Session ENG 202-034

Molecular Beam Epitaxy Growth and Instrumentation

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Abstract

Molecular Beam Epitaxy (MBE) is a versatile technique for growing epitaxial thin films of semiconductors and metals by impinging molecular beams of atoms onto a heated substrate under ultra-high vacuum conditions. Growth conditions can be monitored in real-time with the help of Reflection High Energy Electron Diffraction (RHEED) technique. The period of one RHEED oscillation corresponds exactly to the growth of one monolayer of atoms of the semiconductor material. Therefore it is crucial to dynamically monitor the oscillation rate in order to precisely control the epitaxial thin film growth to the monolayer accuracy. In this paper, a LabVIEW program is developed that would form the basis of a real-time control system that would transform MBE into a true-production technology. The PCI-1409 frame grabber card supplied by National Instruments is used in conjunction with the LabVIEW software to capture the RHEED images and capture the intensity of RHEED oscillations. The intensity values are written to a text file and plotted in the form of a graph. A Fast Fourier Transform of these oscillations gives the growth rate of the epi-wafer being grown. All the data being captured by the LabVIEW program can be saved to file forming a growth pedigree for future use.

Introduction

The ever growing demand of high performance semiconductor devices calls for a need of controlled and precise growth of the semiconductor compounds to achieve the targeted device properties. Epitaxy is the process of depositing, or growing, atomically thin crystal layers of typically dissimilar elemental materials onto a substrate to produce a compound semiconductor. A novel and the most popular means to achieve these requirements is to use the Molecular Beam Epitaxy [1] (MBE) growth process. MBE allows growth of crystalline layer combinations with accurate dimensional control down to the atomic level. This precision would not be possible without adequate accurate characterization techniques. One of the most useful tools for in situ monitoring of the crystal growth is the Reflection High-Energy Electron Diffraction (RHEED) system. RHEED provides resolution on the atomic scale while at the same time being fully compatible with the crystal growth process. It has been well established that the period of these oscillations corresponds exactly to the growth of one monolayer of atoms of the semiconductor material during the growth [2].

The development and refinement of MBE over the last two decades has transformed this ultra-high vacuum crystal growth technique into a near production-ready technology. Commercial MBE vendors have made a great progress in terms of producing clean wafers and source cells with accurate dimensions. For advanced epi-based structures such as high electron mobility transistors (HEMTs) [3] and hetrojunction bipolar transistors (HBTs) [4], MBE is capable of preparing these extremely complex structures with atomic layer precision. However, important concerns in mass production of these materials are reproducibility from run to run, over period of times and from systems to systems. Frequent system calibration runs and test runs still have to be prepared routinely. These non-productive runs increase average cost and reduce growth yield. 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. This requires automating the MBE growth process to improve wafer to wafer processing repeatability and reduce run-time by eliminating error prone process to produce devices on a large scale without compromising on the quality of the device structures grown. In this paper we concentrate on developing a LabVIEW [5] program that overcomes limitations of the existing RHEED software that prevents the MBE growth from automation. The work would form the basis of in situ monitoring of MBE growth for the development of a production ready MBE.

Methodology

Unattended automation can be achieved by designing a control system that monitors the growth in real-time and compares it with the data available from the previous growth. The difference between the real-time data and ideal data can be calculated and feedback to the control system and the growth parameters can be adjusted in real-time, thereby achieving accurate device structures. The variables that strongly affect the layer growth are the substrate temperature and flux emitting from the individual source materials. In the MBE reactor, it is not possible to rapidly change the diffusion (by controlling surface temperature) over the time period of typical 5-10 monolayer growth because of the slow thermal dynamics of the substrate. Hence, substrate temperature is useful as a "run-to-run" control variable. Alternatively, flux can be rapidly changed by adjusting the effusion cell shutters, and more slowly changed by controlling the cell temperature. Hence, flux is the effective control variable. A change in flux will affect the deposition time to achieve a desired coverage, i.e., decreasing flux increases the deposition time to reach a coverage goal and vice versa.

Because the period of one RHEED oscillation corresponds exactly to the growth of one monolayer of atoms of the semiconductor material, growth conditions can be monitored in real-time with the help of RHEED data. These RHEED oscillation patterns can be observed from time to time and compared to historical data of the material being grown. A schematic depiction of such a system is shown in Figure 1. The wafers are grown in the MBE chamber, and the RHEED images are observed on the computer and the real-time data is compared against the already available data. If any changes are to be made in the growth conditions, the computer calculates the values and sends the signals to change the temperature of the source cells or the control the movement of the shutters in front of the source cells. In addition the current data being captured can also be saved for future reference.

