is achieved but at the expense of a loss of diameter control. If heat flow in the melt is not properly controlled, the interface, while remaining convex at its center, turns over near the crystal surface becoming locally concave, and depending upon its severity, results in polycrystal nucleation. Interfaces shown in figs. 2c and 2d simulate to a greater or lesser extent this eventuality. The “crystal” studied here is assumed to be nominally 76 mm (3 inches) in diameter corresponding to today’s state of the art. The “melt” is assumed to be of 51 mm (2 inch) depth. The boric oxide layer over the melt was assumed to have perfect insulating properties.

The ideal sensor should be uncooled to avoid perturbing growth conditions. Therefore, its response ought not to be sensitive to fluctuations in its temperature. A two-coil (primary/secondary) sensor design has been found useful for this [11,12]. One can measure the current that flows in a primary coil (for example, by measuring the voltage across a precision resistor to ground).

Connecting the secondary coil to a high impedance (say 1 MΩ) voltage measurement instrument allows the induced voltage to be measured independent of the temperature induced changes of the secondary coil resistance. The ratio of these quantities gives the transfer impedance of the sensor, which, to first order, is independent of the sensor’s temperature. Second order changes to the sensor’s impedance can occur because of thermal expansion effects. These can be minimized by design of the sensor, or calculated and compensated for during use.

The sensor designs for study are shown in fig. 3. They are all of an encircling type and can be positioned at selected heights above the liquid surface. For some calculations, only a single (lower) secondary was considered (fig. 3a). For others, a second opposingly wound secondary, either 22 mm or 38 mm above the lower one, was placed in series (figs. 3b and 3c). Lastly, a secondary arrangement with the two coils spread 17 mm radially was considered (fig. 3d). The best preform material for the sensor is boron nitride; a very good electrical insulator that is electromag-

Fig. 3. Encircling sensor designs used for the study: (a) absolute sensor; (b) differential sensor; (c) differential sensor; (d) differential sensor.
netically transparent over the frequencies and temperatures of interest. Like the boric oxide, we have taken its conductivity to be zero.

3. Calculation method

For two-coil (primary and secondary) eddy current sensors, the quantity measured is a transfer impedance, \( Z \) defined as:

\[
Z = \frac{\text{EMF induced in secondary coil}}{\text{current flow in primary coil}} = \frac{V_s}{I_p}.
\]

From Faraday's law:

\[
Z = -\frac{N_s}{I_p} \frac{\partial \phi}{\partial t},
\]

where \( N_s \) is the number of turns in the secondary coil and \( \phi \) is the magnetic flux (Wb). The flux linked by the secondary coil can be calculated from the magnetic vector potential \( A \) (Wb m\(^{-1}\)) of the primary coil’s field and the secondary coil geometry:

\[
\phi = \int A \, dl,
\]

where the integral is taken around the path of the secondary coil. For sinusoidal currents flowing in an axisymmetric sensor:

\[
Z = \frac{2\pi N_s r_s \omega}{I_p} \left[ \text{Im}(A_{ave}) - j \text{Re}(A_{ave}) \right] = R + j\omega L,
\]

where \( r_s \) is the secondary coil radius, \( \omega \) the angular frequency (radians/s), \( A_{ave} \) is the average vector potential over the cross section of the secondary coil wire, \( R \) is the coil resistance and \( L \) the coil inductance. The real part of the impedance (\( R \)) corresponds to eddy current losses in the sample (heating), while the imaginary component (\( \omega L \)) corresponds to the change of phase between voltage in the secondary and current in the primary.

When one conducts measurements on a test sample, it is useful to normalize the impedance by that of the empty sensor, \( Z_0 \) (i.e., when the sensor is far removed from the sample):

\[
Z_0 = \frac{2\pi N_s r_s \omega}{I_p} \left[ \text{Im}(A_0) - j \text{Re}(A_0) \right]
= R_0 + j\omega L_0,
\]

where \( A_0 \) is the vector potential for the empty coil, \( R_0 \) is the empty coil resistance, and \( L_0 \) the empty coil inductance. In general \( \omega L_0 \gg R_0 \) and the normalized impedance:

\[
Z_n = \frac{R + j\omega L}{R_0 + j\omega L_0} = \frac{R}{\omega L_0} + \frac{j\omega L}{\omega L_0} = \left[ -\text{Im}(A_{ave}) + j \text{Re}(A_{ave}) \right]/\text{Re}(A_0).
\]

