A novel setup for spectroscopic ellipsometry using an acousto-optic tuneable filter

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A rotating analyzer ellipsometer for fast measurements at multiple wavelengths as well as for spectroscopic measurements has been developed. The most important novelty of the setup is the use of an acousto-optic tuneable filter (AOTF) as dispersing element. This offers advantages with respect to the speed of measurement, the adjustment of the intensity of the light, the use of lock-in techniques, and the stability and size of the setup. Advantages and limitations of the use of AOTF's in ellipsometry as well as possible changes in the ellipsometric setup are discussed. The ellipsometer has been mounted on an electron cyclotron resonance plasma deposition chamber. As an example, the deposition of amorphous hydrogenated carbon layers has been studied in situ and are compared to ex situ measurements by variable angle of incidence spectroscopic ellipsometry of the same samples. © 1995 American Institute of Physics.

I. INTRODUCTION

Ellipsometry is an experimental technique for the determination of the optical properties of thin films. This can be achieved by measuring the change in the state of polarization upon reflection of a collimated light beam at a sample. The most important components of an ellipsometer are a monochromatic light source, a polarizer, an analyzer and the detector. The extensive development of instrumental techniques during the last decades resulted in a variety of setups for ellipsometric measurements. There are two categories of photometric ellipsometers in dependence on the principle of the modulation of the state of polarization. One is the rotating polarizer ellipsometer (RPE) or rotating analyzer ellipsometer (RAE). The other is the phase modulation ellipsometer (PME), where the polarization can be changed by using a photoelastic device. The advantages of the first one (RPE and RAE) are its insensitivity in wavelength and its conceptual simplicity, however, the detection rate is limited by the frequency of the rotating element (about 50 Hz). On the other hand, in a PME the modulator is a completely electronically controlled solid state device, which can be modulated up to a frequency of 50 kHz. This photoelastic modulator is a wavelength-dependent element and requires electronic components of high speed.

For spectroscopic applications two methods are common: One specific wavelength of a white lamp as light source can be selected by (i) a grating or prism monochromator. This can be done in the detection unit in front of the light collimating optic of the light source. Furthermore, (ii) an optical multichannel analyzer (OMA) can be utilized as the detection unit. With OMA based ellipsometers time resolved ellipsometric measurements can be recorded within about 150 ms. However, the use of monochromator based ellipsometers for real-time measurements is limited by the time necessary for data acquisition and for the selection of the wavelength by the monochromator. This disadvantage can be overcome only by multiple wavelength real-time measurements. For example, by alternately selecting some wavelength with a monochromator, by the use of a few detectors for some fixed wavelengths, by switching between different narrow band light sources (e.g., laser diodes) or by selecting spectral lines from a light source (e.g., Hg lamp) by means of a fast filter wheel. All these systems have limitations in their use. Either the speed is limited by the speed of moving parts, or the wavelength cannot be selected unrestrained when using spectral lines, or it is impossible to perform spectroscopic measurements without changes in the setup. In addition, if a motor driven monochromator and a white light source are used, the time to move to another wavelength depends on the preceding wavelength position.

In this article we present a new setup for a spectroscopic ellipsometer. The novelty is to use an acousto-optic tuneable filter (AOTF) instead of a grating or prism monochromator. This offers a series of advantages, as will be described in the next section.

II. THE ACOUSTO-OPTIC-TUNEABLE FILTER (AOTF) AND ITS BENEFITS IN ELLIPSOMETRY

An AOTF acts as an electronically tuneable spectral bandpass filter. It consists of a crystal of tellurium dioxide (TeO₂) or quartz, and a transducer, bonded to one side of the crystal. In applying radio frequencies to the transducer, it emits acoustic waves in the crystal. These acoustic waves cause refractive index variations which act like a transmission diffraction grating or Bragg diffractor. In a so-called noncollinear configuration, the optical waves of a light beam, which penetrates through this crystal, propagate at quite different angles through the crystal (see Fig. 1) as the acoustic...
waves. Unlike a classical diffraction grating, the AOTF only diffracts one specific wavelength of light. This is a consequence of the diffraction over an extended volume in contrast to the diffraction at the surface of a grating prism. The wavelength of the diffracted light is determined by the "phase matching" condition as described by Chang:

