The Use of Optical Emission Interferometry for Controlled Etching of III V materials.

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ABSTRACT

For plasma etching processes, Optical Emission Interferometry (OEI) combines the advantages of Optical Emission Spectroscopy (OES) and laser interferometry. Radiation emitted by the plasma is reflected from the substrate surface and monitored using a multi-wavelength spectrometer. Analysis of the OEI signal provides endpoint data, and etch rate and etch depth information for both single and multi-component materials. Examples of these applications are described.

INTRODUCTION

Optical techniques are used extensively to monitor plasma-based processes since they are both relatively easy to implement and are non-intrusive. OES is commonly used to monitor emission from species in the plasma which can then be used to determine etch end point[1,2]. Interference techniques, which measure the intensity of a laser reflected from a substrate surface, give information about the reflecting surface and can be used for end point detection, as well as real time etch rate determination[1,2]. OEI combines the two techniques by monitoring the plasma emission which is reflected from the substrate surface.

Here we describe applications where OEI may be used during the etching of III-V materials, which include endpoint detection and process monitoring as well as real time etch rate and etch depth measurement.

EQUIPMENT

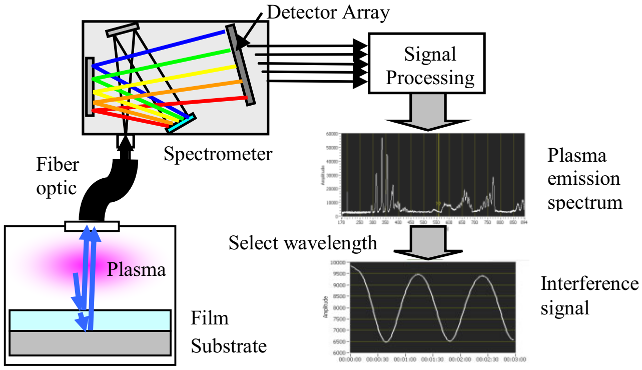


Figure 1 Optical Emission Interferometry schematic

A schematic of the instrumental set-up used to make all OEI measurements is shown in Figure 1. The samples were etched using a Plasma-Therm Versaline etch system fitted with an ICP source. A sapphire window located in the top of the source was used to view the plasma emitted radiation which was reflected normally from the substrate surface. A collimating lens focused this radiation into an optical fiber, giving an effective viewing area on the sample of approximately 2cm diameter. The fiber optic was coupled to a miniature spectrometer (Ocean Optics USB 2000+ UV-VIS) which was set to acquire a complete spectrum (200nm-850nm, 1.5nm resolution) at one second intervals. The spectral data was further processed (Endpointworks software, Plasma-Therm) using functions which are described in more detail in the following sections.

RESULTS AND DISCUSSION

1) OEI functioning as OES

The radiation received by the detector is not only that which has been reflected from the substrate, but also emission reaching the window directly, with no reflection from the substrate surface. As in conventional OES, the intensity of this emission at particular wavelengths is dependent on the material being etched and can be used to determine process endpoint. An example is shown in Figures 2 – 4.

A $Al_{0.1}GaN/GaN$ epi structure with a ~500nm upper layer of AlGaN was etched using a Cl_2-based process. A portion of the spectrum from 350nm to 450nm is shown in Figure 2, and shows both Ga emission at 403.3nm and 417.2nm, and Al emission at 394.4nm and 396.2nm[3].

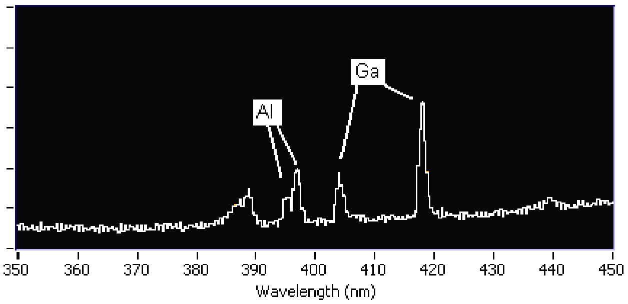


Figure 2 Partial OEI spectrum from AlGaN/GaN etch

When the emission at the Ga and Al wavelengths is monitored *versus* time as the etch progresses it is seen that the Ga emission at 403nm rises initially as the etch starts but is then essentially constant since the Ga content of the structure varies only slightly (Figure 3). However, the Al emission at 396nm increases and decreases during the etch as the Al-containing layers are etched (Figure 4)

