MBE, Production Ready?
Sensor-Based MBE for PHEMT Growth

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ABSTRACT

To provide a truly production ready MBE, we implemented *in situ* sensors for MBE growth monitoring and control of pseudomorphic high electron mobility transistors (PHEMTs). PHEMTs were prepared under continuous monitoring with reflection mass spectrometry (REMS) for growth monitoring and laser light scattering (LLS) for surface roughness. We also demonstrated the use of optical-based flux monitor (OFM) to accurately measure is accurate in measuring both real-time thickness and composition of GaAs/InGaAs QWs. we have succeeded in preparing PHEMTs with all critical growth parameters (thickness, composition, and surface conditions) monitored and documented using these *in situ* sensors.

INTRODUCTION

The development and refinement of III-V molecular beam epitaxy (MBE) over the last two decades have transformed this ultra-high vacuum (UHV) crystal growth technique into a near production-ready technology. Commercial MBE vendors have made great progress in terms of scalability of platen size and source cells. Uniformity across platen is no longer an issue. Unattended automation is achievable and defect density is also greatly reduced. For advanced epi-based devices such as high electron mobility transistors (HEMTs) [1] and hetero-junction bipolar transistors (HBTs) [2], MBE is capable of preparing these extremely complex structures with atomic layer precision. However, important concerns in volume production are reproducibility from run to run, over one period of times and from systems to systems. Frequent system calibration runs and test runs are still prepared routinely. These non-productive runs increase average cost and reduce growth yield.

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Moreover, processing specifications of many devices are tightened because stricter tolerance of certain critical parameters can significantly impact the cost of producing high-performance, low cost modules and circuits. In many cases, the precision and uniformity of these parameters is already determined by the material growth instead of processing. For example with a PHEMT device, the variation in threshold voltage, V_{TH}, is directly dependent on gate-to-channel AlGaAs distance. Use of AlAs Etch-stop in selective gate recess etch can significantly reduce this gate-to-channel distance variation. In this case, the responsibility of controlling critical electrical characteristics shifts from the wafer process engineer to the MBE grower.

In this paper, we will demonstrate that sensor-based MBE growth with *in situ* sensor monitoring is a promising approach for reliably reproducing the growth of these extremely sensitive epitaxial structures.

A sensor-based MBE system can refine an MBE system into a turnkey manufacturing process. Run-to-run reproducibility can be improved through real-time control of critical growth or structural parameters. This paper focuses on our experience in using *in situ* sensors to improve the growth of PHEMTs or similar structures such as InGaAs quantum wells. Sensor-based monitoring and control is especially useful for understanding strained layer growth and improving device structures. We have concentrated on three techniques: reflection mass spectrometry (REMS) to verify shutter operation and effusion cell flux levels during growth; optical-based flux measurement (OFM) to provide on-wafer thickness and composition determination; and laser light scattering (LLS) to monitor surface roughness and strained layer relaxation. We used OFM for real-time determination and control of the InGaAs QW composition/thickness. The data can be used to tune QW to desired energy level with closed-loop growth control. LLS was used as an independent monitor of strained layer relaxation and surface roughness.