$$\lambda = \Delta n \nu / f_a,$$

where $\Delta n$ is the birefringence of the crystal, $\nu$ and $f_a$ are the velocity and frequency of the acoustic wave, and $\alpha$ is a complex parameter depending on the design of the AOTF. The selected wavelength of the light can therefore be varied simply by changing the frequency of the applied RF. One rate limiting factor in changing the wavelength is the time necessary for filling the AOTF crystal—typically 20 $\mu$s. The other limiting factor is the frequency switching speed of the driver unit. For the controller used in this setup (BRIMROSE model-PP) it takes typically 15 ms to switch from $f_{\text{min}}$ to $f_{\text{max}}$. This means that discrete wavelengths may be accessed at rates of 60 Hz or greater, even when they are separated by hundreds of nanometers. The applied RF is generated with digital precision. So, once the AOTF is calibrated, it will not need to be recalibrated. As an example, a typical TeO$_2$ AOTF has a guaranteed wavelength repeatability error of less than 0.05 nm. As indicated in Fig. 1, the diffracted light intensity is directed into two first order beams, termed the (+) and (−) beams, which are orthogonally polarized. The diffraction efficiency of acousto-optic tuneable filters is 20···80%, with the intensity divided between the (+) and (−) beams. The efficiency and the bandwidth of the selected light depend on the device and the wavelength of operation. Characteristic values for the bandwidth are, e.g., 1 nm at 450 nm, 5 nm at 1200 nm, and 20 nm at 3200 nm. Out of band transmission of an AOTF can be as low as $10^{-5}$. AOTF’s are available in the range of 200 up to 4500 nm.

In addition to its high speed for wavelength selection, the use of an AOTF in ellipsometry has many more benefits, which will be described in the next section.

A useful and unique feature of an AOTF is its ability to adjust precisely and rapidly the intensity of the diffracted (filtered) light beam by varying the RF power. (i) Detector overload can be avoided under computer control without moving parts. (ii) The intensity of the light can be changed with the spectral bandwidth, and the beam diameter remaining constant. (iii) The detector offset can be measured without a shutter but by simply switching off the RF power. (iv) The intensity of the selected light can be rapidly modulated without a chopper blade. This makes the AOTF ideal for use with a lock-in amplifier, which has merely to be added to the data acquisition system. This modification would be useful to avoid problems with the offset as well as to increase the signal to noise ratio.

Furthermore, the speed of multiple wavelength ellipsometric measurements is no longer limited by the velocity of moving a grating or prism and does not depend on the absolute value of the wavelength of successive measurements. The speed of the instrument is mainly limited by the rotational frequency of the analyzer, the speed of the driver unit of the AOTF, and the speed of signal processing by the computer. Changing over from spectroscopic to fast multiple wavelength measurements requires only software instructions. As compared to a monochromator, an AOTF does not require any slit, but can be passed by a beam of up to 10 mm diameter. AOTF’s are both compact and rugged.

As the available AOTF’s range up to 4500 nm, it is also an interesting tool for near infrared applications of ellipsometry. For near infrared (NIR) ellipsometry the use of an AOTF offers advantages especially for in-situ applications as compared to the use of a delicate Fourier transform spectrometer. An AOTF based NIR ellipsometer would be small, rugged and cheap as compared to a setup using an FTIR.

Another possible configuration is a rotating polarizer ellipsometer (RPE). In such a setup the white light from the source passes a rotating polarizer, is reflected at the sample, and then passes the fixed analyzer and the AOTF, mounted on a rotating stage. Furthermore, two or more AOTF’s can be put in series, each with it’s own detector. In this way the bandwidth of the spectroscopic ellipsometer can easily be broadened without introducing moving parts like mirrors or order sorting filters. However, the capability of intensity adjustment of the AOTF can no longer be used for offset measurement or for background correction by lock-in technique in the RPE configuration. Also, the state of polarization of the light entering the rotating polarizer has to be known.

Another possibility is to replace the monochromator of a phase modulated ellipsometer by an AOTF. In this way a compact, rugged and completely electronically controlled ellipsometer without moving parts can be constructed.

Compared to this series of advantages of an AOTF for ellipsometry, only a few disadvantages have to be mentioned. The spectral range of an AOTF is smaller than the conventional total range. Examples for available spectral ranges are 200-400 nm, 400-700 nm, 800-1600 nm, etc. Another disadvantage can arise from refraction of the selected beam. As can be seen in Fig. 1, the diffracted light is not perpendicular to the surface of the crystal for a standard AOTF. So the dispersion of the crystal material results in a wavelength dependent angle between zero order beam and diffracted beam. This problem can be solved for one of the two diffracted waves.