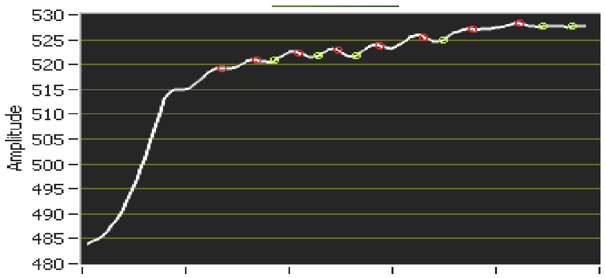


Figure 3 Ga emission at 403.3nm *versus* time

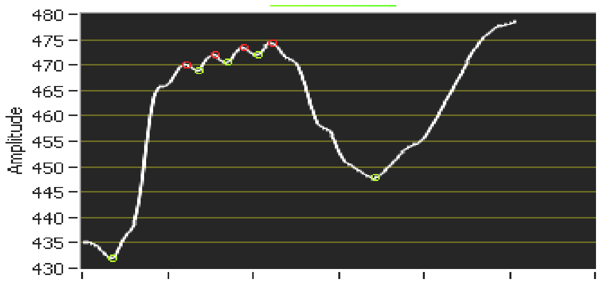


Figure 4 Al emission at 396.2nm *versus* time

It is straightforward to detect the increase or decrease in the Al signal level and use this information to trigger endpoint. With multi-layer structures, it is then possible to stop the etch at a specific layer boundary.

2) OEI for etch rate and thickness measurement

It can be seen in Figures 3 and 4 that there is also a cyclical variation superimposed on the emission signal. This is due to interference caused by reflections from the boundaries within the layered structure. It is more evident at wavelengths which do not otherwise change due to chemical changes within the plasma. An example from the same AlGaN/GaN etch is shown in Figure 5, where the plasma emission at 555nm is monitored *versus* time and the interference cycle is clearly seen.

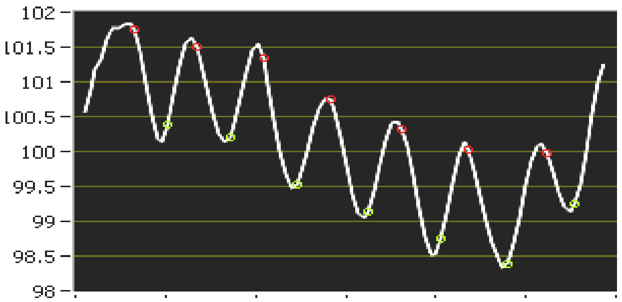


Figure 5 Interference signal from emission at 555nm

The film thickness change (d) for one cycle is given by:

$$d = \lambda / 2.n_f \qquad \ldots\ldots 1$$

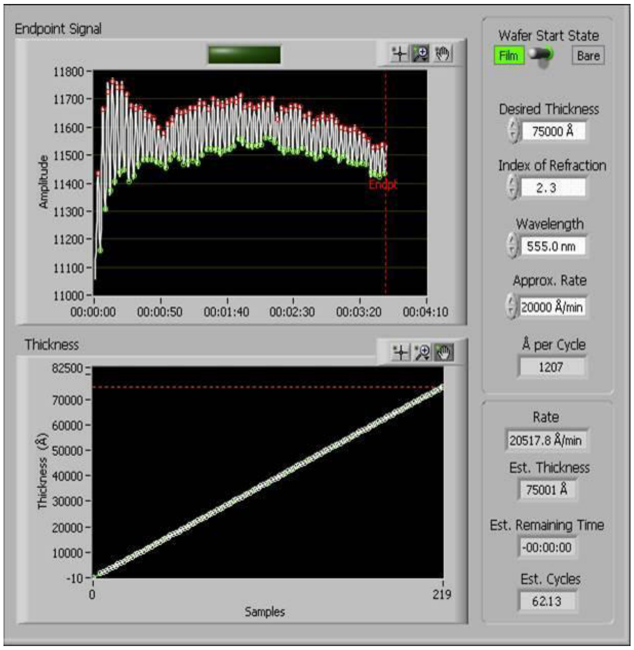
where:

λ is the wavelength at which the interference is monitored

n_f is the refractive index at that wavelength.

