

REAL-TIME MONITORING AND CONTROL OF HgCdTe MBE USING AN INTEGRATED MULTI-SENSOR SYSTEM

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ABSTRACT

We present recent progress on the use of an integrated real-time sensing and control system for monitoring and controlling substrate temperature, layer composition, and effusion cell flux during MBE growth of HgCdTe epilayers for advanced IR detectors. Substrate temperature is measured and controlled in real-time using absorption-edge spectroscopy (ABES). This allows the substrate temperature to be maintained at $\pm 1.5^\circ\text{C}$ from the desired setpoint, even during actuation of effusion cell shutters which under conventional thermocouple-based control would produce a substantial ($10\text{--}15^\circ\text{C}$) temperature change. *In situ* spectroscopic ellipsometry (SE) is used for monitoring HgCdTe layer composition in real-time. We describe the development of a comprehensive temperature- and composition-dependent SE dielectric function database which can be used for accurate and precise monitoring of $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ layer composition over a wide range of x -values, from 0.2 to 0.42. The composition changes inferred from the real-time SE measurements obtained during growth of a two-layer structure are in excellent agreement with actual composition vs. depth profiles obtained using post-growth SIMS analysis. Likewise, the accuracy and precision of SE measurements conducted over multiple growth runs are shown to be suitable for robust SE-based composition control. Changes in gas-phase concentration of Cd atoms produced by a CdTe effusion cell are detected using an atomic absorption method (optical- absorption flux monitoring – OFM). The OFM method allows changes in HgCdTe layer composition to be correlated directly with variations in Cd flux. The *in situ* optical sensors are linked using a custom software framework to provide the foundation for integrated, real-time monitoring and control of HgCdTe MBE growth of high performance IR detector structures over a wide range of compositions, layer thickness, and substrate temperature.

1.0 INTRODUCTION

The performance demands of next-generation strategic and tactical weapons and reconnaissance systems are driving the development of infrared (IR) sensors with increased functionality, and improved resolution, frequency agility and target discrimination capabilities. Specific areas that are receiving particular emphasis include: ultra-large-scale ($>1024 \times 1024$) HgCdTe focal plane arrays; detectors capable of simultaneous and sequential detection at multiple wavelengths throughout the IR spectral region; high sensitivity, fast single element detectors and arrays which employ internal gain; and monolithic integration of detector and processing functions. These demanding applications have, in turn, mandated the development of improved methods for materials fabrication which can be used to reliably produce complex $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ -based IR

detector structures having high detectivity, well-controlled alloy compositions and doping profiles at all requisite spectral bands, in addition to compatibility with Si or other non-lattice-matched alternative substrates.

Molecular beam epitaxy (MBE) has emerged as the pre-eminent method for growth of high performance, multi-layer detector structures in HgCdTe. In principle, MBE can be used to produce HgCdTe structures with precisely tailored compositions, controlled doping characteristics, and atomically abrupt interfaces. However, in conventional MBE systems, the reproducible growth of complex device structures having stringent performance tolerances is seriously compromised by the inability to directly sense and control critical process and wafer state parameters; namely, source fluxes, substrate temperature, and epitaxial layer composition and morphology. For example, it is been found by investigators at laboratories worldwide that MBE growth and doping HgCdTe is extremely sensitive to substrate temperature and minor instabilities or variations in the flux from individual effusion cells. This strong dependence of the HgCdTe materials properties on the fundamental MBE growth variables can severely limit the application of conventional MBE technology for high yield, low cost fabrication of high performance IR devices. Conventional MBE growth procedures generally employ numerous calibration runs to “dial-in” the effusion cell fluxes, flux ratios, and substrate temperatures appropriate for growth of the final device structure. This process is time-consuming and costly, and it is hampered by the lack of real-time information concerning important growth parameters such as alloy composition and surface morphology.

To overcome the limitations of conventional MBE methods, we have been actively engaged in the development and application of *in situ*, real-time sensing and control methodologies which support our goal of “first-pass success” in the growth of advanced HgCdTe device structures, including two- and three-color IR detectors, high-speed, low-noise avalanche photodiodes, and HgCdTe-on-Si focal plane arrays. In the present paper we will summarize recent progress on the application of real-time sensors for monitoring substrate temperature, alloy composition, and Cd flux during HgCdTe MBE. In addition, we will present results on substrate temperature regulation and control, and we will discuss progress on the development of an integrated hardware and software system which will be fully capable of sensing and controlling the important growth variables during MBE of multi-layer HgCdTe detector structures.

The successful application of real-time sensors in the HgCdTe MBE systems in our laboratory has drawn heavily upon the experience and knowledge gained in a related DARPA-sponsored program at HRL Laboratories (HRL) entitled “Integrated Multi-Sensor Control for MBE Growth of III-V Nanoelectronic Devices” (IMSC). Although the emphasis of that on-going program is on the development and implementation of sensing and control strategies for MBE of heterojunction bipolar transistor and resonant tunneling diodes in III-V materials, we have found that the sensor systems, software framework, and data fusion methodologies developed for that purpose can be transferred directly to the II-VI growth environment. The DARPA program has become a vital foundation for the present work and has provided considerable leverage for all of the sensing and control efforts in our laboratory.

