In situ ellipsometry : an accurate analysis of films during plasma deposition and plasma etching

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IN SITU ELLIPSOMETRY: AN ACCURATE ANALYSIS OF FILMS DURING PLASMA DEPOSITION AND PLASMA ETCHING

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ABSTRACT

The two ellipsometers that have been used to monitor plasma etching and plasma deposition are introduced. Some results of time-dependent and spectroscopic measurements are shown.

INTRODUCTION

It is known[1,2] that ellipsometry is a technique which is well suited to study the etching or deposition of materials during plasma processing. With respect to other surface sensitive experimental techniques it has a number of advantages. First of all it is non-destructive. Photons of low energy (< 6 eV) are used that are not likely to damage the material in the coating to be analyzed. Furthermore it is not exclusively sensitive to the surface but also gives information on the bulk properties of the material. This implies that a ultra-high vacuum system is not needed, but also that the technique can be used in-situ. When attached to the etching- or deposition reactor one can closely observe the process. The internal reference of the technique allows for very high accuracies (variations in film thickness of < 0.01 nm can easily be detected). Automatic ellipsometers can operate very fast. The so-called rotating analyzer or rotating polarizer ellipsometers (RAE and RPE respectively) usually can perform one measurement each 10 msec [3]. The polarisation modulated ellipsometers work considerably faster [4]: one experimental point can be taken each 50 μs. Meanwhile the equipment is not very expensive: for a simple spectroscopic RPE with a reasonable accuracy some small optical components like polarizers, retardation plates and lenses are needed, as well as a light source, a monochromator and a photomultiplier tube. For the data aquisition a microcomputer with some A-D and D-A conversion interfaces can be used. This computer then can also perform the analysis and interpretation of the results.

Of course the technique also has some disadvantages. The alignment of the optical components has to be done very accurately. The interpretation of the direct experimental results in terms of thicknesses and refractive indices is rather complicated if evoluting stratified structures are investigated. Usually it has to take place after the deposition- or etching process has been completed. The next step, the 'translation' of the refractive indices into information on the structure of the material is the most difficult one. For inhomogeneous media usually the so-called effective medium theories (EMT's) are used [5].

In our experiments two types of ellipsometers have been used to study plasma etching and plasma deposition: a RAE at λ=632.8 nm and a spectroscopic RPE (wavelength range 200-700 nm). The processes observed are the etching of an SiO_2 film on a Si substrate in an RF discharge in CF_4 on one hand, and the deposition of amorphous carbon coatings from a mixture of CH_4, Ar and H_2 on the other hand. Only a few examples will be shown of time-dependent and spectroscopic measurements.

In the following first the principles of the method will be outlined. Then the experimental setup of the two ellipsometer systems is described. Finally some results are shown together with the conclusions.

METHOD

If a monochromatic light wave is reflected at an interface between two media with refractive indices n_1 and n_0, the components perpendicular respectively parallel (p respectively s-components) to the plane of incidence behave differently. The relative intensities of the reflected and the transmitted waves (R_p, R_s, T_p and T_s) are dictated by the Fresnel laws [6]. When stratified structures are studied the total R_p and R_s can be caculated when the interference of the multiply reflected waves is taken into account. The ratio $\rho = R_p/R_s$ is a complex number. Usually it is written as

$$\rho = \tan(\psi) \exp(i\Delta) \ .$$

The calculation of the ψ-Δ curve of a evoluting multiple layer system is done by a computer program. In the case of a semi-infinite medium the complex refractive index can be calculated directly from ψ and Δ using

$$n_1 = n_0 \tan\varphi_0 \sqrt{\ } (1-4\rho/(1+\rho)^2 \sin^2\varphi_0) \quad ,$$

where φ_0 denotes the angle of incidence.