For the example given, the refractive index of the layer is 2.3 at 555nm, and so the thickness change corresponding to one complete interference cycle is 120.7nm. By measuring the elapsed time between successive cycles the etch rate of the AlGaN/GaN material can be calculated. A simple algorithm is used to detect and count peaks/valleys and interpolate between cycles using the calculated etch rate, giving a real time measure of etched depth.

This technique is extremely useful when it is required to remove a given thickness of material, but there is no etch stop layer present. Figure 6 illustrates OEI used to endpoint a process which removes 7.5µm of a GaN epi layer at a rate of approximately 2µm/min. The upper plot shows the interference signal measured at 555nm and the lower plot shows the calculated etch depth *versus* time. The etch process is terminated once this depth exceeds the specified etch depth (in this instance 7.5µm)



Wafer Start State: Film / Bare

Desired Thickness: 75000 Å

Index of Refraction: 2.3

Wavelength: 555.0 nm

Approx. Rate: 20000 Å/min

Å per Cycle: 1207

Rate: 20517.8 Å/min

Est. Thickness: 75001 Å

Est. Remaining Time: -00:00:00

Est. Cycles: 62.13

Figure 6 Removal of 7.5µm GaN, monitored using OEI

In the example given it is assumed that the etch rate remains constant with time, and it is the value of the average calculated etch rate that is used to interpolate between cycles. However, when etching layered stuctures which etch at different etch rates it is necessary to use the instantaneous calculated etch rate rather than the average value. This value can be updated at the completion of every half cycle of the interference signal.

This also highlights another capability of OEI which is the ability to monitor etch rate *versus* time and adjust a process based on the detection of an etch rate change. An example of this is shown in Figures 7 and 8. A structure which consists of an approximately 300nm thick GaP layer on top of a AlInGaP layer was etched using a BCl_3/Cl_2 process. In Figure 7 the interference signal observed at 650nm is shown, and in Figure 8 the etch rate calculated at every half cycle is plotted *versus* time. It is clear from this plot that there is a sharp drop in etch rate as the Indium containing layer is reached. This change can be used to trigger a process change, for example adjusting the process parameters to optimize the etch for the second material, or to simply terminate the process.

3) OEI for multiple etch rate measurements

The data shown in the above examples was obtained using samples of blanket (i.e. un-masked) material. The interference signal obtained closely approximates the theoretical response expected, which is a simple sine wave.

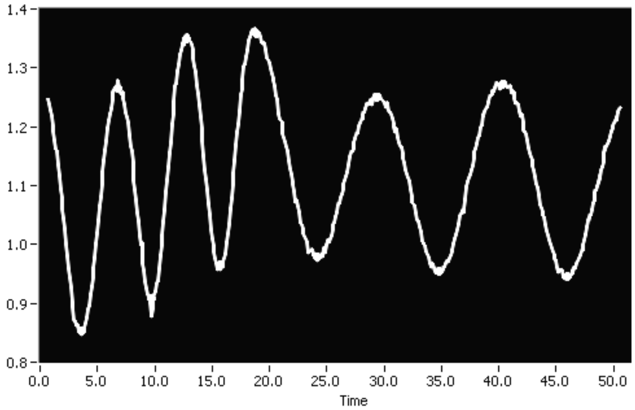


Figure 7 Interference signal from GaP/AlInGaP stucture

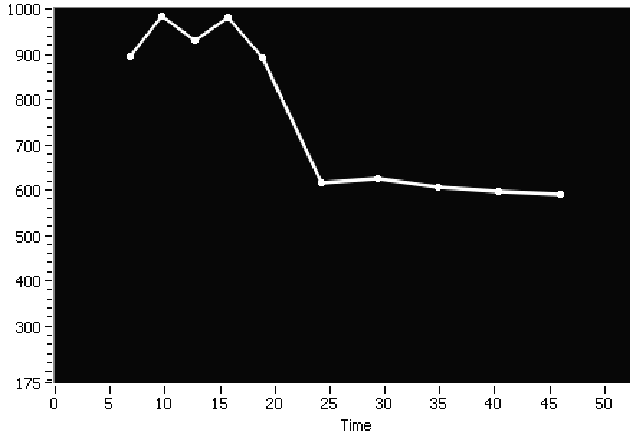


Figure 8 Etch rate of GaP/AlInGaP structure *vs* time

However, when more than one material is present on the substrate and is within the reflectance acceptance angle of the collection optics, separate interference signals will be generated by the different materials. The resultant interference signal will no longer be a simple sine wave, but will consist of superimposed sine waves, each generated according to Equation 1 for the different materials. The time for an individual cycle is dependent on the etch rates of the different materials.