2.0 INTEGRATED SENSING AND CONTROL SYSTEM

A schematic illustration of the *in situ* sensors and their implementation on a HgCdTe MBE system at HRL is given in Figure 1. Three primary real-time sensors are employed in the system: 1) Absorption-Edge Spectroscopy (ABES) for sensing substrate temperature, 2) Spectroscopic Ellipsometry (SE) for monitoring alloy composition and growth rate, and 3) Optical Absorption Flux Monitoring (OFM) for monitoring Cd concentration in the growth chamber during HgCdTe MBE. These non-invasive optical sensors complement the conventional sensors employed for routine MBE operation (e.g., ion gauges, thermocouples, etc.—not shown in Figure 1).

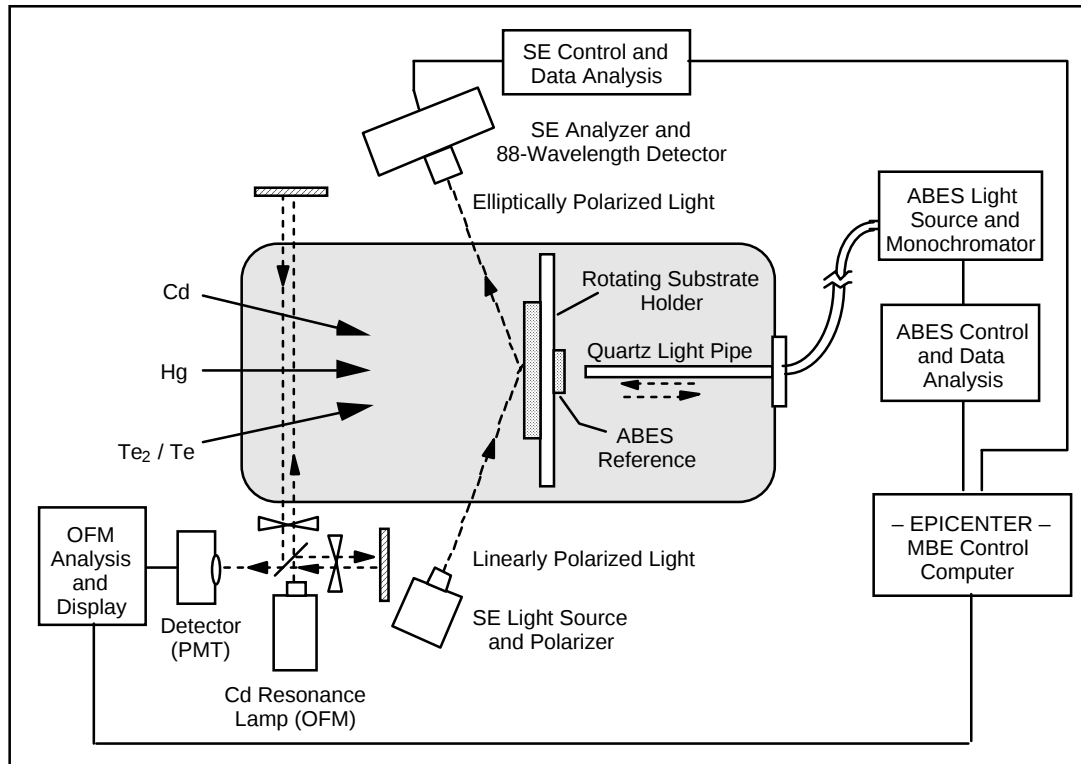


Figure 1. Integrated, multi-sensor system for real-time monitoring and control of substrate temperature, alloy composition and Cd flux during HgCdTe MBE.

The sensor systems illustrated in Figure 1 each contain data analysis and display capabilities in addition to basic data acquisition functions. The individual systems are linked to the general MBE control system via an integrated hardware/software platform ("EpiCenter") developed under the IMSC program and customized for use on the HgCdTe MBE system. The software supports "recipe-based" operation as well as generalized A/D and D/A conversion, digital inputs and outputs, GPIB, Ethernet and a variety of serial communication protocols. An advanced module for generalized data logging allows convenient storage and display of arbitrary sets of input signals at variable time intervals. The EpiCenter system is capable of integrating all sensor inputs for robust real-time control of substrate temperature, HgCdTe alloy composition, and CdTe effusion cell flux during growth of multi-layer IR detector structures.