FIG. 1. Schematic representation of a noncollinear AOTF.
beams by a special design of the crystal or by the use of a wedge behind the AOTF.

III. THE ELLIPSOMETER SETUP

The optical setup of the rotating analyzer ellipsometer (RAE) utilizing an AOTF is presented in Fig. 2. It is similar to the well-known configuration described by Aspnes and Studna. Therefore, only the differences will be described in more detail in this section.

The light source consists of a convection cooled high-pressure 75 W Xe short arc lamp with fiber coupling optic. A fiber with 200 μm core diameter is used to transfer the white light from the source to a collimating optic to produce a parallel beam. The fiber and its collimating optic as well as the AOTF are adjustably mounted on a base plate. This base plate and a prism calcite Glan polarizer are mounted on a stepper motor driven rotation stage, not shown in Fig. 2. The polarizer is aligned at an angular position in that way, its axis of transmission is parallel to the plane of polarization of the beam filtered by the AOTF. In this way intensity losses due to the polarizer are minimized. All these elements are aligned in such a way that the monochromatic, linearly polarized beam coincides with the axis of rotation. The rotation stage has an angular resolution of 0.001°. If the angle of polarization has to be changed, the polarizer, the AOTF, the collimating lens and the optical fiber holder are all together rotated around the optical axis.

The detection unit consists of a prism calcite Glan polarizer, mounted on the hollow shaft of a stepper motor of 200 steps per revolution (2000 steps in microstep mode). A timer/counter card is used to generate the pulses for the stepper motor. So the rotational frequency of the analyzer is of quartz stability. The pulses from the timer/counter card also trigger a 12 bit analogue to digital converter (ADC) in connection with the personal computer (PC). Only one pulse per revolution is necessary for the determination of the analyzer angle. It is generated by a zero detector on the holder of the rotating analyzer. As compared to other ellipsometers, no angular encoder is used in this setup. A photodiode, with the front window removed to avoid strain birefringence, is used as detector. It is closely connected to an amplifying current to voltage converter. The output voltage is transferred to the 12 bit analogue to digital converter.

The RF generator (RF) for the AOTF is connected to the PC via a parallel printer port (PP). On this line the information on wavelength and the status of the AOTF are transmitted. An 8 bit digital to analogue converter (DAC) within the PC is also connected to the controller unit. The output voltage in the range of 0···5 V is used to control the RF voltage of the driver and thus the intensity of the filtered beam.

The angle between the filtered and the zero order beams has a slight dependence on the wavelength, as already mentioned in the previous section. This is corrected by placing a BK7 wedge closely behind the AOTF.

The ellipsometer has been installed at an ECR plasma deposition chamber. This chamber is equipped with two viewports at 70° with respect to the normal of the sample. Adjustable bellows are used for aligning the windows. The cell windows are O-ring sealed fused silica planes, held by atmospheric pressure to avoid strain birefringence. The rotation stage with AOTF, polarizer, lens and fiber has been adjustably mounted to the base-plate of the deposition chamber. This unit has been aligned when the ellipsometer was installed and remained unchanged afterwards.

The sample holder has been mounted on a small electrode (10 cm diameter) inside the vessel. To this electrode a direct current (DC) or radio frequency (RF) voltage can be applied to deposit films with a DC or RF bias. The sample holder is adjustable by means of three screws with a fine lead. Inside the output view-port a 10 cm long blackened tube with a 2 mm diameter aperture has been mounted. This aperture is used to align the sample as well as to reduce stray light from the plasma striking the detector. The rotating analyzer/detector unit is also adjustably mounted to the base-plate of the deposition chamber. Alignment of the ellipsometer is normally restricted to alignment of the sample. All other components remain unchanged. To avoid mechanical vibrations of the deposition chamber and the ellipsometer, the whole system is fixed to a heavy block of concrete and the rotary as well as the turbo molecular pump are connected via bellows.

The films have been deposited in the ECR plasma deposition chamber. The base pressure in the vessel is about 10^-6 Pa, the total pressure during deposition was 0.1···1 Pa. The vessel is equipped with a heatable, adjustable substrate electrode. The substrate temperature can be varied from room temperature up to 400 °C. The flow of methane for the deposition experiments and hydrogen or oxygen for etching experiments is controlled by a flow controller and is ranging from 5 up to 20 sccm. The microwave input power, the substrate temperature, as well as the voltage between the electrode and the vessel, are measured in real-time during the experiments.

