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Nonintrusive wafer temperature measurement using *in situ* ellipsometry

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It is shown that *in situ* HeNe laser ellipsometric measurements performed during and after rf plasma exposure of a Si wafer with or without oxide can be used to obtain the wafer temperature during plasma exposure. The method utilizes either the temperature coefficient $\delta n/\delta T$ of the refractive index of Si or the linear thermal expansion coefficient $\delta l/l\delta T$ of SiO_2. The values of these parameters have been redetermined in this work.

One of the important parameters in plasma processing is the temperature of the surface to be treated. It is however also a parameter which is difficult to measure nonintrusively. The standard technique is infrared (IR) pyrometry, which cannot be used in the low-temperature regime (0–400 °C) because of the transparency of the Si wafers in the IR. In the literature a few methods have been suggested. For instance, Bond *et al.*[1] used laser interferometry to measure the thermal expansion of a thick glass substrate. Donnelly *et al.*[2] applied essentially the same method using an infrared laser and a silicon substrate polished on both sides. For both methods special thick substrates are required. It would be desirable to have a method that gives the same accuracy on a conventional semiconductor wafer, possibly covered with oxide films of a thickness used for device processing.

A simple method to measure the temperature nonintrusively is demonstrated in this communication. A conventional Si wafer, with or without an oxide film in a technologically important thickness range, is used. The change of the refractive index of the silicon substrate and the thermal expansion of the oxide film with temperature are determined after exposure to a plasma process using *in situ* ellipsometry and *in situ* surface temperature measurements with a fluoroptic thermometer. Precise knowledge of the corresponding temperature coefficients enables the ellipsometric determination of the substrate temperature. In this work we have calibrated this method and determined the temperature coefficients.

The experiments were performed in a diode reactor equipped with a 12-in. water cooled, quartz covered rf-powered (13.56 MHz) electrode. The gases were fed through mass flow controllers at a rate of 100 sccm. A throttle valve in the pumping line to a 500 l/s Leybold turbomolecular pump maintained the pressure at 25 mTorr in all experiments. The wafer was placed on the powered electrode, and its temperature was measured with a Luxtron fluoroptic probe. The fiber of the Luxtron probe was connected to the wafer with a thermally conducting, aluminum-containing epoxy glue. The ellipsometer was an automated, rotating compensator type in the PSCA (polarizer–sample–compensator–analyzer) configuration, operating at the He–Ne laser wavelength (632.8 nm). The rotating compensator principle offers the advantage over rotating analyzer configurations that the ellipsometric angle Δ is determined unambiguously, with an accuracy which is approximately uniform over the Ψ–Δ plane. An Analog Devices RTI-850 16-bits analog input board located in a IBM PC-AT was used for the ellipsometer data acquisition. Experimental details have been described elsewhere.[3] A measurement was taken every second, each measurement yielding a pair of the ellipsometric angles Ψ and Δ. The principle of operation and the interpretation of the results of ellipsometry are described in the literature.[4] Temperature readings were taken from the Luxtron analog output by the same RTI-850, synchroneously with the ellipsometry measurements. Also the dc self-bias voltage of the plasma was measured in order to detect the exact time the plasma is extinguished.

Either O_2 or CF_4 was used to feed the plasma. Since in O_2 plasmas the oxide etch rate is small, many measurements on the same wafer at about the same thickness can be performed. CF_4 was used to etch the oxide in order to be able to do measurements at several thickness values. Furthermore, analysis of the Ψ–Δ contours measured during the etching process (see Fig. 1) yields the refractive index of the oxide (1.52) and the angle of incidence (74.14 deg). The experiments concerning the oxide film were done with film thickness values that place the ellipsometric angle Δ around 0 or 360 deg. This occurs at Ψ values near 70 deg (see Fig. 1). In this region of the well known Ψ–Δ contours the angle Ψ hardly changes with film thickness, whereas Δ is very sensitive: 1 deg increase of Δ corresponds to a thickness change of roughly 0.2 nm. The angle Ψ is however very sensitive to the refractive index of the bulk oxide. Therefore it is very convenient to perform the measurements in this part of the Ψ–Δ plane: the changes of the refractive index (if detectable) and of the film thickness show up independently.

Measurements were also taken on the oxide-free silicon substrates after complete oxide film removal by the plasma.