For substrate temperature measurements, we use the method of absorption-edge spectroscopy,¹ implemented in the reflection mode.² As shown in Figure 1, a substrate for HgCdTe epilayer growth is contacted to a rotating holder using a colloidal graphite suspension (DAG) which forms a thermally conductive bond between the substrate and the holder. A single-crystal Si "witness" wafer utilized for temperature measurements is mounted (also using DAG) to the backside of the holder. A broadband, chopped light beam from the ABES optical source is directed via a fiber bundle into a quartz light pipe located within the MBE chamber. The light reflected from the Si wafer is directed back into the ABES monochromator and detector system along the same optical path. The temperature of the Si wafer (and hence the substrate which is in thermal contact with the witness piece) is accurately determined by measuring the shift in the Si absorption band-edge as the temperature changes. The ABES system is based on a commercial instrument, Model NTM-1, manufactured by CI Systems, Inc. A key feature of the experimental embodiment of the ABES technique in our laboratory is the use of an in-line substrate

manipulator which features unobstructed line-of-sight through the heater assembly along the rotation axis. This allows reflection-mode ABES measurements to be routinely conducted during MBE growth. As will be shown in the next section, this method of temperature sensing allows the accurate, real-time determination of changes in temperature that occur during MBE, and it overcomes the problems encountered using conventional methods such as pyrometry or non-contacting (remote) thermocouple techniques.

In order to achieve the goals of fabricating complex, multi-layer device structures with first-pass success and maintaining the optimum experimental conditions throughout multiple growth runs, it is essential to have an accurate knowledge of the HgCdTe alloy composition during growth. In the present work, spectroscopic ellipsometry is used for real-time measurements of HgCdTe alloy composition. The ellipsometer employed in these studies is an 88-wavelength (277-766 nm) system manufactured by J.A. Woollam, Inc. As shown in Figure 1, a broadband, linearly polarized beam from the SE light source (Xe lamp) is directed onto the sample at an angle of incidence of approximately 75°. Upon reflection from the sample, the polarization state of the light changes, and this change is used to infer the composition, temperature, and surface morphology of the growing film. The polarization state of the reflected beam is measured using a detector consisting of a rotating analyzer, diffraction grating, and two diode arrays. Although not shown in the figure, the input and output optical ports are low-birefringence windows (BOMCO, Inc.) which are heated to prevent inner-surface coating during MBE growth. The SE data are acquired during sample rotation, with a single SE data point representing an average of all data acquired during one rotation period (4 sec). The HgCdTe alloy composition is inferred by fitting the SE data using an optical model which contains the temperature- and concentration-dependent dielectric functions characteristic of the HgCdTe layers being grown. The data acquisition and analysis methods were developed by J.A. Woollam, Inc., and they have been tested and refined through an on-going collaboration with HRL on the IMSC program. We have devoted considerable effort to the acquisition and testing of a comprehensive dielectric function database for HgCdTe; this will be described in greater detail in the next section.

Real-time monitoring of the Cd flux is accomplished using resonance radiation (228.8 nm) from a Cd hollow-cathode lamp to detect changes in Cd absorption. A beamsplitter separates the resonance radiation into reference and signal beams which are modulated using separate choppers. A double-pass geometry is employed for the signal beam. For clarity, Figure 1 shows the path of the OFM beam at a position near the effusion cell flange on the MBE system. In the real experimental configuration, the input and output ports are located on the chamber so that the 1 cm diameter beam passes approximately 3 cm from the substrate surface. The beam intensities are measured using a photomultiplier tube. Demodulation of the signal and reference intensities is performed using a digital lock-in amplifier, and the digitized values are divided in software to generate the net optical absorption. As in the SE data acquisition system, heated BOMCO windows are used as optical ports in the OFM experiments.

3.0 MEASUREMENT AND CONTROL OF SUBSTRATE TEMPERATURE

Accurate knowledge of the substrate temperature is critical to the successful growth HgCdTe epilayers by MBE. The relatively low growth temperature ($\sim 200^{\circ}\text{C}$), the narrow window for growth of layers with optimal structural and electrical properties ($\pm 5^{\circ}\text{C}$), and the sensitivity to temperature perturbations caused by thermal radiation from effusion cell shutters, pose serious challenges to methods for accurate and precise determination of substrate temperature in real-time in a production HgCdTe MBE environment. We have found that the ABES technique offers numerous advantages over conventional methods (e.g., pyrometry and thermocouple-based sensing) for real-time, *in situ* measurement of temperature, and we have adopted this technique as the primary method for sensing and controlling substrate temperature.

When a heated substrate is exposed to thermal radiation from an MBE effusion cell, the increased heat load can produce a significant increase ($>10^{\circ}\text{C}$) in the substrate temperature. A non-contacting thermocouple is insensitive to those changes because it probes the thermal environment surrounding the substrate and not the actual substrate temperature. Consequently, it is not possible to achieve robust temperature control using that technique. Likewise, when a pyrometer is used to sense and control the substrate temperature in the low growth temperature regime characteristic of HgCdTe MBE, the stray thermal radiation produced by the open effusion cell produces a large apparent temperature offset which seriously impacts the accuracy and precision of the temperature measurement.

