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Reflectivity Thickness Corrections for Silicon Dioxide Films on Silicon for VAMFO

In recent years, a great deal of interest has been centered on the non-destructive measurement of the thicknesses of oxide or glass films on silicon, based on the production of interference fringes by varying the angle of observation (VAMFO—variable angle monochromatic fringe observation[1–3]) or by spectrophotometric variation of the observed wavelength of radiation.[4–7] The film thickness d can be determined from

$$d = (N\lambda/2n_2 \cos\theta_2) + \Delta t_\phi + \Delta t_r , \quad (1)$$

where

- N is the order given by $N = 1/2, 3/2, 5/2, \cdots$ for minima;
- n_2 is the SiO_2 refractive index at wavelength λ;
- θ_2 is the angle of refraction in the SiO_2;
- Δt_ϕ is the phase shift correction; and
- Δt_r is the reflectivity correction.

The phase shift thickness correction has been adequately covered for the visible region[1–3] and for the ultraviolet region[7,8] of the spectrum. The reflectivity corrections for the spectrophotometric technique have been determined theoretically.[8] Experimentally, approximate compensation for reflectivity corrections is obtained by reflection off a silicon wafer in the reference beam of the double beam spectrophotometer,[6] but more complete compensation can be obtained by using a silicon wafer with a thick nonuniform SiO_2 film in the reference beam.[8]

The reflectivity correction for VAMFO differs from that for the spectrophotometric technique. In the former, one must consider the reflectivity variations for a fixed wavelength and varying incident angle; whereas with the latter, the angle of incidence is fixed, but the wavelength is varied.

VAMFO consists of a microscope equipped with a monochromatic filter, a polarizing filter to pass the perpendicular component, and a stage capable of rotating on an axis normal to the optical axis of the microscope so as to observe the reflected light at various angles. From observed minima positions, film thicknesses can be determined. However, the reflectivity varies with the angle of observation, and thus, when uniform thickness films are being measured, corrections must be made to the simple interference formula $d = N\lambda/2n_2 \cos\theta_2$ to obtain the correct film thickness.

Using VAMFO, reflectivity corrections can be eliminated experimentally by making a 100 Å step in or on the film;[1] however, production of a step is not always practical. Therefore, this note is being written to show the corrections necessary for accurate film thickness determinations on uniform films.* Approximately, these corrections are proportional to λ, inversely proportional to the order of N, and angle dependent with a maximum correction near an incident angle of 55°.

* The simplified Eqs. (A-2) and (A-3), which are in Appendix 3 of Ref. 1a, together with the discussion given there on reflectivity corrections for uniform thickness films are inadequate. However, the transformation of Eq. (A-3) in terms of a thickness correction predicts a correction which is roughly proportional to λ and inversely proportional to N as shown by the present analysis. With a nonuniform thickness film, the sample is rotated to reach an angle at which the point being measured is centered within the reflection minimum on the wafer. This minimum corresponds to $\sin(2\beta - \phi_{23}) = 0$ as can be verified by taking the derivative of R with respect to d which varies across the wafer. Thus, no reflectivity correction is necessary for films of nonuniform thickness.

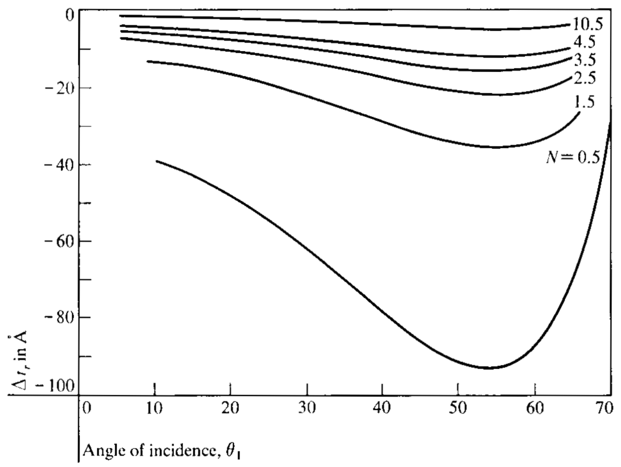


Figure 1 VAMFO reflectivity corrections for $\lambda = 5456$ Å and orders $N = 0.5, 1.5, 2.5, 3.5, 4.5$, and 10.5.

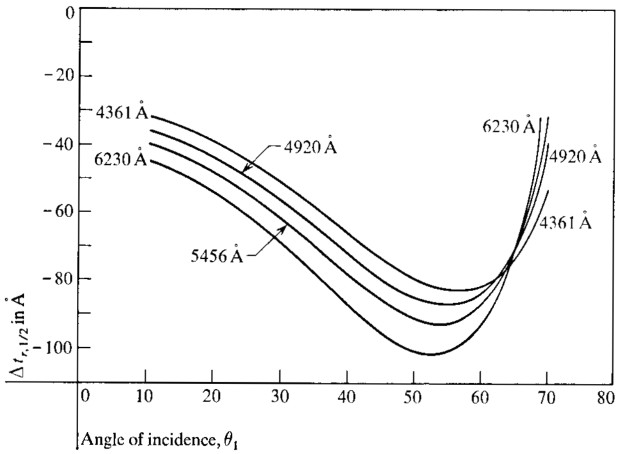


Figure 2 VAMFO reflectivity corrections for various wavelengths and $N = 0.5$.