The response of a differential sensor is found by summing the impedance of the individual secondaries. For two secondary coils of the same radius and number of turns wound in opposition:

\[
Z = Z_1 + Z_2 = \frac{2\pi r_s N_s \omega}{I_p} \left\{ \left[ \text{Im}(A_{ave}^{(1)}) - j \text{Re}(A_{ave}^{(1)}) \right]
- \left[ \text{Im}(A_{ave}^{(2)}) - j \text{Re}(A_{ave}^{(2)}) \right] \right\},
\]

where \( A_{ave}^{(1)} \) and \( A_{ave}^{(2)} \) are the vector potentials at the two secondary coil locations. This can be normalized with respect to the empty coil impedance in the usual way.

We have used an axisymmetric finite element code (MAGGIE developed by the MacNeal-Schwendler Corp.) to compute the magnetic vector potential needed by eq. (6) or (7) to compute impedance.

Roughly 1000 grid points were used with care being taken to ensure that in regions of significant current induction the grid points were closely spaced compared with the skin depth in that region for the highest frequencies considered. In setting up the finite element model, we were careful not to allow the grid to change between different melt height and interface shape models. Fig. 4 shows the finite element grid used in the interface region. By varying the electrical conductivities of the elements, we could investigate the range of interfaces of interest without incurring a
change of mesh and potential errors attendant with this. For the calculations, crystal conductivity was taken as $1.123 \times 10^3 \ \Omega^{-1} \ cm^{-1}$ and that of the melt as $1.062 \times 10^4 \ \Omega^{-1} \ cm^{-1}$.

4. Absolute sensor

4.1. Melt level

Using the methods described, we have calculated the impedance for an absolute sensor with a single secondary coil in the bottom location (nearest the liquid). The normalized impedance is plotted on an impedance plane diagram for excitation frequencies between 50 Hz and 2 MHz for a range of lift-off (i.e. melt height) values in fig. 5. Curve A corresponds to a sensor located 4.8 mm (3/16 inch) above the liquid. It looks superficially like the curves one calculates for either a sensor located above a conducting plane or encircling a conducting cylinder [13], and indeed, to first order, one can think of the gallium arsenide sensing problem as a superposition of these two subproblems.

As the sensor–liquid surface separation increases (curves B, C and D), several things happen to the curves. First, at high frequencies (above 10 kHz) the data approach the imaginary axis and the extrapolated intercept moves up (towards the inductance of an empty coil). At high frequencies, the sensor's response is dominated more by geometry than sample conductivity. When the sensor is near the melt, the strongest induced currents are in the (more conductive) liquid. As the frequency increases, the current density here increases, but this is offset by the skin effect which expels the flux towards the surface and reduces the resistive losses within the liquid. In the absence of a crystal, the flux is eventually driven from the sample and the impedance approaches the resistive losses within the liquid. In the absence of a crystal, the flux is eventually driven from the sample and the impedance approaches the imaginary axis at infinite frequency making an intercept determined only by the sensor–melt interaction.
As the coil is raised, the flux that links the sample is reduced and the intercept moves up towards that of an empty coil. This is a well-known result that is frequently used to measure the separation between a coil and a conducting surface [12]. In the presence of the crystal, we find that the intercept stops its approach to the empty coil inductance. If, for the moment we ignore the liquid, then we have a (weakly) conducting cylindrical crystal in a solenoid. Now as the frequency is increased, the flux within the crystal is increasingly expelled by the skin effect (it requires higher frequencies (than the melt) to do this because the skin depth, \( \delta = (2/\omega \sigma \mu)^{1/2} \) where \( \sigma \) is the crystal conductivity and \( \mu \) the magnetic permeability, is larger than for the liquid at the same frequency due to the crystal's lower conductivity). The impedance, at very high frequency again approaches the ordinate and intercepts the imaginary axis at the value \((1 - r_c^2/r_s^2)\) where \( r_c \) is the crystal radius and \( r_s \) the sensing coil radius [13]. This also is a well-known result that has been frequently exploited to measure the radius of conducting cylinders [11]. The combination of these two flux exclusion effects results in the observed variation of the high frequency intercept with the imaginary axis. We see that for sensors located closer to the melt, there is good sensitivity to small changes in melt level (if the sensor position is fixed) whilst for large melt–sensor distances one could measure the crystal diameter (though this would not be very useful for process control since it corresponds to crystal grown several hours in the past).