EXPERIMENT

The He-Ne ellipsometer has the standard polarizer sample analyzer (PSA) configuration. The light emitted by the laser is polarized by a sheet polarizer mounted on a precision rotator. Through an adjustable window it enters the vacuum system and impinges on the substrate. After reflection it passes a rotating analyzer. Then the intensity as a function of time is detected by a EG&G SGD100A pin diode. 256 times each evolution of the analyzer an optical encoder triggers the conversion of the 12 bits ADC . An index pulse calibrates the absolute position of the analyzer. The computer, based on the M68000 microprocessor, reads the data and performs Fourier analysis. Only the first two terms of the transform are used. They can be converted directly into ψ and Δ. Figure 1 presents an overview of the setup.

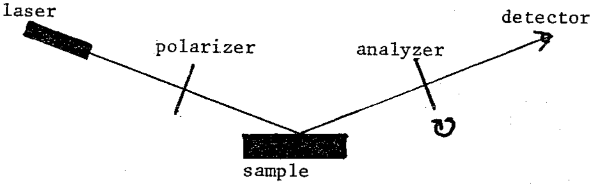

Figure 1: outline of the setup of the He-Ne ellipsometer

The second ellipsometer used in our experiments also has the PSA configuration. As a light source a cascaded arc is used. The light that is emitted is not polarized because flat windows can be used. Furthermore the spectral emissivity in the UV-region is considerably larger than in the case of the Xenon short arc. When the system has to be aligned a He-Ne laser can be projected through the arc channel.

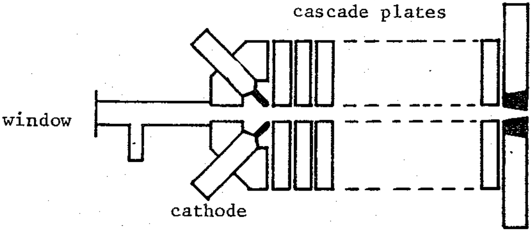

Figure 2: Schematic view of the construction of the cascaded arc

Figure 2 outlines the arc construction. The light is focused on the sample by a quartz lens. As rotating polarizer a Glan-Taylor prism made of calcite is used. The fixed analyzer is mounted on a steppermotor controlled rotation stage (0.01 degree per step). A stepper motor controlled Jobin-Yvon 0.25 m monochromator selects the wavelength. Operated at slit widths of 0.1 mm its spectral resolution is 0.3 nm. The power supply of the photomultiplier tube is controlled by the computer in order to keep the signal between 0.3 and 0.8 µA. Before a spectrum is taken the plane of incidence is calibrated automatically by the computer using a method described by Aspnes [3].

The resolution of both ellipsometers is 0.01 degree in ψ and Δ. This corresponds with a film thickness of about 0.01 nm.

RESULTS

The He-Ne ellipsometer was used to study the etching of an SiO_2 film on a Si substrate by an RF plasma in a mixture of CF_4, Ar and H_2. A typical example of a ψ-Δ curve that is generated when the SiO_2 film is etched is shown in figure 3, together with its numerical simulation. The shape of the curve clearly indicates that a top layer is growing during the etching process. The third evolution of the curve deviates from the pattern expected in the case of homogeneous etching without surface damaging. The numerical simulation indicates that slowly the thickness of the toplayer increases to a value of about 50 nm. Using a modified effective medium theory [7] the volume fractions of SiO_2 and vacuum inside the top layer are estimated to 0.7 and 0.3 respectively. The conventional theories all yield an isotropic dielectric constant whereas our modified theory leads to an anisotropic dielectric constant, which gives better approximations of the measurements.

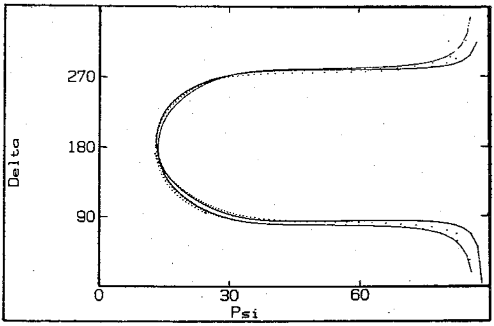

Figure 3:
Trajectories in the ψ-Δ plane representing the etching of SiO_2 on Si. Solid line: model Points: experiment

When the same ellipsometer is used to analyze the growth of an amorphous carbon film on a substrate of evaporated gold one can observe that the refractive index usually is not changing during the deposition process (see figure 4).