The reflectivity for the perpendicular component is given by[7,9]

$$R = \frac{r_{12}^2 + \rho_{23}^2 - 2r_{12}\rho_{23}\cos(2\beta - \phi_{23})}{1 + r_{12}^2\rho_{23}^2 - 2r_{12}\rho_{23}\cos(2\beta - \phi_{23})}, \tag{2}$$

where

$$r_{12}^2 = \left(\frac{n_2\cos\theta_2 - n_1\cos\theta_1}{n_2\cos\theta_2 + n_1\cos\theta_1}\right)^2 \tag{3}$$

is the reflectivity at the air-SiO_2 interface;

$$\rho_{23}^2 = \frac{(n_2\cos\theta_2 - u_3)^2 + v_3^2}{(n_2\cos\theta_2 + u_3)^2 + v_3^2} \tag{4}$$

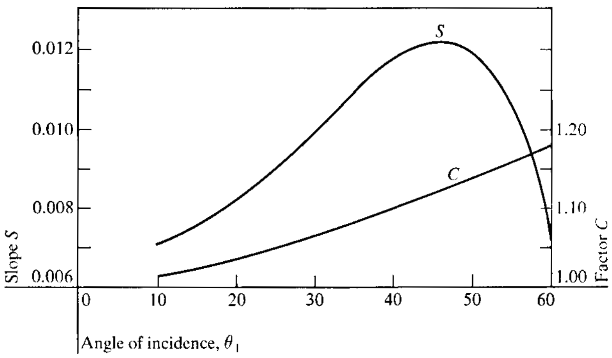
is the reflectivity at the SiO_2-silicon interface;

$$2u_3^2 = w + (w^2 + 4n_3^2k_3^2)^{1/2},$$
$$2v_3^2 = -w + (w^2 + 4n_3^2k_3^2)^{1/2},$$
$$w = n_3^2 - k_3^2 - n_1^2\sin^2\theta_1, \text{ and}$$
$$\beta = 2\pi d n_2(\cos\theta_2)/\lambda;$$

ϕ_{23} is the phase change at the SiO_2-silicon interface, θ_1 is the angle of incidence, n_1 is the refractive index of air or the external dielectric, n_3 is the refractive index of silicon, and k_3 is the extinction coefficient of silicon.[10,11] Note that in the relationship for w we have made use of Snell's law, $n_1\sin\theta_1 = n_2\sin\theta_2$, to show that w, u_3, and v_3 are independent of n_2.

Reflectivity minima as given by Eq. (2) do not coincide with those determined by the simple relation $d = N\lambda/(2n_2\cos\theta_2)$ even with phase change considerations. The differences between the two as given in terms of thickness corrections were calculated on a computer. Figure 1 shows the reflectivity corrections for various interference orders using $\lambda = 5456$ Å. This wavelength is one of the

Figure 3 Slope S and factor C for calculating VAMFO reflectivity corrections.



effective wavelengths[2] being used in two particular VAMFO models. For all practical purposes, Fig. 1 can also be used for the Hg green line of 5461 Å. Figure 2 shows the reflectivity correction for the first minimum ($N = 1/2$) for various wavelengths. The shapes of the curves in Figs. 1 and 2 are similar except for a slight shift in the maximum correction with order and wavelength. The correction is nearly linear with wavelength especially at the higher wavelengths ($\lambda > 4900$ Å). For $N = 1/2$ and $\theta_1 \leq 60°$, the correction is given by

$$\Delta t_{r,\lambda,1/2} \cong \Delta t_{r,5456,1/2} + S(\lambda - 5456), \tag{5}$$

where S is the slope representing this linearity. It is given as a function of the incident angle θ_1 in Fig. 3. Using the correction curve for $\lambda = 5456$ and $N = 1/2$ from Figs. 1 or 2 together with S from Fig. 3, the reflectivity thickness correction for $N = 1/2$ can be calculated for any visible

Table 1 Corrections for SiO_2 film thickness determinations.

Sample	*Filter and method*	*Angle for minimum*	*Order N*	*Uncorrected thickness (Å)*	*Step or reflectiviy corrections (Å)*	*Corrected thickness (Å)*
111-1	6230 Å-step	32.7 ± 0.6°	0.5	1148 ± 3	+ 50	1198 ± 3
	5775 Å-step	48.1 ± 0.1		1147 ± 1	+ 50	1197 ± 1
	6230 Å-no step	56.0 ± 1.4	0.5	1295 ± 10	−100	1195 ± 10
	5775 Å-no step	65.0 ± 0.7		1259 ± 5	− 71	1188 ± 5
120-4	6230 Å-step	26.6 ± 0.1	2.5	5607 ± 2	+ 50	5657 ± 2
	6230 Å-no step	29.7 ± 0.6		5674 ± 13	− 15	5659 ± 13

wavelength by Eq. (5). For higher orders of N, the reflectivity correction is approximately inversely proportional to N and can be given by

$$\Delta t_{r,\lambda,N} \cong C\left(\frac{0.5}{N}\right)\Delta t_{r,\lambda,1/2} \qquad (6)$$

where C is a factor the average of which is given in Fig. 3 for $\theta_1 \leq 60°$. The reflectivity corrections for any order or visible wavelength calculated on basis of Eqs. (5) and (6) are within tenths of an Angstrom of the computer calculated corrections for wavelengths >4900 Å and within 2 Å of the computer calculations for $\lambda = 4361$ Å.

Experimental application of these techniques on two thermally oxidized silicon wafers is shown in Table 1 where the thicknesses determined using a 100 Å step with those obtained from the reflectivity minima on the uniform films using reflectivity corrections are compared. The agreement shown is considered to be excellent.

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