These problems are obviated by the use ABES for real-time substrate temperature measurements. For example, Figure 2 compares the use of thermocouple-based temperature control during effusion cell shutter actuation with ABES-based control conducted under the same experimental conditions. During the first half of the growth run, the power to the substrate heater was controlled using a feedback loop that maintained a constant temperature at the thermocouple. Since the thermocouple is detached from the rotating holder, it is relatively oblivious to changes in temperature that result from opening and closing of the shutters. (This problem can be largely overcome if the thermocouple is contacted directly to the rotating holder; however, that embodiment presents its own set of non-trivial experimental problems in a production MBE system). The temperature change under thermocouple control when the shutters are opened and closed is approximately 10°C ; a quantity that is significant compared to the $\pm 5^{\circ}\text{C}$ temperature window for high quality layer growth. In contrast to the result obtained using thermocouple control, the substrate temperature remains essentially constant during shutter opening and closing when ABES is used to sense and control the substrate temperature. We find that ABES allows the temperature to be controlled to $\pm 1.5^{\circ}$ or less throughout the growth of the HgCdTe epilayer.

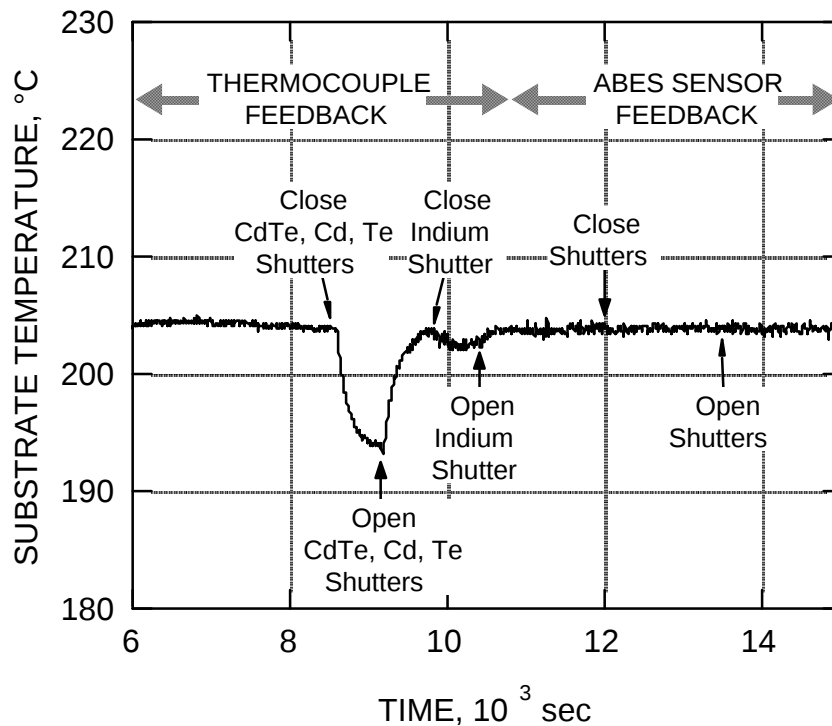


Figure 2. ABES sensor-based feedback totally eliminates temperature variations caused by opening and closing of effusion cell shutters.

For ABES sensor-based feedback regulation of the substrate temperature, we have employed a cascade-PID control approach as illustrated in Figure 3. In this figure, the temperature of a Si witness wafer contacted to the backside of the rotating sample holder is monitored by ABES. The ABES-inferred temperature (“true temperature” in Figure 3) is compared with the desired substrate setpoint temperature. The resulting error signal produced by the software PID algorithm is used to generate a new thermocouple setpoint for the hardware PID controller which, in turn, regulates the power to the substrate heater. We have found this approach to feedback control to be a reliable and robust method for stabilizing and controlling the substrate temperature during MBE growth.

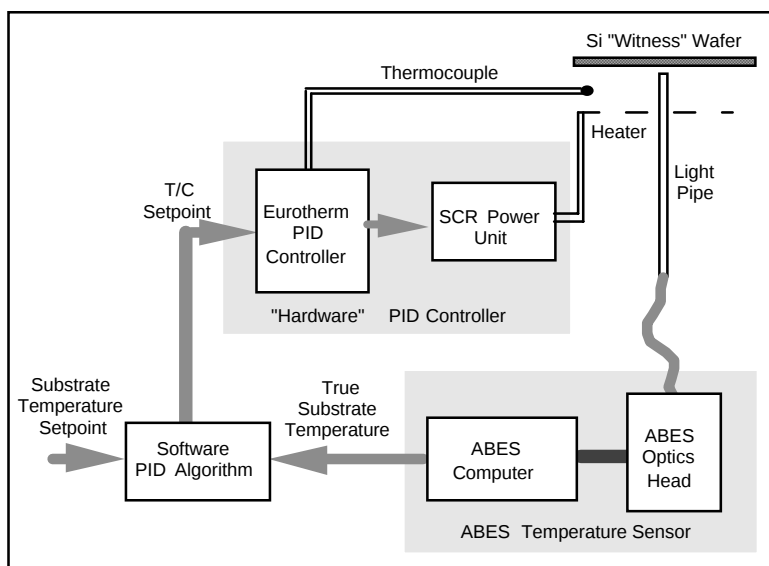


Figure 3. Method for regulating substrate temperature using ABES feedback control.