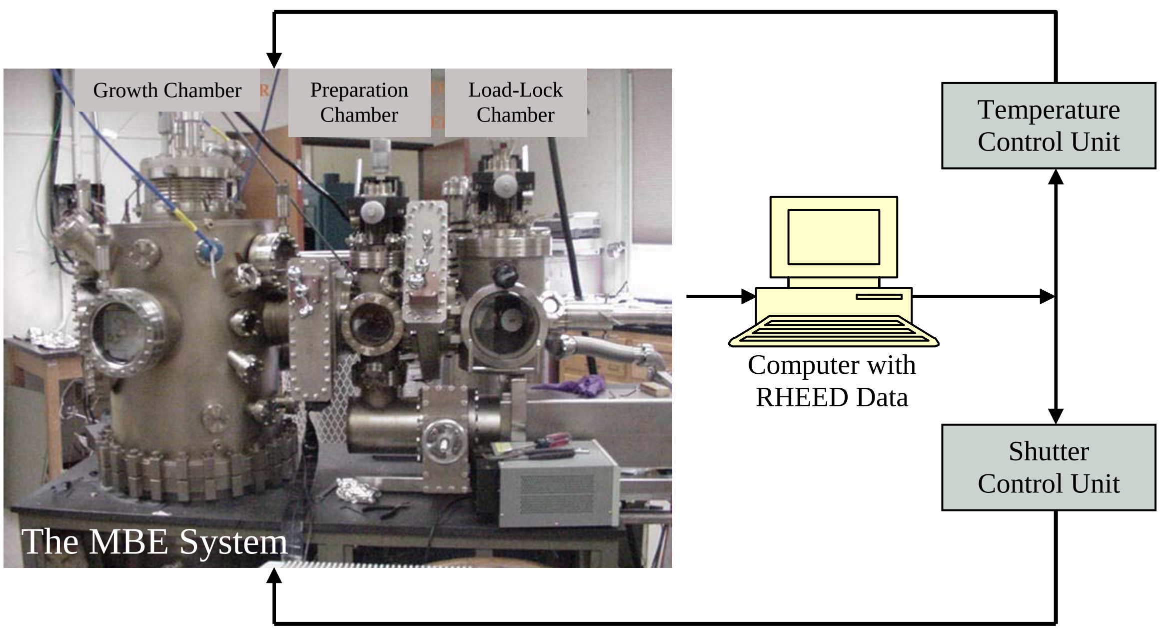


Figure 1: Block diagram of the control until that can be designed depending on the RHEED oscillations

With the existing Video RHEED Intensity Measurement Program for the MBE system in our laboratory, the data was recorded only in the form of a graph, it could not be written to a spread sheet so that it could be analyzed further for more accurate results. If the recording of oscillations was stopped at a particular point of time, (e.g. to alter the temperature of the sample being grown or the temperature of the source cell) new oscillations could not be appended to the existing file which made it difficult to observe the change in oscillations accurately when the temperature was varied. The user did not have a choice to change or specify the rate at which the oscillations were recorded. Also the RHEED program and the video card did not have the necessary software and hardware interface associated with it so that it could form the basis of a real-time control unit as shown in Figure 1. Moreover the program did not have an option to record the images before, during, and after the growth of the semiconductor material.

It is important to save the RHEED images so that they can be used in future growths when similar materials are being grown. For example, if a sample material is grown in ideal conditions and gives accurate results, the RHEED images obtained during this growth cycle can be used to compare with the RHEED images that are obtained during mass production. If it is seen during mass production that the RHEED images differ from the ideal images already available then, necessary corrections can be made to the growth conditions.

To overcome the limitations in the Video RHEED Intensity Measurement Program a LabVIEW program has been developed. The PCI-1409 frame grabber card supplied by National Instruments is used in association with the LabVIEW software to capture the RHEED images and calculate the intensity of the oscillations. The LabVIEW program developed performs the following functions:

1. Measure the intensity at a particular point on the image through a Panasonic CCD camera and using the frame grabber card to read the intensity values. Plot the intensity values as Time vs. Amplitude graph.
2. Observe the RHEED images continuously on the same computer monitor that has the LabVIEW code in it. Record the RHEED images before, during, and at the end of the sample growth. The program has the flexibility to change the point of measurement on the image during the growth.
3. Write the recorded intensity and the time values to a spreadsheet. While growing different samples the user are given the choice to append the data to an existing file or write data to a new file. The program has flexibility to record the intensity values at different time intervals as specified by the user.
4. This program is portable. It does not depend on the MBE system that is being used to take the measurements. It can be used in conjunction with any MBE system that has RHEED in it.