EXPERIMENTAL AND IN SITU SENSORS

Fig. 1 shows a schematic of an MBE system utilizing REMS, OFM, and LLS sensors. For the HEMT test structures, the samples were grown in a 4-inch VG V90-MBE system on 2-inch, epi-ready GaAs(100) wafers. Following oxide desorption at 600 ºC for 2 minutes, 5 periods of AlAs/GaAs superlattice layers and a buffer layer of 0.8 µm GaAs was first grown on all samples. A superlattice buffer consisted of 20 Å periods of AlAs/GaAs layers were then deposited to smoothen the surface and eliminate defects. The double PHEMT structure consisted of two AlGaAs barriers separated by an InGaAs channel. Silicon pulse doping on both sides was used as doping sources. A 20A thick AlAs was used as etch-stop layer for later gate recess selective etching. Fig. 2 shows a cross-section of the PHEMT structures. All growths except the InGaAs layer were conducted at a nominal temperature of 580 ºC with the substrate rotating at 20 or 40 rpm.
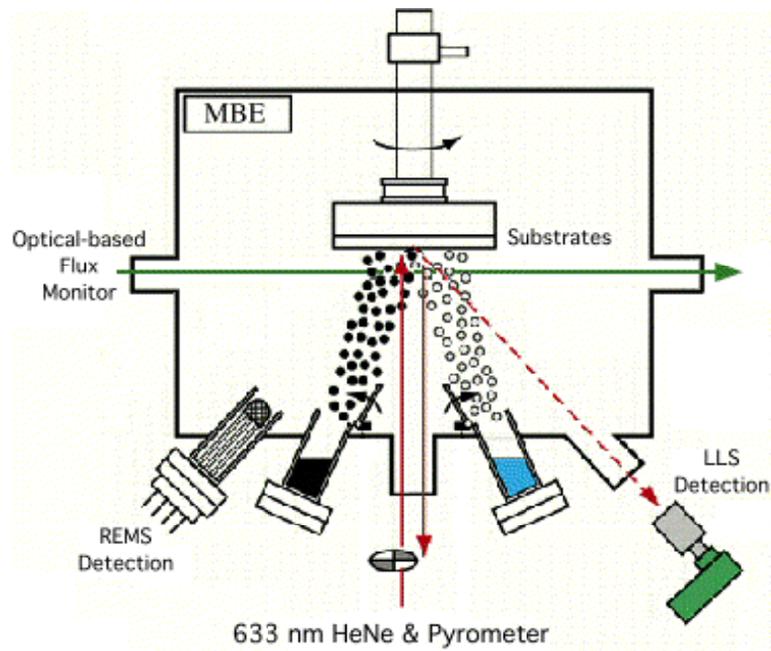
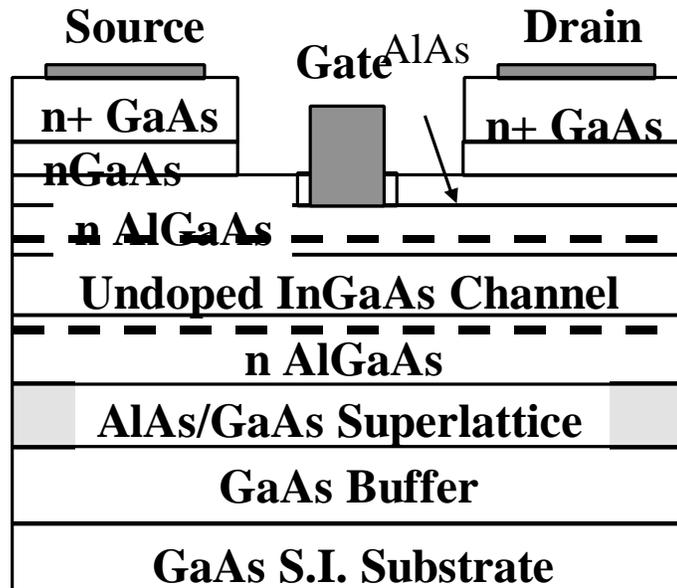**Fig. 1.** Schematic of a Sensor-Based MBE.

Fig. 2. The cross-sectional schematic of a PHEMT with AlAs etch stop layer.

Optical-based flux Measurement (OFM) - This approach utilizes an optical atomic absorption technique to monitor the molecular beam fluxes of the group III elements in real-time during growth. Because each atomic specie absorbs light at a distinct wavelength, their flux rates can be monitored simultaneously. A more detailed description of an OFM setup is given elsewhere [3,4]. Briefly, the system uses atomic emission lines from Al, Ga, and In hollow cathode lamps as the light sources. The light from each of the three lamps is mechanically chopped at a different frequency and combined into a single beam. This combined beam is passed through the growth chamber to probe the molecular beam fluxes just in front of the substrate. The signals are then detected with photomultiplier tubes (PMT's). The flux rate for each specie is related to its monitored atomic absorption signal. With an OFM, the useful parameters such as growth rates, layer thickness, and composition can be monitored continuously during growth. Closed-loop control of MBE using an OFM with time resolution of 0.1 seconds has already been achieved.

Reflection mass spectrometry (REMS) - An unapertured VG SX-300 mass spectrometer was installed with a direct line-of-sight to the growth surface at 70° from the surface normal. The REMS signal is, in general, a combination of directly-reflected atoms representing the effusion cell flux and desorbed atoms from the wafer surface. In this study, REMS was used to monitor shutter operation and effusion cell flux levels during growth. REMS can also provide thickness measurement for closed-loop growth control, and is simple to implement, but requires frequent calibration [5].