4.0 REAL-TIME MEASUREMENT OF HgCdTe ALLOY COMPOSITION

The use of spectroscopic ellipsometry for characterization of the properties and behavior of semiconductor, dielectric, and metal surfaces is a vast subject that has been thoroughly investigated for the last 20 years.³ However, the use of SE for *in situ* measurements in an MBE growth environment is far less mature. This is largely due to the experimental difficulties in conducting SE measurements in an MBE system and in analyzing data from a sensor that is often extraordinarily sensitive to more than one experimental variable. Some of these problems include, for example, deleterious effects due to substrate wobble during sample rotation, temperature-composition cross-coupling effects which prohibit accurate composition determination if the substrate temperature is not independently available, and lack of reliable dielectric function databases which characterize the optical properties of the desired layer during MBE growth. These problems notwithstanding, there have been several recent reports on *in situ*, real-time studies of composition changes during HgCdTe growth.⁴⁻⁷ Our goal in the present investigation is to extend that earlier work to achieve highly repeatable monitoring and control of MBE growth of multi-layer samples with precisely defined spectral cut-offs.

Our approach has been to build upon the experience gained on the IMSC program in order to test and establish SE as a “workhorse” sensor capable of meeting the demanding requirements imposed by next-generation IR sensors. That goal has motivated considerable effort on the characterization of the SE system under a range of SE and MBE operating conditions, and has

led to the development of improved optical constant databases and measurement and analysis procedures. The accuracy and precision of the composition inferred from SE measurements depend strongly upon the quality of the dielectric function database used in the data analysis. In a typical SE experiment, the ellipsometric variables “psi” and “delta” are determined during the MBE growth run. Those data are compared in with the predictions of a model which simulates the optical behavior of a user-defined structure comprising materials with specified thicknesses and optical properties. The model parameters (e.g., composition, surface roughness) are adjusted using a fast fitting procedure to minimize the difference between the model parameters and the experimental data. The dielectric function database is the quantity which gives the dependence of the real and imaginary parts of the dielectric function on variables such as composition and temperature. Since the database contains virtually all of the important information in the optical model , it is imperative to have a detailed and accurate description of that functional behavior .

We have conducted a series of temperature-stabilized growth runs in order to obtain a comprehensive concentration- and temperature-dependent dielectric function database for HgCdTe under the growth conditions employed in our laboratory. We have investigated the range of $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ alloy compositions from $x=0.2$ to 0.42 and temperatures from 185° to 205°C . This work builds on the previous studies of Johs and co-workers⁸ who conducted similar measurements over a more limited range of compositions and temperatures. The approach we used to construct the database involved the acquisition of SE data during growth of multi-layer HgCdTe alloy “stacked” structures under ABES temperature control. The composition of the individual layer steps was determined using secondary ion mass spectrometry (SIMS) depth profiling which was carefully calibrated using companion reference samples whose compositions were derived from FTIR measurements. The SE data segments were then “tagged” with the appropriate compositions and temperatures and the resulting database was parameterized using both polynomial and oscillator fitting functions.

To illustrate the systematic dependence of the real (ϵ_1) and imaginary (ϵ_2) parts of the HgCdTe dielectric functions on alloy composition, in Figure 4 we show the values for ϵ_1 and ϵ_2 at several

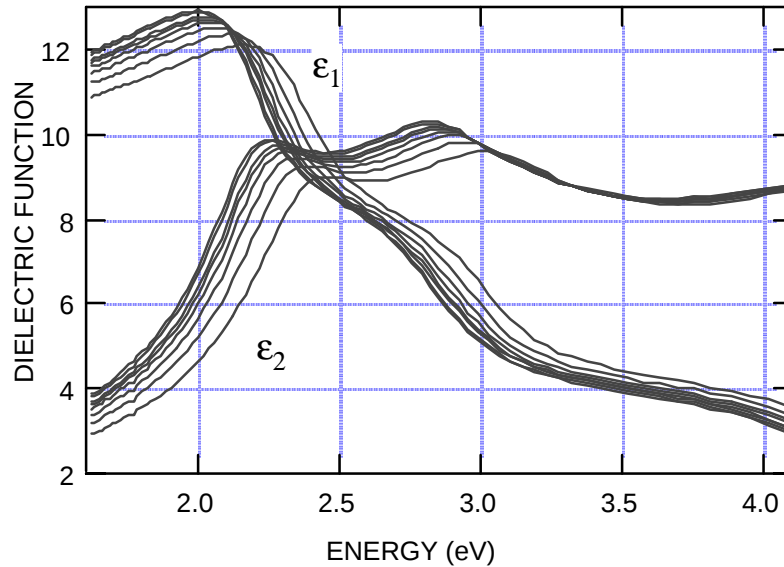


Figure 4. Dependence of the measured HgCdTe dielectric functions, ϵ_1 and ϵ_2 , on composition over the range of x -values for 0.21 to 0.41. (Substrate temperature: 200°C).

different compositions ($x=0.21-0.41$) for constant temperature (200°C). The data are well-behaved over the entire spectral range, and the dielectric functions show sufficient sensitivity to composition to be suitable for sensitive detection of changes in HgCdTe alloy composition during growth. A particularly demanding test of the SE system and the quality of the HgCdTe database is the comparison of the composition inferred from SE measurements during layer growth and measurements of the actual composition measured by post-growth SIMS depth profiling. Figure 5 shows the composition derived from *in situ* SE and from SIMS depth profiling of a HgCdTe layer containing a stepped composition profile grown by MBE on a CdZnTe substrate. The Cd mole fraction (x -value) is plotted as a function of growth time on the lower abscissa and as a function of depth into the epilayer on the upper abscissa, where “0” is the surface of the sample. The SE and SIMS data show good agreement over the entire layer profile; even the subtle changes in x -value that occur in the “constant composition” regions are evident in the SE data. This agreement not only supports the validity of the HgCdTe optical constant database, but it also strongly suggests that SE will serve as an invaluable tool for monitoring and controlling the growth of complex multi-layer structures.