At lower frequency, the sensor's response is affected by both sample geometry and conductivity. This is because the real part (resistive) of the impedance due to dissipation of the eddy currents in the sample becomes more significant. We can intuitively understand the overall shape of the curves in fig. 5 by again considering the behavior, at intermediate frequencies, of separate conducting cylinders/planes [13]. For both, the real part of the impedance goes through a maximum and a knee is formed on the impedance curve. The frequency at which the maximum is reached depends upon the sample's conductivity. It occurs at lower frequency for more conductive cylinders and planes. When the sensor is near the higher conductivity melt, the knee in the curve is controlled by a combination of the melt and the crystal. At higher sensor locations, the knee fre-
frequency becomes increasingly dominated by the crystal’s lower conductivity, and the impedance curves cross. In practice, this intermediate frequency eddy current data, while strongly affected by the melt and crystal conductivities, are difficult to analyze because of the sensitivity to the (usually unknown) geometry (melt surface–sensor separation and crystal diameter).

4.2. Interface shape

In fig. 6, we show the frequency dependence of the imaginary impedance component for four sensor–liquid surface separations and the four interface shapes. Table 1 lists the actual normalized impedance values at a lift-off of 4.8 mm. There is a small (approximately 3%) variation in impedance due to the interface shape changes at intermediate frequency (2–5 kHz), but at high and low frequencies, the curves for the four interfaces overlap at the resolution of the graph (and eddy current instrumentation). The differences at intermediate frequencies also decrease with increasing sensor–melt separation. We note that in the intermediate frequency range the value of the imaginary Z-component varies inversely with the liquid level (just inside the crystal) at the solid–liquid interface (fig. 4).

These differences in impedance for different interface shapes again arise from a perturbation to the electromagnetic field by the crystal and the underlying melt (where there is a 3- to 4-fold difference in skin depth). At low frequency, the eddy current density is low everywhere in the sample and the electromagnetic fields penetrate easily both the low conductivity crystal and the liquid as shown in fig. 7a. As the frequency increases, the skin effect begins to concentrate flux towards the periphery of the crystal and more so the surface of the melt (fig. 7b). The level of the conductive liquid within a skin depth of the edge of the crystal significantly perturbs the fields and the closer this region is to the sensor, the higher is the imaginary Z-component. As the frequency increases (fig. 7c), the annular region of the interface that is seen by the electromagnetic field becomes increasingly concentrated at the crystal outer surface, and in the limit, becomes infinitesimal. In this high frequency limit only the crystal

Table 1
Normalized impedance values for the absolute sensor

<table>
<thead>
<tr>
<th>Interface No.</th>
<th>Normalized impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f = 500$ Hz</td>
</tr>
<tr>
<td>1</td>
<td>0.2229 + j0.7505</td>
</tr>
<tr>
<td>2</td>
<td>0.2204 + j0.7548</td>
</tr>
<tr>
<td>3</td>
<td>0.2254 + j0.7477</td>
</tr>
<tr>
<td>4</td>
<td>0.2238 + j0.7431</td>
</tr>
</tbody>
</table>

Fig. 7 Lines of constant magnetic flux resulting from the interaction of the coil, crystal and melt: (a) low frequency; (b) intermediate frequency; (c) high frequency.
diameter, melt level and meniscus shape effect the impedance. But at the lower frequencies, the topology of the interface is revealed, and the possibility of its measurements exists provided other factors (e.g. crystal diameter, meniscus and melt level) affecting the eddy current response are sufficiently controlled or known.