Laser light scattering (LLS) - The LLS experimental apparatus has been described previously [6]. Briefly, a HeNe laser (5 mW at 632.5 nm) is optically chopped at 1kHz and diffuse reflectance is detected using a GaAs PMT. Two 65° ports with periscope attachments are employed for both the incident laser and diffuse light collection. For high sensitivity, we use a telescope, narrow bandpass filter, and lock-in detection. The LLS azimuthal pattern (i.e. intensity signature from a rotating wafer) can distinguish 2-D vs. 3-D relaxation. The onset of surface roughening is also observed in real-time [6].

DISCUSSION

Thickness and composition by OFM: One of the critical steps for PHEMT growth is the InGaAs channel. To achieve high performance, both the layer thickness and composition of the channel needs to be determined accurately. Traditionally, without *in situ* sensors, the information regarding the InGaAs layer can only be verified indirectly by post-growth measurements such as photoluminescence (PL) or x-ray. By using a multi-channel OFM during the growth process, both the indium and the gallium fluxes of an InGaAs layer can be monitored simultaneously in real-time. As an example, Figure 3 shows the flux profile corresponding to the growth of three InGaAs

multi-layers of varying thicknesses with GaAs cladding in between them. The growth pauses between the InGaAs and GaAs layers were intentionally programmed into the recipe for the purpose of improving the interface quality. From the indium and gallium OFM flux data, the thickness and composition for each InGaAs layer are calculated. Figure 4 compares a set of measured PL peak energy position (E_{PL}) of InGaAs quantum wells (solid diamonds)—thin layer of InGaAs sandwiched between thick GaAs cladding layers—to the calculated PL peaks based on the OFM data (crosses). The solid curve through the graph is E_{PL} as a function of InGaAs layer thickness at 20% indium composition. Each error bar corresponds to a 5% uncertainty in InGaAs layer thickness. As shown here, the calculated PL peak from the OFM data matches to the actual measured PL data, which is much closer than the typical 5% dead-reckoning variation. Additional benefit of an OFM system includes immediate out-of-specification warning for fault detection when the source shutters do not actuate properly. This becomes critical cost saving factor as current MBE system is scaled up to such a larger capacity because each failure involves loss of wafers, source materials, and valuable machine time.
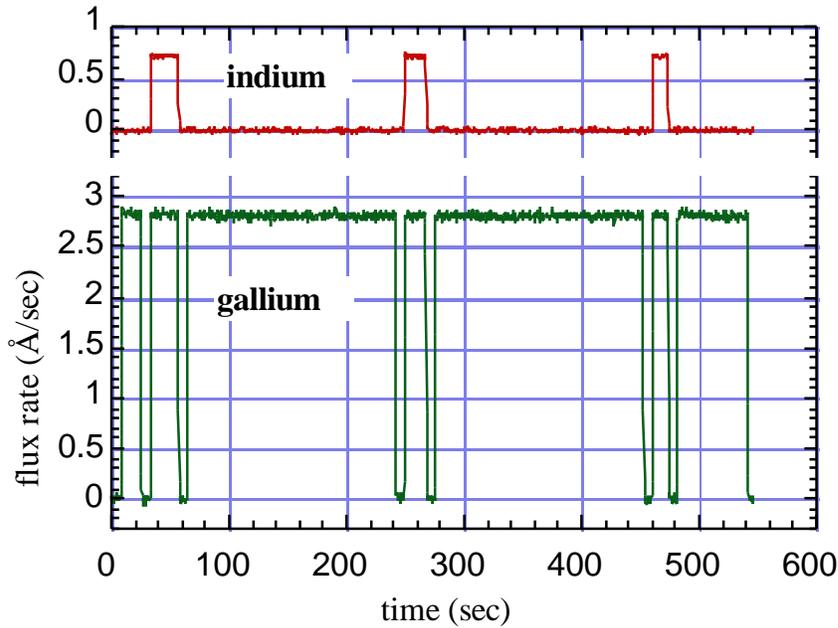

Fig. 3. In and Ga OFM flux rate profiles during the growth of $In_{0.2}Ga_{0.8}As/GaAs$ quantum wells. The growth rate and the composition are determined from the In and Ga fluxes. The quantum well thicknesses are 88Å, 67Å, and 50Å, respectively.