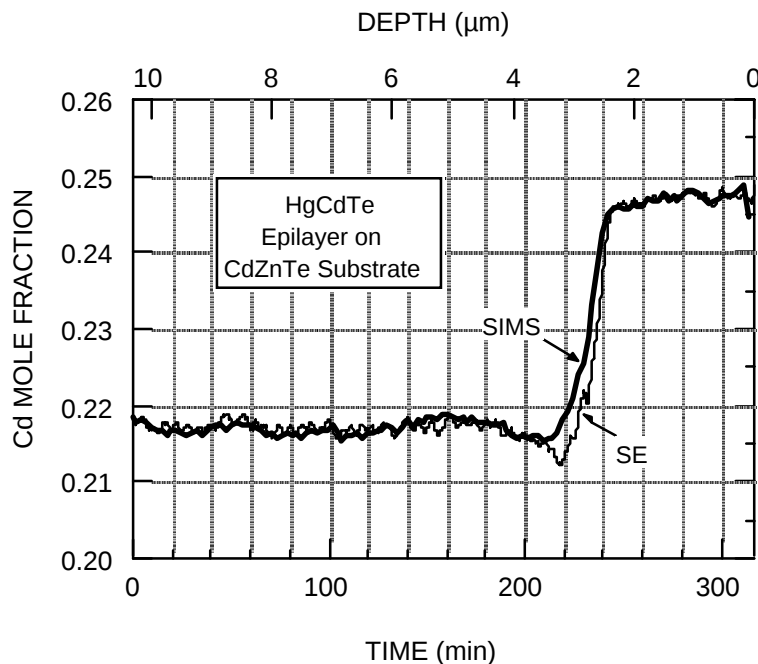


Figure 5. Cd mole fraction (x -value) in stepped-composition structure inferred from real-time SE measurements during MBE growth and comparison with x -value measured by post-growth SIMS sputter profiling.

Although the ability to correctly determine the composition profile in a graded structure is essential, it is perhaps even more important to fully characterize the accuracy and precision of the SE-inferred composition values over multiple growth runs. To address this issue, we compare in Figure 6 the x -values determined from SE measurements made during MBE growth to the x -values determined from FTIR measurements of the IR spectral cut-off for a set of 15 different HgCdTe samples grown over a period of several months. The solid line through data points is a linear fit to the data, whereas the dashed lines give tolerance limits ($x \pm 0.002$) that we have established for acceptable accuracy for robust SE-based composition control. Given the range of conditions and the time span over which different data sets were acquired, we are satisfied that the precision and accuracy obtained using SE are acceptable for real-time closed-loop feedback control of layer composition.

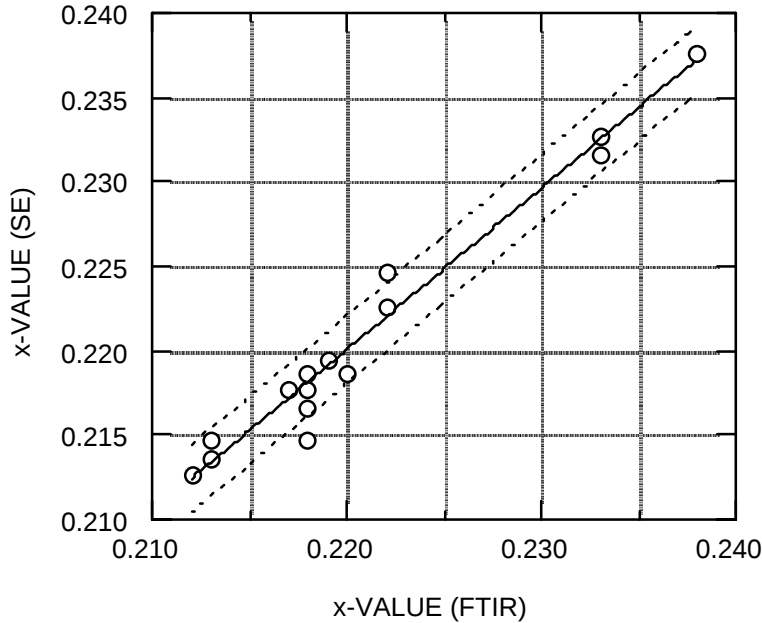


Figure 6. $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ x-value determined by SE during MBE growth of different layers as a function of x-value determined using post-growth FTIR analysis.