These results lead us to the conclusion that an absolute sensor exhibits significant enough sensitivity to melt level to make it a useful in-situ monitoring tool. The sensitivity to interface shapes is rather small, however, and resolving the interface shape would be difficult to accomplish with this sensor design. The sensitivity to interface shape changes could also be masked by other factors that influence the sensor's response (e.g. melt level, crystal diameter or meniscus geometry), and unless these are controlled or independently measured, anomalous results would be expected. Currently, the liquid level is usually not known or controlled to better than 2 mm (1/16 inch) during growth, and observed changes of impedance at intermediate frequency due to these melt level fluctuations could easily be mistaken for changes of interface shape. If one uses high frequency data to infer melt level to significantly better than 2 mm (1/16 inch), the prospects for interface sensing would be greatly improved. However, sensor designs that enhance the sensitivity to interface shape at intermediate frequency and to melt height at high frequency (to increase the precision of its measurement), and that reject the effects of other factors influencing the perturbation to the electromagnetic fields would be desirable. We consider several of these in the section that follows.

5. Differential sensor

Differentail sensors are well known to provide a discrimination against some eddy current signal components and to have enhanced sensitivity to lift-off. We have explored the feasibility of using this approach to better resolve the interface shape. We have investigated cases in which the two secondaries are either axially or radially displaced.

5.1. Axial separation

The calculated response of a differential sensor with a 22 mm axial secondary spacing is shown in fig. 8. The curves no longer lie between

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**Fig. 8.** Normalized impedance curves for a differential sensor with a 22 mm axial separation and a flat interface.
1 and 0 on the imaginary and real axes reflecting the measurement of a difference in induced voltages which may be negative in some instances and much greater than the empty coil in others (i.e., when the empty coil impedance is very much smaller than with the sample present). We note the strong effect of melt–sensor separation which is clearly seen over the entire frequency range. We also note that the imaginary impedance component now increases with decrease in melt surface–sensor distance. This occurs because the secondary coil nearest to the melt is much more affected by the sample than the one further from the melt. The calculated response is due to this difference in individual coil response.

In fig. 9, we show the impedance curves for each of the four interfaces and in table 2 list the normalized impedance values at a lift-off of 4.8 mm (3/16 inch) for test frequencies of 0.5, 2 and 10 kHz.

We again see that at intermediate frequencies (2–10 kHz) there is a separation in the curves for the different interfaces, but that at both low and high frequencies the curves again converge. For this sensor design, we find that the most desirable interface (fig. 2b) has the lowest impedance and as the interface liquid level near the outer crystal edge rises, the imaginary impedance component progressively increases for the reasons discussed in section 4.2. We have found that this interface shift can be increased by locating the second secondary further from the first (fig. 3c). For example in fig. 10 we show the calculated response for a secondary separation of 38 mm (1 1/2 inch). Now, at 2 kHz the shift in normalized imaginary impedance component is 0.3, provided the melt surface–sensor distance is small. We see again that the curves for the different interfaces converge at high frequency and in the high frequency limit, the impedance then depends only on melt level.

5.2. Radial separation

The sensitivity to melt height fluctuations could be reduced by using differential coils positioned so that they are similarly affected by the melt, i.e., a differential secondary coil arrangement with a radial separation (fig. 3d). Figs. 11 and 12 show the impedance curves for a flat interface calcu-
lated for such a sensor. We observe that the imaginary component of impedance still however depends upon the melt level (it decreases with a decrease in melt surface–sensor distance). A comparison of the sensor's response to the four interface shapes is shown in fig. 13 for two melt–
sensor separation distances. Table 3 lists the normalized impedance for the four interfaces at a lift-off of 4.8 mm (3/16 inch).

It can be seen that the variation in impedance due to changes of interface shape at intermediate frequencies (2–5 kHz) is ~45% at a lift-off of 4.8 mm (3/16 inch) (fig. 13). This interface resolution becomes progressively smaller as the melt–sensor distance increases. In the frequency range of greatest interface sensitivity, we see from fig. 13 that there is a relatively small dependence upon melt level. Increasing the separation of the secondaries enhances the sensitivity to the interface until the outer secondary begins to be influenced by other factors (e.g., furnace hardware). We believe that a 17 mm separation...
Table 2
Normalized impedance values for the differential sensor (22 mm axial coil separation)