IV. DATA ACQUISITION

The principles of data acquisition for rotating analyzer ellipsometers have been described in excellent papers. So we can restrict ourselves to a short summary.

The intensity of the polarized light beam after reflection
The optical offset, originating from background light as well means of a shutter). Offset correction is normally done by be subtracted. This is necessary, because the DC part of the offset intensity \( I_o \) is measured at every angular position of malized Fourier coefficients, see denominator in Eqs.(4). The normalized as measured ones (\( a_m, b_m \)) of light, which is polarized parallel (\( p \)) to the plane of incidence or perpendicular (\( s \)) to it. From the \( N \) intensity values \( I_i \) measured per signal period, the normalized as measured Fourier coefficients (\( a_m, b_m \)) are calculated by:

\[
\begin{align*}
a_m &= 2 \sum_{i=1}^{N} I_i \cos \left( \frac{2\pi(i-1)}{N} \right) / \sum_{i=1}^{N} I_i, \\
b_m &= 2 \sum_{i=1}^{N} I_i \sin \left( \frac{2\pi(i-1)}{N} \right) / \sum_{i=1}^{N} I_i.
\end{align*}
\]  

The angular position \( P \) of the analyzer is determined by residue calibration\(^3\) or phase calibration\(^1\), depending on the value of \( \Delta \) of the sample used for this calibration. Before the ellipsometric angles are calculated, the attenuation ratio of the AC/DC signals and the phase shift of the signal as well as the angular position of the analyzer have to be corrected for. These correction values (\( a_c, b_c \)) are measured with the polarizer set to the position \( P = 0^\circ \), where the light is polarized parallel to the plane of incidence. The corrected Fourier coefficients (\( a, b \)) are related to the as measured ones (\( a_m, b_m \)) and to the correction values (\( a_c, b_c \)) by:

\[
\begin{align*}
a &= \frac{a_c a_m + b_c b_m}{a_c^2 + b_c^2}, \\
b &= \frac{-b_c a_m + a_c b_m}{a_c^2 + b_c^2}.
\end{align*}
\]  

The ellipsometric angles (\( \Psi, \Delta \)) are calculated from the Fourier coefficients (\( a, b \)) by:

\[
\begin{align*}
\cos(2\Psi) &= \frac{\cos(2P) - a}{1 - a \cos(2P)}, \\
\cos\Delta &= \frac{b}{\sqrt{1 - a^2}}.
\end{align*}
\]  

The optical offset, originating from background light as well as the electronic offset, arising from the dark current of the photodiode and the offset of the operational amplifiers, has to be subtracted. This is necessary, because the DC part of the measured intensities is used for the calculation of the normalized Fourier coefficients, see denominator in Eqs.(4). The offset intensity \( I_{oi} \) is measured at every angular position of the rotating analyzer with the source switched off (e.g., by means of a shutter). Offset correction is normally done by calculating the average offset of the signal intensity \( I_o \)

\[
I_o = \frac{1}{N} \sum_{i=1}^{N} I_{oi}
\]  

V. RESULTS

As an example for the application of the current ellipsometer setup utilizing an AOTF, measurements with amorphous hydrogenated carbon (a-C:H) layers are presented. With the same samples ex-situ measurements with a variable angle spectroscopic ellipsometer (VASE, J.A.Woollam Co.) have been performed. Since the growth of hydrogenated carbon films is not the main topic here, a comprehensive description of the deposition experiment as well as a much more detailed interpretation of the results will be the subject of another paper.

An in-situ real-time measurement at 500\,nm, 600, and 700 nm, recorded during the growth of an a-C:H film on silicon, is presented in Fig. 3A. The deposition conditions are: 15 sccm CH\(_4\), 0.1 Pa, 30 W absorbed microwave power in the plasma, \(-50\) V RF bias, no external substrate heating. The in-situ real-time measurement presented in Fig. 3A has been evaluated in a three step procedure. At first the angle of incidence and the thickness of the native oxide on the silicon substrate have been calculated from the first \( \Psi, \Delta \) values, taken before the deposition process has been started. For this procedure reference data for the refractive index and the extinction coefficient of silicon and silicon dioxide are used.\(^1\) The angle of incidence is found to be \( 70.1^\circ \), the thickness of the oxide to be 4.5 nm. The oxide thickness is slightly increased as compared to the native oxide as a result of substrate cleaning with an oxygen plasma.

