beaglehole instruments

Leader in thin film meterology

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Application Note 7

Very thin gate oxide/nitride layers on silicon

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When surface layers are thin the changes in the ellipticity signal due to the layers are small. The changes can be expanded into first order terms $O(t/\lambda)$, second order terms $O(t/\lambda)^2$, etc, where t is the layer thickness and λ is the wavelength of light. For a 1nm layer measured at 400nm, the second order term is typically t/λ ~400 times smaller than the first term.

First order η measurement

The first order term is proportional to η, as discussed below. The design of our Picometer is such that, with just one wavelength, we can measure η very accurately- for the 1nm layer to better than 1%. In general the quantity η is proportional to the total excess surface polarisation. If this is modelled by a single surface layer, η depends upon the layer dielectric constant and the layer thickness

$$\eta = \frac{(\varepsilon - \varepsilon_1)(\varepsilon - \varepsilon_2)}{\varepsilon} t$$

where ε is the layer dielectric constant $\varepsilon = n^2$, ε_1 and ε_2 the ambient and substrate dielectric constants. If the layer dielectric constant ε ($\varepsilon = n^2$, n the layer refractive index) is known we obtain a very accurate value for the thickness t, while if the thickness is known we obtain an accurate value for ε. To get a separate evaluation of ε and t we have two options:

(i) We could measure the second order term. This term is partly proportional to $(\eta)^2$ and contains no extra information, and partly proportional to the product εt^2 which allows the separation. However the second order term is small, and very difficult to quantify reliably even with the Picometer .

(ii) ε and the substrate properties ε_2 are functions of wavelength, so measurements at 2 or more wavelengths give different measures of η, which then provides enough information to separately determine ε and t.

A more general expression for η where the surface is coated with molecules of different polarisabilities is

$$\eta = \int dz \frac{(\varepsilon - \varepsilon_1)(\varepsilon - \varepsilon_2)}{\varepsilon}.$$

There are two important ways of looking at this quantity.

(i) η is proportional to the total excess polarisability of layer molecules per unit area This

follows from the following approximations: The dielectric constant for silicon is very large (ε_2 ~ 15 in the red), while the refractive index of oxide or nitride is much closer to air (ε(oxide) ~ 2.15, ε(nitride)~ 4, ε(air) = 1). Thus $\eta \sim \Delta\varepsilon\, t\, (\varepsilon_1 - \varepsilon_2) / \varepsilon_1$, and since ε depends upon the product of layer surface molecules per unit volume and their polarisability, η becomes proportional to the total excess polarisability per unit area in the surface region.

(ii) η is directly related to t_{eq} the equivalent oxide thickness which produces the same capacitance density C/A:

The capacitance of a single layer of thickness t, low frequency dielectric constant κ and area A is $C = \kappa A / t$. Usually there are several layered materials making up a gate layer, and these act in series so that

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots$$

$$t_{eq} = \alpha_1 t_1 + \alpha_2 t_2 + ..$$

where α_i are the coefficients that convert a layer thickness t to the equivalent oxide thickness. For several layers

$$\eta \approx (\Delta\varepsilon_1 t_1 + \Delta\varepsilon_2 t_2 + \ldots)\frac{(\varepsilon_1 - \varepsilon_2)}{\varepsilon_1}$$

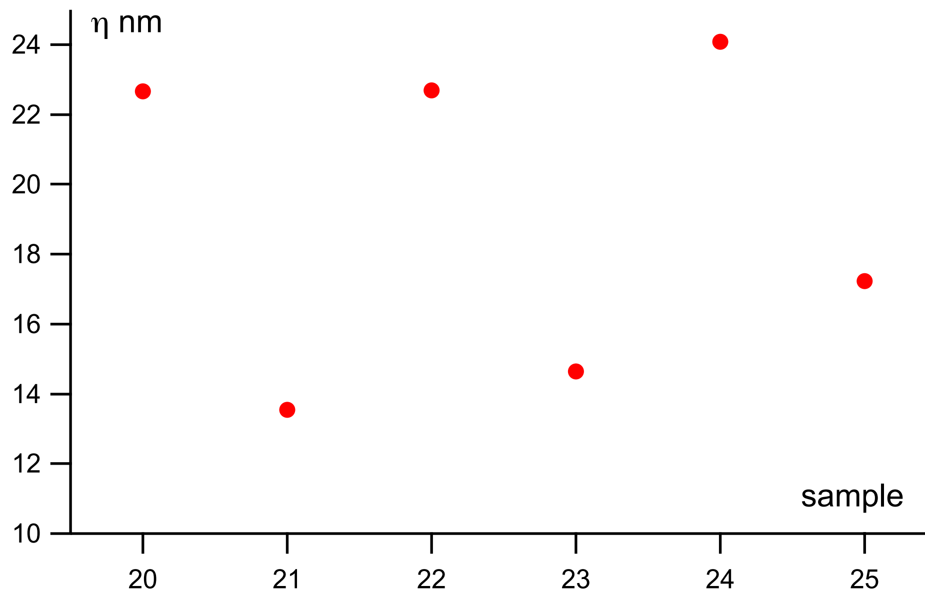
$$\eta \approx \Delta\varepsilon_{oxide}\, t_{eq} \frac{(\varepsilon_1 - \varepsilon_2)}{\varepsilon_1}$$