Figure 2 shows, near the endpoint of the oxide etch, the evolution with time of several experimental parameters while the plasma is switched off. Figure 2(a) displays the dc self-bias voltage, and Fig. 2(b) shows the time evolution of Ψ and of the substrate temperature. The oxide etch end point occurs at time t_e. After that time the silicon substrate is exposed, and the value of Ψ is strongly related to the real part of the refractive index of silicon. After the plasma is switched off, both the temperature and Ψ show an exponential decay towards their asymptotic values. This is demonstrated better in Fig. 1(c), where the changes of Ψ and

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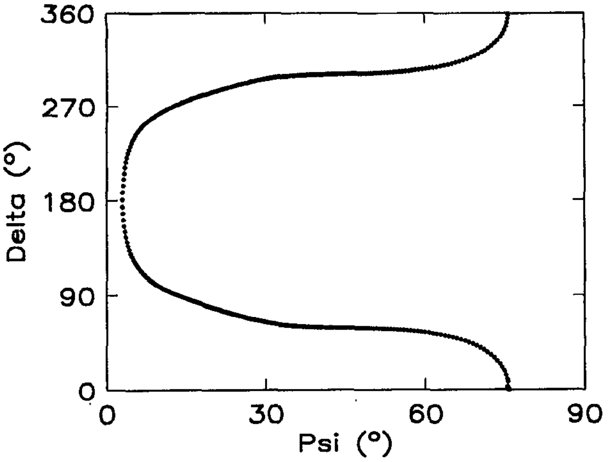

FIG. 1. The Ψ–Δ plot which is measured with the *in situ* ellipsometer during the etching of an SiO_2 film on Si. The temperature measurements were performed at the locations where $\Delta \sim 0$, where the influence of the refractive index can be distinguished from thickness changes.

the temperature with respect to their asymptotic values are plotted logarithmically. Before plasma switch-off, the temperature increases, with a different time constant. As there is still oxide film present on the substrate before the etch endpoint t_e [see Fig. 2(a)], undergoes drastic changes (see for instance Fig. 1). After the endpoint t_e,Ψ assumes a slow variation which corresponds to the temperature increase.

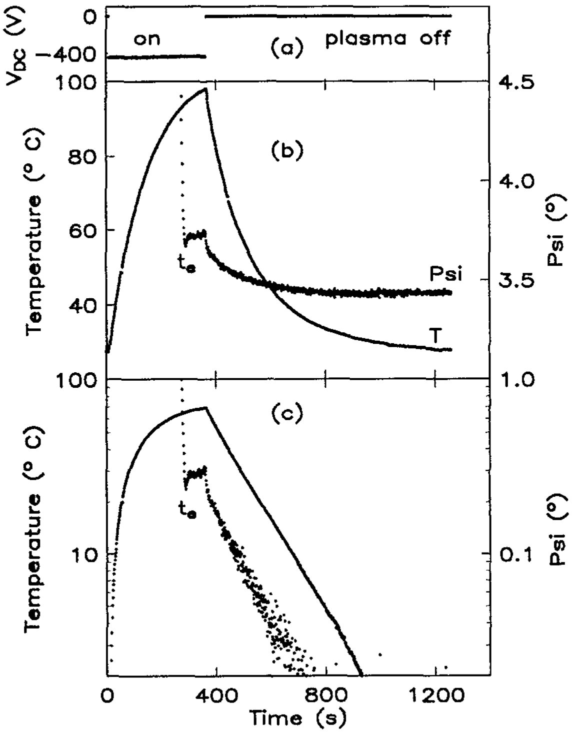

FIG. 2. (a) The dc self-bias of the electrode as a function of time. This signal is recorded in order to monitor exactly when the plasma is switched on and off. (b) The substrate temperature as measured by the Luxtron fluoroptic probe (left axis) and the ellipsometric angle Ψ (right axis) as a function of time. At time t_e the oxide etch end point is reached. (c) Logarithmic plots of the temperature data displayed in (b) and of the difference $\Psi(t) - \Psi(\infty)$.

Measurements similar to the ones described above were performed with oxide still present on the substrate. Each time that the Ψ–Δ curve passed through the already mentioned regions around $\Delta \sim 0$, the plasma was switched off, and the temperature and the ellipsometric angles Ψ and Δ were measured as a function of time. In all cases no significant change of the refractive index of the oxide film could be detected while the substrate cooled down. This is in agreement with the literature, where refractive index temperature coefficients of about 4×10^{-6} are reported.[5] The changes induced by those values fall well below the detection limit of the present setup. They might however cause small errors in the thickness values calculated from the Ψ–Δ combinations using a fixed index of refraction (1.52). Therefore this effect has to be taken into account. As is illustrated in Fig. 2, the refractive index of the silicon substrate also changes when the wafer cools down. This effect has also been taken into account. The thickness values were calculated using an algorithm similar to the one introduced by McCrackin.[6]

