THE EDDY CURRENT SENSING OF GALLIUM ARSENIDE CRYSTAL GROWTH:

CALCULATED RESPONSE

H. N. G. Wadley, K. P. Dharmasena and H. S. Goldberg*

University of Virginia, Charlottesville, Virginia 22903
* General Electric R&D, Schenectady, New York 01234

INTRODUCTION

Gallium arsenide grown by the high pressure liquid encapsulated Czochralski (HPLEC) process suffers from a low yield of electrically useful material and widely varying opto-electronic properties. These types of problems are typical of emerging materials/new processes, and in this case, can be traced back to inadequate process control during crystal growth. In particular, it is important to measure and control local solidifications during crystal growth in order to maintain an optimum liquid-solid interface shape that results in single crystal solidification and more uniform electro-optic properties [1].

There are many physical differences between solid and liquid gallium arsenide near its melting temperature that could be considered a basis for sensing interface shape. They include (together with their measurement methodologies):

- Dielectric constant (optical scattering)
- Density (x or γ tomography)
- Elastic moduli (ultrasonic imaging)
- Emissivity (Infra-red imaging)
- Electrical conductivity (Eddy currents)

Here we report on feasibility studies of eddy current methods for sensing and control of crystal growth.

The eddy current method relies upon the large difference in electrical conductivity of solid and liquid gallium arsenide at the melting point [2,3]. Fig. 1 shows that at the melting transition gallium arsenide undergoes a semiconductor-metal transition with a large change of electrical conductivity. At the melting point solid gallium arsenide has an electrical conductivity of \( \approx 0.55 \times 10^3 \Omega^{-1}\text{cm}^{-1} \). Upon melting, there is a fifteen fold jump in conductivity to a value of \( 8.3 \times 10^2 \Omega^{-1}\text{cm}^{-1} \). Thus, one expects the currents induced in a gallium arsenide volume element that encloses a liquid-solid interface would depend strongly upon the liquid fraction, and a means might be found to infer the interface shape. Similar concepts are being explored for controlling the interface of HgCdTe during
Figure 1. Temperature dependence of electrical conductivity for gallium arsenide [2,3].

solidification, though in that case the geometry is different to that studied here [4].

THE MODEL SYSTEM

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 model lab bench system [5] for experimental study of sensor concepts that consists of a mercury bath (representing the liquid) and a graphite cylinder (representing the crystal). By machining the graphite, it is possible to reproduce the interface shapes of interest, Fig. 2.

The "crystal" is assumed to be nominally 3" in diameter: This corresponds to current industrial state of the art. The "liquid" is assumed to be of 2" depth and 9" diameter, and is contained in Lucite, a material that is transparent to the eddy current fields. Among the interface shapes shown in Fig. 2, the ideal interface shape is designated ②. During most crystal growth runs, the interface gradually changes towards the shape designated ③. Interface shapes ① and ④ represent intermediate shapes between these good and bad extremes.

Figure 2. Interface shapes chosen for study of sensing concepts.
The ideal sensor should be uncooled and therefore its response ought not to be sensitive to fluctuations in temperature. A two coil (primary/secondary) sensor design has been found useful in other work [6,7]. By measuring the current that flows in a primary coil (by for example measuring the voltage across a precision resistor to ground) one can compensate for temperature induced changes in the primary resistance. Connecting the secondary coil to a high impedance (say 1MΩ) voltage measurement instrument allows the induced voltage to be measured in a way that is independent of the secondary coil resistance. The ratio of these quantities is the transfer impedance of the sensor. Thus, the only change to the impedance due to temperature fluctuations would be due to thermal expansion effects which can be minimized (or calculated).

The sensor design for our initial studies is shown in Fig. 3. It is 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. For others, the upper secondary was either 7/8" or 1 1/2" above the lower one. The preforms are taken to be boron nitride; a very good electrical insulator that is electromagnetically transparent over the frequencies and temperatures of interest.

**CALCULATION METHOD**

The quantity measured by the sensor is a transfer impedance, \( Z \):

\[
Z = \frac{\text{E.M.F. Induced in Secondary Coil}}{\text{Current Flow in Primary Coil}} = \frac{V_s}{I_p} \quad (1)
\]

From Faraday's law,

\[
Z = \frac{N_s}{I_p} \frac{\partial \phi}{\partial t} \quad (2)
\]

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 depends upon the magnetic vector potential \( \mathbf{A} \) (Wb m\(^{-1}\)) and the coil geometry:

\[
\phi = \int A \cdot d\mathbf{l} \quad (3)
\]

where the integral is taken around the path of the secondary coil.

![Figure 3. Encircling sensor design used for the study.](image-url)
For sinusoidal currents flowing in an axisymmetric sensor:

$$Z = \frac{4\pi^2 N_s r_s f}{I_p} \left[ \text{Im}(A_{ave}) - j \text{Re}(A_{ave}) \right]$$  \hspace{1cm} (4)$$

where $r_s$ is the secondary coil radius, $f$ the frequency, and $A_{ave}$ is the average vector potential over the cross section of the secondary coil. The real part of the impedance corresponds to eddy current losses in the sample (heating) while the imaginary component corresponds to the change of phase between voltage and current.