Surface roughness by LLS - LLS provides a convenient method for detection of surface roughening through concomitant changes in surface morphology. Real-time

detection of surface morphology changes by LLS during MBE growth provides a timely detection of fault growth. This is extremely valuable in lengthy growths such as GaAs buffer layer in PHEMT structures. The growth run can either be corrected, if roughening is caused by a non-optimized V/III ratio, or terminated if it is due to an unrecoverable error, such as shutter failure.
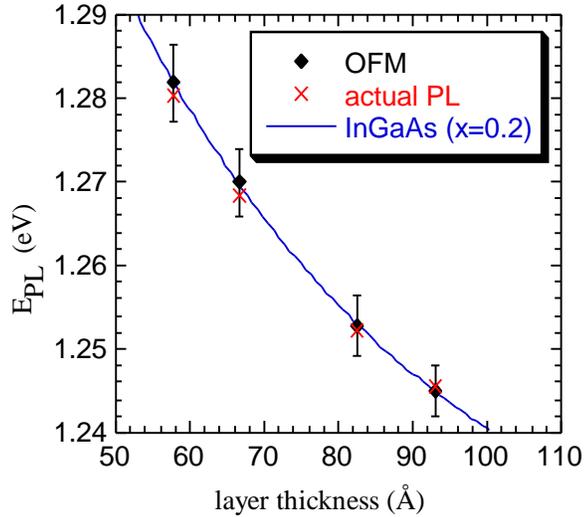

Fig. 4. Photoluminescence peak energy (E_{PL}) of $In_{0.2}Ga_{0.8}As$ multiple QWs as a function of layer thickness. Diamonds are data based on *in situ* OFM measured layer thickness and composition. Post growth measured PL peaks are showed in crosses. The curve and error bars indicate the theoretical energy-thickness curve and uncertainty in energy for 5% thickness variations, respectively.

Figure 5 shows the arsenic REMS signals and LLS spectra of two PHEMT structures. The difference in growth conditions between two samples is the V/III ratios. Significant roughening can be observed from the black LLS spectrum, while the gray spectrum indicates continuous smoothening over buffer layer growth. The roughening is corrected after arsenic flux is increased, and is further improved after AlAs/GaAs superlattice buffer growth prior to active AlGaAs/InGaAs channel growth. Variations in roughness are directly observed using LLS in real-time during the growth.
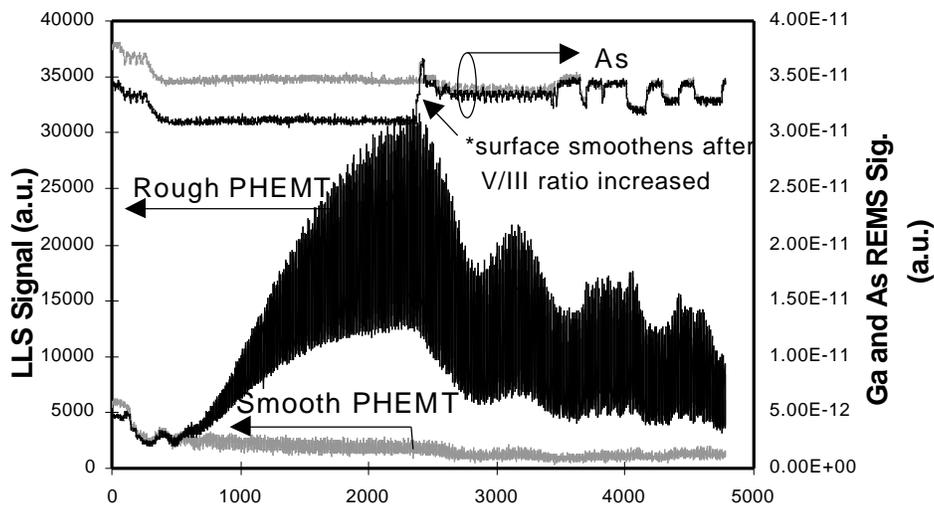
Fig. 5. Two PHEMT LLS spectra and arsenic REMS signals. The gray spectrum shows surface roughening due to low V/III ratio and recovering after V/III ratio increasing. Black spectrum shows a smooth PHEMT growth and continuous improvement of surface roughness.

CONCLUSIONS

We implemented *in situ* sensors for MBE growth monitoring and control of PHEMT growth. We demonstrate the effectiveness of OFM as a tool for monitoring the thickness and composition of InGaAs channel layer in real-time during growth with accuracy surpassing the conventional time-based "dead-reckoning" growth. Laser light scattering (LLS) was effective in monitoring surface roughness. By accurately controlling V/III ratios and buffer superlattices, we have succeeded in preparing PHEMTs with smooth surface and abrupt interfaces. All these developments will help provide tighter control of device critical parameter and significantly impact the cost of producing high-performance, low-cost circuits and modules.

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