<table>
<thead>
<tr>
<th>Interface No.</th>
<th>Normalized impedance</th>
<th>$f = 500$ Hz</th>
<th>$f = 2$ kHz</th>
<th>$f = 10$ kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.3181 + j1.3957</td>
<td>-0.1683 + j1.7202</td>
<td>0.1518 + j1.6694</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.3154 + j1.3897</td>
<td>-0.1706 + j1.7147</td>
<td>0.1504 + j1.6658</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.3212 + j1.3997</td>
<td>-0.1681 + j1.7269</td>
<td>0.1531 + j1.6737</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.3332 + j1.4051</td>
<td>-0.1652 + j1.7292</td>
<td>0.1516 + j1.6773</td>
<td></td>
</tr>
</tbody>
</table>

sensor design is close to the optimum for interface discrimination for current crystal puller technology.

These simulations have allowed an understanding to be developed of the interaction between the electromagnetic fields of various eddy current sensor concepts and the features of importance to crystal growth in the gallium arsenide system. All of the sensor concepts have a high frequency response that is sensitive (particularly so for axially displaced differential secondaries) to the melt level and could provide a convenient means of determining this. The determination of the interface shape by eddy current methods looks more promising with the radially displaced differential secondary concepts. Provided the melt level is already known (or held constant), the 2 kHz imaginary impedance of a 17 mm radially separated secondary sensor increases from 0.197 to 0.286 in going from a good to poor interface shape.

The simulations performed above were based on several simplifying assumptions including:

- Circular cylindrical crystal geometry (in practice, slightly triangular or square shapes are frequently found).
- Coaxial alignment of crystal and sensor.
- Absence of temperature gradients in the melt and crystal.
- No crystal rotation.

To some extent, each assumption is only approximated, and some comment is needed about their significance to the conclusions of the research.

Since the encircling design of the eddy current sensor measures circumferentially averaged sample parameters, small deviations from a circular cross section leading to a polygonal cross section of the same area cause very weak perturbations to the sensor’s response. Provided the cross-sectional area of the crystal does not change, the sensed response will be very close to that calculated. This circumferential averaging also compensates for misalignment of the growth and sensor axes. The shortening of the crystal–sensor distance at one side of the sensor is simultaneously accompanied by a lengthening on the other. Because the response of the sensor is dominated by the conductivity of the melt, changes in the crystal thermal gradient are likely to have a negligible effect on the sensor’s response. More serious would be changes in the “average” temperature of the melt sampled by the sensor since the melt conductivity is temperature dependent. These changes are likely to be small and we do not anticipate that under normal conditions of growth they would pose a serious problem to the interpretation of the sensor’s response. The last potential error arises from crystal rotation within the sensor. Viewed from the sensor, this appears as an increase or decrease in sample current density (depending upon direction of rotation). It will be a weak effect because of the small ratio of rotational current to that induced by the sensor and at this preliminary stage of the study seems reasonable to ignore [14].

These calculations and conclusions have been developed for the gallium arsenide system. However, they apply in principle, to other materials provided there is an increase of conductivity during melting (e.g., InP). The detection of the liquid–solid interface shape depends quite sensitively upon the $\sigma_l/\sigma_s$ ratio. Ratios of 5–100 are best suited to this approach. We caution that
further calculations are needed for the systems where \( \sigma_r/\sigma_c < 1 \) (i.e., most metals) and designs proposed here may be suboptimal.

### 6. Summary

The response of an absolute (single secondary coil) eddy current sensor encircling a gallium arsenide crystal being grown from the melt has been calculated. A strong effect of melt height upon the sensor’s response has been predicted, indicating a possible method for the measurement of this important quantity. Calculations of the sensor’s response to changes of liquid–solid interface shape reveal a small effect upon the imaginary impedance component. It has been found that the magnitude of the sensor’s response to both melt height and interface shape can be enhanced by the use of differential sensors and several designs have been examined. The optimal for interface shape determination is a radially displaced differential sensor. The degree to which the interface can be characterized in practice will depend upon the accuracy of the liquid level determination and control of other factors affecting eddy current response. Using the high frequency data of an axially separated differential sensor provides a possible solution to this. Although the calculations have been conducted for gallium arsenide, they apply to any system for which there is a significant increase in conductivity upon melting. They should not be used to assess systems where the conductivity decreases upon melting.

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