Figure 2 illustrated the strong relation between the ellipsometric readings and the substrate temperature. This relation becomes even stronger in Fig. 3. Here the ellipsometric angles Ψ and Δ are converted into film thickness values in the case of measurements on oxide films, and into refractive indices in the case of a naked silicon substrate. The thickness changes are displayed for four values of the oxide film thickness. Both SiO_2 film thickness and Si refractive index are plotted versus the temperature as measured simultaneously with the fluoroptic probe. In all cases the curves appear to be linear. Figure 3(b) directly provides a value for the temperature coefficient of the refractive index n of silicon at 632.8 nm: $\delta n/\delta T = 4.52 \times 10^{-4} K^{-1}$, which is in excellent agreement with the value reported by Jellison.[7]

Figure 3(a) illustrates that the exponential change of the ellipsometric angles after plasma switch-off is due a change in the bulk of the oxide, and not due to a surface phenomenon like the desorption of weakly bound, plasma related species. In the latter case the thickness decrease would be independent of the oxide film thickness. The temperature coefficients one can extract from the lines in Fig. 3(a) are plotted versus the oxide film thickness in Fig. 4. The slope of the line through the points in Fig. 4 yields the linear thermal expansion coefficient of the oxide: $\delta l/\delta T = 9.9 \times 10^{-6} K^{-1}$. This value of the thermal expansion coefficient of SiO_2 films on Si agrees remarkably well with the literature value for crystalline SiO_2.[8] Since the present material is amorphous this should be a coincidence and may possibly be explained by a change in the thermal behavior of amorphous SiO_2 when attached to a silicon substrate.

Using the temperature coefficients calibrated above, nonintrusive temperature measurements may be performed using *in situ* ellipsometry. Measurements have to be taken on silicon wafers, with or without an oxide film on it. The

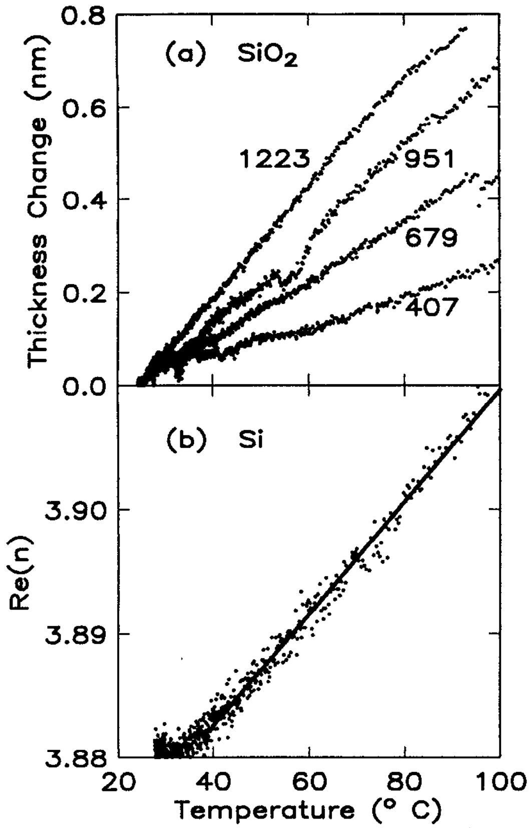

FIG. 3. (a) The thickness change of SiO_2 films on silicon plotted vs the temperature change. The four lines represent four different film thickness values: 407, 679, 951, and 1223 nm. (b) The refractive index of silicon as a function of substrate temperature.

exponential decay of either the silicon refractive index or the oxide film thickness which will be observed after the plasma is switched off, can be extrapolated back to the exact switch-off time using a logarithmic plot. The temperature coefficients can then be used to derive the temperature during plasma exposure.

To conclude, we have demonstrated a method for nonintrusive *in situ* wafer temperature measurement using ellipsometry. The method is essentially not real time, because the plasma has to be switched off. Otherwise the thickness change due to heating or cooling would be dwarfed by changes due to processing, e.g., etching or deposition. The thermal expansion coefficient of SiO_2 films and the temperature coefficient of the refractive index of Si, either of which is needed to apply the method, have been determined.

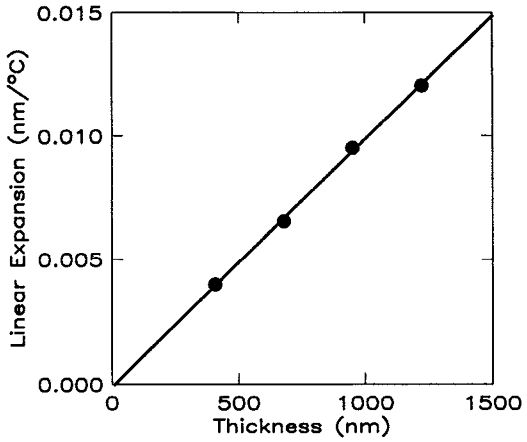

FIG. 4. The temperature coefficients as extracted from Fig. 3(a) as a function of the oxide film thickness. The slope of the line directly gives the thermal expansion coefficient.

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