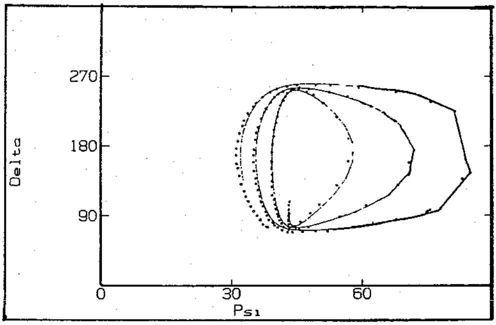

Figure 4:
ψ-Δ curve representing the deposition of amorphous carbon on gold. The good agreement between model and experiment indicates that the refractive index is constant

A ψ-Δ curve like figure 4 can be interpreted into a plot of the film thickness as a function of time (fig. 5). In this case the deposition rate appears to decrease during the process.

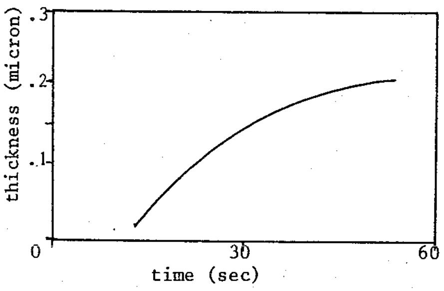

Figure 5:
Film thickness as a function of time.

Using the spectroscopic ellipsometer the absorption coefficient and the refractive index of the analyzed amorphous carbon coatings have been determined as a function of wavelength for various discharge conditions. Here only one example will be given. The spectral behaviour of the real and imaginary parts of the refractive index are shown in the figures 6 and 7 respectively.

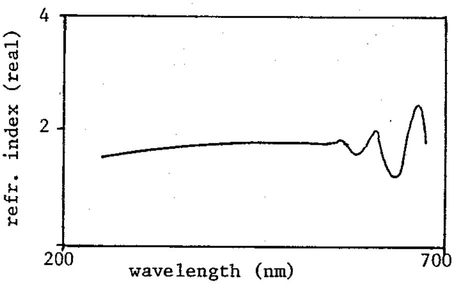

Figure 6:
Real part of the refractive index as a function of wavelength.

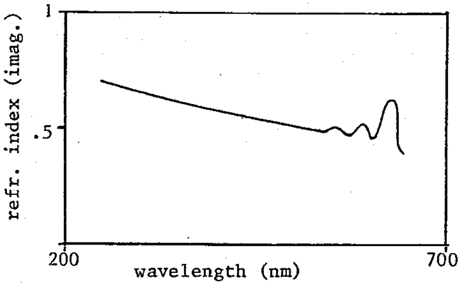

Figure 7:
Imaginary part of the refractive index as a function of wavelength.

If the square root of the product of absorption coefficient and photon energy is replotted as a function of the photon energy the band gap behaviour of the material is shown. The band gap can be calculated by extrapolating the linear part of the curve towards the horizontal axis.

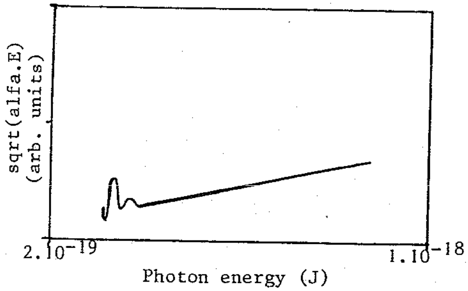

Figure 8:
Alternative representation of figure 7. The linear part of the curve indicates a band gap behaviour.

CONCLUSIONS

In-situ ellipsometry has proven to provide for accurate information about the processes that take place during plasma etching and plasma deposition. Surface damage can clearly be seen in the etching process. It appears that during plasma deposition the deposition rate and (sometimes) the refractive index are a function of time. The spectroscopic ellipsometer yields detailed information on the optical parameters of the film.

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