The accuracy and precision of *in situ* SE measurements can be influenced by a variety of factors, including insufficient knowledge of substrate temperature, changes in the optical properties of the input and output optical windows, excessive sample wobble during substrate rotation, and improper correction of cross-coupling effects (e.g., temperature-composition, composition-surface roughness) during data analysis. In the course of the present investigation, we have examined these issues, and have made adjustments in the experimental procedure and data analysis routines to properly account for them. An especially important issue concerns the effects of possible changes in window birefringence on SE data acquisition and analysis. Very small run-to-run changes in window birefringence can be misinterpreted as being due to changes in the optical properties of the sample. A procedure has been developed for compensation of changes in window birefringence, and initial tests look very promising for real-time operation. The results of those studies will be reported in a future publication.

5.0 IN SITU MONITORING OF Cd FLUX

Optical absorption has been shown to be a useful method for detecting gas phase atomic species generated by heated effusion cells in an MBE system.⁹⁻¹¹ OFM is particularly well-suited for the detection and control of shutter “transients” and for the detection of flux changes caused by effusion cell instabilities. In the course of the IMSC program we have developed and implemented multi-element OFM to monitor and control the flux of In, Ga, and Al during III-V layer growth. In the present studies, we have utilized the experimental methods developed on that program for the measurement of Group II fluxes during HgCdTe MBE. In particular, we have employed OFM to monitor both short-term transients as well as long-term drift in the flux of Cd atoms during the growth of thick IR sensing layers in multi-layer detector structures. An example which illustrates the application of OFM to for Cd flux monitoring during HgCdTe MBE is shown

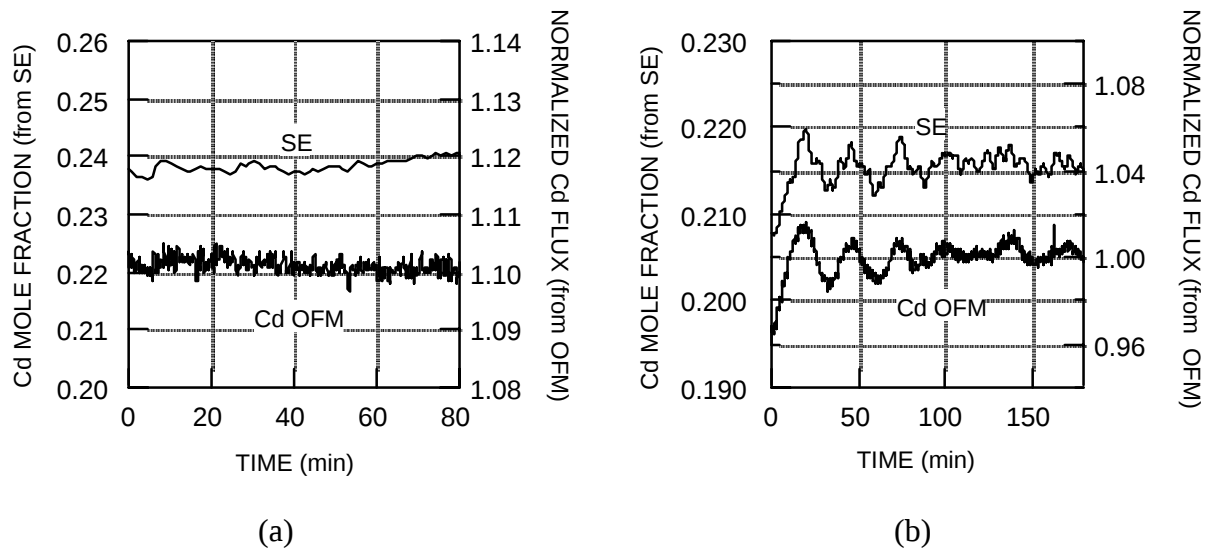


Figure 7. Comparison of normalized gas-phase Cd concentrations (from OFM) and Cd mole fraction in the growing layer (from SE) acquired two HgCdTe MBE growth runs: (a) normal growth run; (b) growth run with effusion cell instability.

in Figure 7 for growth of two different HgCdTe layers. The Cd OFM data are compared with the layer x-value obtained from SE measurements acquired during the same two runs. Figure 7(a) shows the OFM and SE data acquired over an 80 minute span during growth of a HgCdTe single layer under normal growth conditions. Figure 7(b) shows similar data for an MBE run in which there was an instability in the Cd flux. There is a strong correlation between the changes in layer composition inferred from the SE measurements and the oscillations in the gas-phase Cd concentration, suggesting that an instability existed in the CdTe effusion cell. In the absence of the OFM data, it would be much more difficult to isolate the cause of the composition variation.