When one conducts measurements it is useful to normalize the impedance by that of the empty sensor, $Z_0$.

$$Z_0 = \frac{4\pi^2 N_s r_s f}{I_p} \left[ \text{Im}(A_0) - j \text{Re}(A_0) \right] = R_0 + j\omega L_0$$  \hspace{1cm} (5)$$

where $A_0$ is the vector potential for an empty coil, $R_0$ is the empty coil resistance, $L_0$ the empty coil inductance and $\omega$ the frequency in radians/sec. In general $\omega L_0 >> R_0$ and the normalized impedance,

$$Z_N = \frac{R + j\omega L}{R_0 + j\omega L_0} = \frac{R}{R_0} + \frac{j\omega L}{\omega L_0} = \left[ -\text{Im}(A_{ave}) + j \text{Re}(A_{ave}) \right] / \text{Re}(A_0)$$  \hspace{1cm} (6)$$

When we calculated the response of the differential sensor, the impedance was calculated by summing the impedance of the individual secondaries:

$$Z = Z_1 + Z_2 = \frac{4\pi^2 N_s r_s f}{I_p} \left[ \left( \text{Im}(A_{ave}) - j \text{Re}(A_{ave}) \right)_1 - \left( \text{Im}(A_{ave}) - j \text{Re}(A_{ave}) \right)_2 \right]$$  \hspace{1cm} (7)$$

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. 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. The graphite conductivity was taken as $1.123 \times 10^{4} \Omega^{-1} \text{cm}^{-1}$ and that of mercury $1.062 \times 10^{4} \Omega^{-1} \text{cm}^{-1}$.

**ABSOLUTE SENSOR**

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 from 50Hz to 2MHz for a range of lift-off (i.e. melt height) values in Fig. 4. Curve [A] corresponds to a sensor located 3/16" (4.76mm) 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 [8], and indeed, to first order one can think of the gallium arsenide problem as a superposition of these two subproblems.

As the sensor-liquid surface separation increases (curves [B], [C] and [D]) we note that at high frequency (f>10kHz) the intercept with the imaginary axis moves towards the empty coil value. This
Figure 4. Normalized Impedance Curves for an absolute sensor and a flat interface.

again can be thought off as the usual lift-off effect for a probe coil above a conducting plane, though the precise form of the relationship is affected by the exclusion of flux from the central region of the sample due to the skin effect acting in the (lower conductivity) graphite.

At lower frequency, more complicated behavior is observed. As the liquid level is dropped, the sensor's response increasingly becomes dominated by the graphite cylinder. Its lower conductivity results in smaller eddy current losses, a shift in the frequency of the knee of the curve, and the different curves are able to cross.

In Fig. 5, we show the frequency dependence of the imaginary impedance component for the four sensor-liquid surface separations and the four interface shapes. There is a small (~3%) variation in impedance due to interface shape at intermediate frequency (~2-5kHz), but at high and low frequencies the curves for the four interfaces overlap at the resolution of the graph, and the differences at intermediate frequencies decrease with sensor-melt separation.

The results lead us to conclude that such a sensor is very sensitive to melt level. For current practical applications the liquid level usually is not known or controlled to better than 1/16" or so. Resolving the interface shape when there is approximately a tenfold difference of conductivity between liquid and solid would then be difficult. Changes of impedance at intermediate frequency due to melt level fluctuations could be mistaken for changes of interface shape.

We do note that a high frequency impedance measurement (say ~1MHz) depends upon the melt level and not interface shape, and there is a good prospect for sensing this important control variable, perhaps to much better than 1/16".
DIFFERENTIAL SENSOR

Differential sensors can provide a discrimination against some eddy current signal components and we have explored the feasibility of using this to resolve better the interface shape. The calculated response of a differential sensor with a 7/8" secondary spacing is shown in Fig. 6. The curves no longer lie between 1 and 0 on the imaginary and real axis reflecting the measurement of a difference in induced voltages which may be negative in some instances and much greater than unity in others (i.e. when the empty coil impedance is very much smaller than with the sample present). We note that at intermediate frequencies (2-10kHz) there is a separation in the curves for the different interfaces, Fig. 7. At low and high frequencies the curves however again overlap.

We find that the most desirable interface (○ in Fig. 2) has the lowest impedance and as the interface worsens, the impedance progressively increases. This interface shift can be increased by locating the second secondary further from the first. For example we have found the calculated response for a secondary separation of 1 1/2", at 2 kHz to have a shift in normalized impedance component of 0.3 for small lift-offs. We also find that the curves for the different interfaces overlap at high frequency and the impedance there depends only on melt level.

These differences in impedance for different interface shapes arise from subtle interaction between the crystal and the underlying melt associated with the three fold difference in skin depth of crystal and melt. At low frequency, the eddy current density is low everywhere and the electromagnetic fields penetrate easily both the low conductivity crystal and the liquid. As the frequency increases the skin effect begins to concentrate flux towards the periphery of the crystal and the surface of the melt. The level of the interface within a skin depth in of the edge of the graphite crystal is now seen by the fields. As the frequency increases, the annular region of the interface that is seen by the electromagnetic field becomes increasingly concentrated at the crystal outer surface. In the high
Figure 6. Normalized impedance curves for the differential sensor (7/8" separation) and a flat interface.

Figure 7. Imaginary component of normalized impedance versus frequency for the differential secondary with 7/8" separation.

frequency limit only the crystal diameter, melt level and meniscus shape affect the impedance. However, at lower frequencies the topology of the interface is revealed, and the possibility of sensing its changes exists provided other factors affecting eddy current response are sufficiently controlled or known.

SUMMARY

The response of an eddy current sensor has been calculated when it encircles a gallium arsenide crystal being grown from the melt. A strong effect of melt height upon the sensor response has been
predicted, and indicates a possible method for 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. The magnitude of the phase effect can be enhanced by the use of a differential sensor and several designs have been examined. The degree to which the interface can be characterized in practice depends upon the accuracy of the liquid level determination and control of other factors affecting eddy current response. Using the high frequency data provides a possible solution to this though experiments must be conducted to determine the measurement precision with available technology.

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