As an example, in order to demonstrate this capability, we prepared samples which consisted of a patterned layer of silicon nitride on top of an un-patterned layer of silicon dioxide: the pattern was a simple grating structure with a nominal 50/50 line space ratio. Thus there were approximately equal areas of silicon dioxide and silicon nitride reflecting the plasma emission to produce the composite OEI signal. The sample was etched using an SF_6

- based process, with the process parameters adjusted to etch the silicon nitride approximately 3 times faster than the silicon dioxide.

The interference signal obtained during the etching of this structure is shown in Figure 9 and illustrates the complex nature of the interference signal.

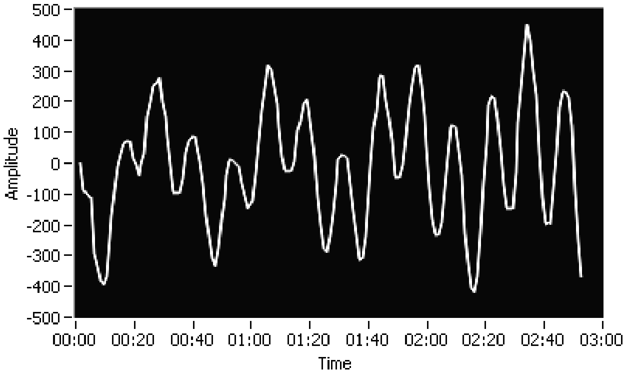


Figure 9 Interference signal from oxide/nitride etch

Rather than using a simple peak counting algorithm, this interference signal was analyzed using a Fast Fourier Transform (FFT) routine. In its basic form this gives an output which indicates the magnitude of signal at the different frequencies contained within the raw data. For example, it can be seen from Figure 9 that there is an obvious cyclical signal with a period of approximately 15 sec, or 0.067Hz.

It is more useful however to convert the frequency data to etch rate information. From the frequency data, the cycle time is calculated, which in turn is used to calculate etch rate using equation 1). The output of the FFT can then be presented in the form of the etch rate of the components contained within the interference signal. Such an output is shown in Figure 10, which shows two distinct peaks with etch rates of approximately 500nm/min and 150nm/min. These correspond to the etch rates of the nitride and oxide films respectively. Note that these rates are obtained from completely in-situ measurements, and avoid the usual need for pre- and post-etch measurements.

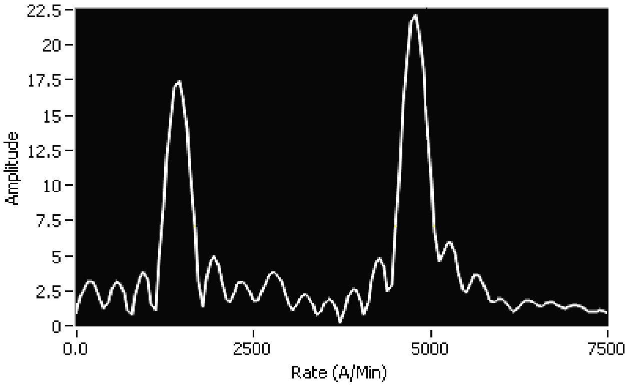


Figure 10 Fourier Transform of interference signal

CONCLUSIONS

It has been shown that OEI is a useful technique which can be used to monitor III-V etch processes. In its simplest form it can be used to determine process endpoint much like the more established OES. When the interference component of the signal is analyzed, both etch rate and etch depth information can be found. For multi-component layers, a FFT analysis permits etch rates of the individual components to be calculated. This type of analysis should prove extremely useful during process development or for routine process monitoring, where maintaining etch rates within defined limits is important for process stability.

Future work will attempt to extend the FFT capability for more commonly encountered structures such as III-V materials masked with photo-resist or other mask materials, and will also investigate what effect the mask/open area ratio has on the accuracy of the etch rate determinations.

REFERENCES

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[3] A.N.Zaidel et. al.,1970, *Tables of Spectral Lines*, IFI/Plenum.

ACRONYMS

OEI: Optical Emission Interferometry
OES: Optical Emission Spectroscopy
FFT: Fast Fourier Transform