Figure 8 further illustrates the utility of OFM to detect CdTe effusion cell anomalies and changes in effusion cell flux during growth. The upper curve was obtained under conditions where the effusion cell was fully charged; whereas the lower curve was obtained when a the cell was nearly empty during the MBE run. At the initial stages of growth, both curves reveal a rapid increase followed by a decrease in Cd flux. This flux increase is the “shutter transient” – an overshoot the Cd flux which accompanies the opening of the CdTe effusion cell. The hot cell immediately cools as the thermal radiation establishes a new value after the shutter is opened. Knowledge of the dynamics of this transient flux change is important so that the temperature of the effusion cell can be appropriately adjusted to eliminate the transients. In Figure 8, it can be seen that after the initial transient, the OFM data for the two different runs are qualitatively different. As expected, when the CdTe cell is full, the Cd flux is constant. However, when the cell is depleted, problems such as non-uniform heating of the remaining charge and inaccuracies in cell temperature can degrade the flux stability. These changes are readily observable in the Cd OFM data, and this provides the MBE grower with important information concerning the quality of a critical growth parameter.

We have found that Cd OFM signal is strongly influenced by changes in the substrate temperature. We believe that this is due to changes in the adsorption/desorption rates from that sample and/or the sample holder. (OFM measures the *total* Cd concentration - both incident and

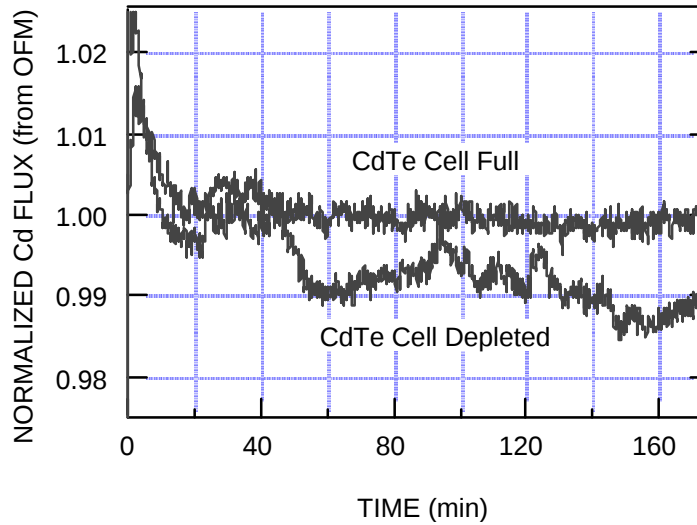


Figure 8. OFM measurements of Cd flux under conditions where the CdTe effusion cell was fully charged (upper curve) and nearly empty (lower curve).

desorbed Cd- in the path of the probe beam). Without a knowledge of the substrate temperature, this becomes a serious impediment to the use of OFM for reliable determination of the Cd flux. However, with the availability of an ABES sensor for accurately monitoring the substrate temperature, it is possible to de-couple substrate temperature effects from the OFM signal, thereby permitting a straightforward interpretation of the OFM data.

Although OFM is well-suited to measurements of Group II atomic fluxes, it would also be valuable to obtain information concerning the flux of Te species and dopants during HgCdTe MBE. However, the low absorption cross sections and weak signal strengths make detection of molecular species or species present at very low concentrations extremely difficult using conventional OFM methods. We are currently investigating complementary approaches, including fluorescence techniques, for detection of dopants and other molecular species required for growth of advanced IR detector structures.

6.0 SUMMARY

We have described recent progress on the development and implementation of an integrated multi-sensor system for monitoring and control of HgCdTe MBE. The system comprises real-time optical sensors for substrate temperature (ABES), layer composition (SE), and Cd flux (OFM) that are linked and controlled using a flexible custom software framework. ABES has been used to monitor substrate temperature with a precision of $\pm 1.5^\circ\text{C}$ during growth, and it has been used for active control of substrate temperature resulting in elimination of temperature changes induced by actuation of effusion cell shutters.

An improved composition- and temperature-dependent dielectric function database for HgCdTe has been acquired and tested. The parameterized database spans a range of x-values from 0.2-0.42, and temperatures from $185^\circ\text{-}205^\circ\text{C}$. Using this database for SE data analysis excellent agreement between compositions inferred from real-time SE measurements and compositions deduced from post-growth SIMS analysis were obtained for two-layer, composition-stepped

structures. The accuracy and precision of the SE measurements were discussed, and it was concluded that the values are acceptable for SE inputs to be used for reliable, robust control of HgCdTe composition. Although “hands-off”, SE-based composition control has not yet been conducted, the algorithms and software that have been successfully used on the IMSC program to achieve real-time control of III-V layer composition are fully compatible with the HgCdTe system, and they will be implemented into that growth environment.

Measurements of Cd flux from a CdTe effusion cell was measured in real-time during MBE growth using Cd OFM. Excellent correlation between the Cd flux and SE measurements of the Cd mole fraction in the growing layer was observed. In addition, it was shown that Cd OFM can be effectively used as a “fault sensor” to detect anomalies or undesired changes in the CdTe cell due to cell depletion or other instabilities.

We believe that the present sensing and control system will be an indispensable addition to MBE systems demanding first-pass or near-first pass success in growth of complex multi-layer detector structures in HgCdTe. Future work will involve the full integration of all sensors for control of layer composition, temperature, and Cd flux and the implementation of sensor fusion algorithms which will combine sensor inputs and facilitate optimized control strategies.

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