Experiments

The Group IV MBE system is used to grow samples to demonstrate the functioning of the LabVIEW program. The RHEED system present on the MBE chamber is used to monitor the growth of the samples. The experimental setup used to capture the RHEED images is shown in Figure 2. The camera, connected to the PCI-1409 frame grabber card which is installed in a PCI slot of a computer, is placed in front of the phosphor screen of the IV MBE system. During the growth process the camera controlled by LabVIEW program continuously record the RHEED images and intensities, through the PCI-1409 frame grabber card. A detailed description of the LabVIEW code has been reported somewhere else [6].

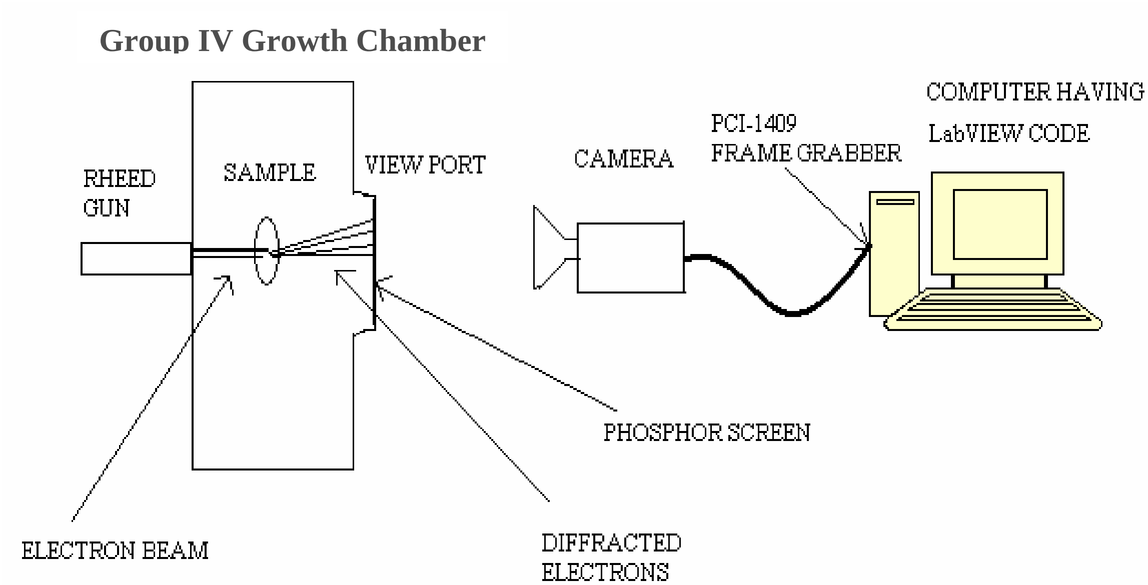


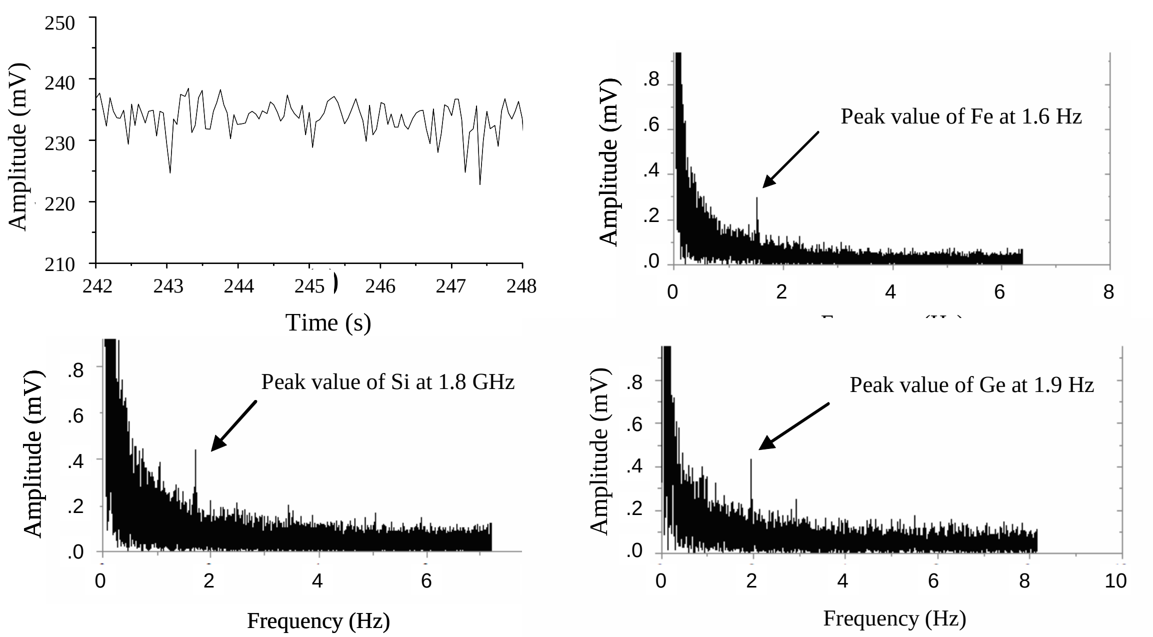
Figure 2: Experimental setup to capture RHEED images and intensities of the Group IV MBE chamber

