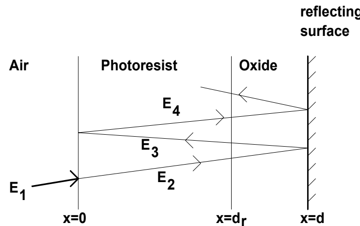
Derivation of Standing Waves in optical lithography [Optional reading for EE143]

The following figure illustrates the interference between the electric fields of incident light wave $E_2(x)$ and reflected light wave $E_3(x)$where:

$E_2(x) = \mathbf{E_2} \sin(\omega t - k x + \phi)$

$E_3(x) = \mathbf{E_3} \sin[\omega t - k(2d-x) + \phi + \pi]$



The phase shift π is due to the reflection and $k = 2\pi n/\lambda$ where n is the real part of the film dielectric constant. As shown in figure, multiple reflections can also happen due to the photoresist/air interface but are ignored in this problem. For simplicity, let us also assume that n is the same for both photoresist and SiO_2 (n = 1.6) so that they can be treated as the same optical medium.

Questions:

(a) (i) Derive an expression for the time-averaged intensity $I_{23}(x)$ where $I_{23}(x) =$ time average of $[E_2(x)+E_3(x)]^2$

(ii) Repeat part (i) with both amplitudes equal (i.e., $\mathbf{E_2} = \mathbf{E_3}$). This case represents the situation where the resist absorption is negligible. Comment on the energies deposited in the resist as a function of depth for the cases (i) and (ii) with the same exposure time.

(b) Sketch the cross-section of a developed positive photoresist line (thickness = 2500Å) on SiO_2 (thickness = 500Å), both with n = 1.6 and λ = 3200Å

(c) Consider the case where the oxide thickness has a process variation of ± 250Å for a nominal thickness of 1250Å. Discuss the developed resist dimension at the photoresist-SiO_2 interface for (i) oxide thickness = 1500Å and (ii) 1000Å

Answers

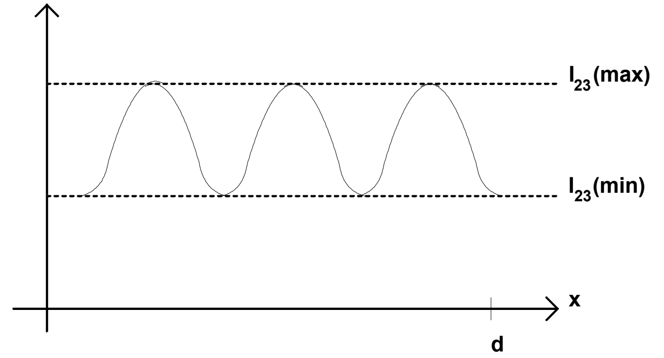
(a) (i)

$$I_{23}(x) = \frac{1}{T}\int_0^T (E_2(x)+E_3(x))^2 dt$$

$$= \frac{\omega}{2\pi}\int_0^{2\pi/\omega} (\mathbf{E_2}\sin(\omega t-kx+\phi) + \mathbf{E_3}\sin(\omega t-k(2d-x)+\phi+\pi))^2 dt$$

$$= \frac{\mathbf{E_2}^2}{2} + \frac{\mathbf{E_3}^2}{2} + \frac{\omega}{2\pi}\int_0^{2\pi/\omega} \mathbf{E_2}\,\mathbf{E_3}\,[\cos(2k(d-x)-\pi) - \cos(2\omega t + 2kd + 2\phi + \pi)]\,dt$$

$$= \frac{E_2^2}{2} + \frac{E_3^2}{2} + E_2E_3\cos[2k(d-x) - \pi]$$
$$= \frac{E_2^2}{2} + \frac{E_3^2}{2} - E_2E_3\cos[2k(d-x)]$$
$$= \frac{E_2^2}{2} + \frac{E_3^2}{2} - E_2E_3 + 2E_2E_3\sin^2[k(d-x)]$$
$$= \frac{1}{2}(E_2 - E_3)^2 + 2E_2E_3\sin^2[k(d-x)]$$
$$\therefore I_{23}(\max) = \frac{1}{2}(E_2 + E_3)^2 \quad ; \quad I_{23}(\min) = \frac{1}{2}(E_2 - E_3)^2$$



(ii) $E_2(x)+E_3(x) = E_2[\sin(\omega t-kx+\phi) + \sin(\omega t-k(2d-x)+\phi+\pi)] = 2E_2\cos(\omega t-kd+\phi)\sin[k(d-x)]$

$\therefore I_{23}(x) = 4|E_2|^2 \sin^2[k(d-x)] < \cos^2(\omega t-kd+\phi)>_{\text{time avearge}}$

$= 2|E_2|^2 \sin^2[k(d-x)]$ (Note: the time average of $\cos^2 = 1/2$)

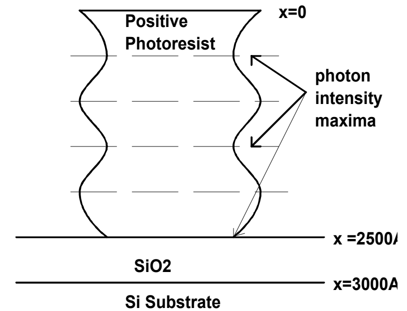
For Case (i) , we have a constant background $\frac{1}{2}(E_2 - E_3)^2$ superimposed with a depth modulation of $2E_2 E_3\sin^2[k(d-x)]$. Case (ii) has no such background term, $I_{23}(x)$ can vary between 0 and $2|E_2|^2$. Therefore, for a resist with little absorption (i.e., $E_2 \sim E_3$), there will be more prominent intensity variation between minima and maxima.

(b) The reflection surface is at the Si/SiO_2 interface (x= d= 3000 Å)

Intensity minima occur at : $\frac{2\pi n}{\lambda}(d-x) = 0, \pi, 2\pi, \ldots\ldots$

Intensity maxima occur at : $\frac{2\pi n}{\lambda}(d-x) = \pi/2, 3\pi/2, 5\pi/2, \ldots\ldots$

For n=1.6, λ =3200 Å, d=3000 Å
minima at : x = 0, 1000Å, 2000 Å ,3000Å.
maxima at : x = 500Å, 1500Å, 2500 Å....



(c) (i) d=4000 Å, $\therefore$ x=2500 Å (the oxide /resist interface) will have maximum intensity $\rightarrow$ narrower resist linewidth after development.

(ii) d=3500 Å, $\therefore$ x=2500 Å (oxide/resist interface) will have minimum intensity $\rightarrow$ wider resist linewidth after development..

If this resist line is used as etching mask for the oxide layer underneath, oxide linewidth variations will occur even when the optical lithography step is exactly reproducible.