In a second step the optical constants of the a-C:H film at the three wavelength have been calculated. Homogeneous film growth without surface roughness is used as an optical model, only a thickness nonuniformity is taken into account. In this procedure the refractive index and the extinction coefficient are varied to match the measured curvature in the \( \Psi, \Delta \) plane as close as possible. The results are shown together with the results of the spectroscopic measurements in Fig. 5 (big filled triangles).

The last step in the evaluation of the in-situ measurements is the calculation of film thickness vs deposition time and its time derivative, the deposition rate. This is performed with WVASE program\(^3\) (J.A. Woollam Co.), using the results of the previous steps of data analysis. A point to point fit of the film thickness, calculated simultaneously for the three wavelength with a thickness nonuniformity of 5.2%, is presented in Fig. 3B (filled squares). The first derivative of these results, the growth rate, is also presented in this figure.
FIG. 3. Real-time ellipsometry measurement at λ=500, 600 and 700 nm on an ECR plasma deposited a-C:H film with −50 V RF-bias on silicon (A) and the calculated film thickness in dependence on the deposition time as well as its first derivative (growth rate) and a fit to the growth rate (B). (open squares). The small oscillations in the growth rate arise from the thickness nonuniformity of the film and a slight dependence of the beam diameter at the sample on the wavelength, caused by the collimating optical system.

Two conspicuous features are visible in Fig. 3A. Δ=0°, 180°, 360° are not reached. This is a result of lateral inhomogeneity of the film thickness, as can also be seen from the interference color in the deposited area. Second, the distance between successive data points in the Ψ, Δ plane slightly increases with increasing film thickness. This results from an increasing growth rate during the deposition process.

An in-situ spectroscopic measurement in the wavelength range from 475 up to 700 nm has been taken with the AOTF ellipsometer after termination of the deposition process. This measurement is shown in Fig. 4. At the same sample an ex-situ measurement with VASE has been taken at three angles of incidence (65°, 70° and 75°) in the range of 250 up to 1000 nm. The measurement at 70° in the wavelength range of the AOTF ellipsometer is also presented in Fig. 4, showing good conformity. The differences can be explained by differences in the angle of incidence and the beam diameter. All spectroscopic data have been analyzed with the WAVE program assuming a homogeneous film of 192 nm thickness, as calculated from the in-situ measurement. Surface roughness has not been taken into account because it is known to be negligible for this film growth process. Data analysis has been started with a Cauchy dispersion model layer in the long wavelength region (600 up to 1000 nm) and was continued by a point by point fit of the optical constants, started at the longest wavelength. The result in the wavelength region of the AOTF ellipsometer is presented in Fig. 5 and shows good agreement with the results of the in-situ measurement.

VI. DISCUSSION

The measurements with the new AOTF based ellipsometer give results in good agreement with those obtained by VASE. It can be concluded that an AOTF is a suitable device to construct a fast, small and rugged spectroscopic ellipsometer. The AOTF has some unique properties and can be used in a variety of ellipsometer setups.

The data analysis of the in-situ measurement during the growth of an a-C:H film in an ECR plasma deposition chamber shows a slight increase of the growth rate from about 0.07 to 0.11 nm/s during growth.

The growth rate of hydrocarbon films is determined by the ion energy and ion flux from the plasma towards the film surface. Furthermore, the optical properties of the deposited films are directly correlated to the ion energy. So an increase...
ing ion energy leads to an increasing index of refraction of the hydrocarbon layers. Generally, the observed increase in the growth rate can be a consequence of an increasing ion energy or an increasing ion flux. However, by comparing the measurement with an optical graded layer model, the film shows only a negligible vertical grading of the optical constants. So it is not expected that an increasing ion energy is responsible for the increasing growth rate.

This leads to the conclusion that the ion flux is increasing during film growth. The inner walls of the deposition chamber have been cleaned by oxygen plasma treatment subsequent to deposition experiment. Therefore, during the deposition process the state of the walls of the chamber changes from clean metallic conducting to coated with an insulating film. In this view the confinement of ions in the plasma may be enhanced, due to decreasing loss process at the inner walls of the vessel. This is also in accordance with an observed slight increase of the pressure in the vessel during the deposition process. Furthermore, in similar deposition experiments it has been observed that with coated walls no increase in the deposition rate occurs.

A more detailed investigation on these processes in combination with the results of other techniques (e.g., mass spectrometry) will be the subject of a forthcoming paper.