A layer of Si is grown on a Si wafer for 10 minutes at 500˚C. Then a layer of Fe is grown for 19 minutes at 550˚C. Next a layer of Ge is grown for 4.5 minutes at 475˚C. Two RHEED images recorded during the growth are shown in Figure 3. Figure 3(a) is the image taken right after the Fe source is opened while Figure 3(b) is captured when Ge source is opened.

Figure 4(a) represents a typical oscillation pattern captured during the Fe growth. The FFT calculations, using ORIGIN software [7], at various stages of growth are shown in Figure 4 (b) through Figure 4(d). Figure 4(b) shows the growth pattern when Fe is being deposited. The FFT has a predominant peak at approximately 1.6Hz. Figure 4(c) shows the growth pattern when Si is being deposited. The FFT has a predominant peak at approximately 1.8Hz. Figure 4(d) shows the growth pattern when Ge is being deposited. The FFT has a peak at approximately 1.9 Hz. From the FFT calculations it can be observed that different materials exhibit different RHEED patterns. The time to grow one monolayer is the reciprocal of the oscillation frequency. Therefore the accurate device structure can be precisely controlled by the growth time. These RHEED oscillations and images can be saved and can be compared with the data obtained from the similar samples that are being grown. These samples are then sent out for further analysis to test if they exhibit required characteristics. Once the good samples are identified, the related RHEED data can be pulled out and be used to grow similar wafers on a large scale production basis.

(a) (b)

Figure 3: Captured images when the Fe source is deposited at 550˚C (a) and after Ge is deposited at 475˚C (b)



(c) (d)

Figure 4: RHEED intensity recording for Fe (a) and FFT oscillations for Fe (b), Si (c), and Ge (d) Growth

Limitations

The LabVIEW program is limited to be used with PCI-1409 frame grabber card. The data acquisition rate of the frame grabber card is limited to 30 frames/second with the National Television System(s) Committee (NTSC) camera that is used for this study. The accuracy of the intensity of oscillations being captured depends highly on the resolution of the camera. In this program the intensity is recorded every 50 milli-seconds.

Conclusions and Future Work

An MBE system coupled with a feedback control system can refine the MBE system into a turnkey manufacturing process. A real time MBE control system has to be designed in such a way that it works with the already existing MBE growth systems. It must be able to provide real-time information of the wafer growth states, simple to install and maintain, allow fast processing of data at a low cost. We have demonstrated the first step towards converting MBE to a true mass production technology. The LabVIEW program developed during this study can record the RHEED intensity oscillations, RHEED images, and save the data to an EXCEL sheet for future analysis. Combining with the ORIGIN software FFT calculations can be made successfully on the data obtained from the LabVIEW program. The RHEED images can be recorded at any particular point of time during the growth and the FFT calculations can be stored effectively. Also, if more than one sample of same kind is being grown, the oscillations can be appended to the same file if needed. This is particularly useful for comparison purposes when it is need to observe the growth pattern of a single sample under different growth conditions such as temperature and pressure.

A control-system has to be designed, that accepts the signals from the computer having the RHEED program and accordingly sends signals to the temperature-control unit and the shutter-control units on the MBE system in order to establish a truly production MBE system thereby increasing yield and decreasing the cost of production.

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Biography

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Shuping Wang received th B.S. in electronics from Peking University, China, in 1982, the M.S. degree in physics from Georgia State University, Atlanta, in 1990, and the Ph.D degree in electrical engineering from The University of Alabama, Huntsville, in 1996. Her Ph.D. dissertation was thin-film electrooptic polymeric etalon modulators. She is presently an assistant professor in Engineering Technology Department of the University of North Texas.