$$\Delta\varepsilon \approx (\varepsilon - 1) \approx (\kappa - 1)$$

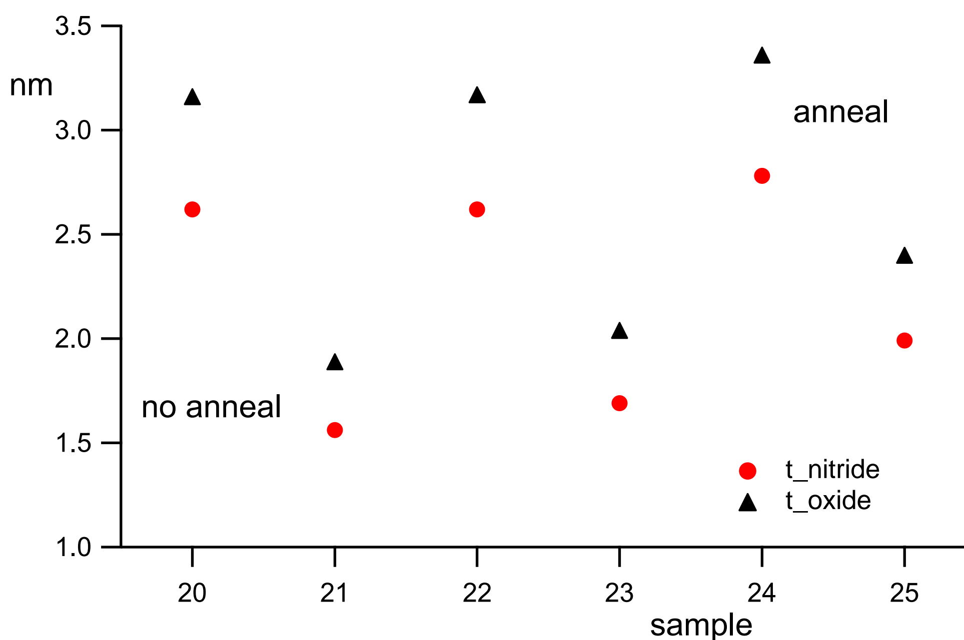
The low frequency dielectric constant for non-polar molecules such as silicon dioxide or silicon nitride lies reasonably close to the high frequency dielectric constant ε. Thus the simple optical measurement of η will quickly yield a quantity close to the EOT.

The cleanest measurement of η is obtained from an ellipticity measurement at the Brewster Angle for the substrate, around 74° for silicon at 633nm where silicon is essentially transparent. Ellipticity measurements characterise the reflectance ratio $r = r_p / r_s$ which in general is a complex number. At the Brewster angle Re(r) = 0 andfor a transparent substrate the Im(r) is directly proportional to η.

An example of the measurement of η at 633nm is given in the figure below. These were 6 silicon wafers, 3 (odd numbers) treated to have just a thin oxide, while the other three (even numbers) had been further annealed in a nitride environment, with a slightly different recipe for each sample. The experimental error for each point is less than 0.1nm.



The layer thicknesses assuming the layer is all oxide or all nitride are shown in the following figure.



The samples are likely to be a mixture of both oxide and nitride. The one measurement of η cannot determine the composition, but the t_oxide data shown should be closely related to the EOT. Unfortunately we do not have, at this point in time, the values of the capacitances for these wafers.

Additional information on the layer structure can be obtained by a set of measures of η at different wavelengths.