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Full Length Research Paper

Effects of thin film thickness on emittance, reflectance and transmittance of nano scale multilayers

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Knowledge of the radiative properties of multilayer consisting of silicon and related materials, such as silicon dioxide (SiO_2), silicon nitride (Si_3N_4) and gold (Au) with different thicknesses is required for many microsystem applications. This paper describes the study of the effects of thin film thickness on radiative properties of nano scale multilayer. The results showed that silicon dioxide and silicon nitride coating act as anti reflector and these coatings reduce reflectance toward bare silicon. If thickness of non metal coating increases, reflectance of multilayer decreases and transmittance increases. Gold thin film coating increases reflectance. The reflectance of multilayer coated with gold increases by increasing the thickness of coating. This study will benefit and enhance the value of nano coating technology in the semiconductor industries, particularly in the development of micro electromechanical and nano electromechanical devices.

Key words: Nano scale multi layer, thin films, thickness, metal coating, non metal coating, radiative properties.

INTRODUCTION

Optical techniques and radiative processes play important roles in current industrial and daily life. Examples are advanced lighting and display, materials and surface characterization, real time process monitoring and control, laser manufacturing, rapid thermal processing (RTP), communication, data storage and reading, radiation detection, biomedical imaging and treatment, ground and space solar energy utilization, direct energy conversion, etc. Optical and thermal radiative properties are fundamental physical properties that describe the interaction between electromagnetic waves and matter from deep ultraviolet to far-infrared spectral regions. In fact, optical property measurements and analysis offer powerful tools to understand the physics of solids and other materials. However, optical and radiative properties depend on a large number of variables; modeling of radiative properties of nano scale multilayer is a convenient way to analyze the observed results.

Silicon dioxide (SiO_2) layer coated on lightly doped silicon substrate has higher reflectance than silicon nitride (Si_3N_4) coating for visible wavelengths. In these wavelengths the reflectance increases as the temperature increases due to decreasing emittance; but in infrared wavelengths, the reflectance and transmittance decrease as the temperature increases (Oloomi et al., 2009a).

The reflectance and transmittance of thick silicon substrate with 700 µm thickness and coated by silicon dioxide thin film with 300 nm thickness were already calculated by (Lee et al., 2005) with incoherent formulation. In this paper, the effects of film thickness on radiative properties of nano scale multilayer are considered. The film coating consists of multi-layer structure of metal and non metal thin film coatings with varying thickness from 0 - 200 nm. This work uses incoherent formulation for calculating the radiative properties of semiconductor materials related to the recent technological advancements that are playing a vital role in the integrated-circuit manufacturing, optoelectronics and radiative energy conversion devices. Lightly doped silicon is used and the empirical expressions for the optical constants of lightly doped silicon are employed. Silicon dioxide and silicon nitride are used as non metal thin film coatings and gold is used

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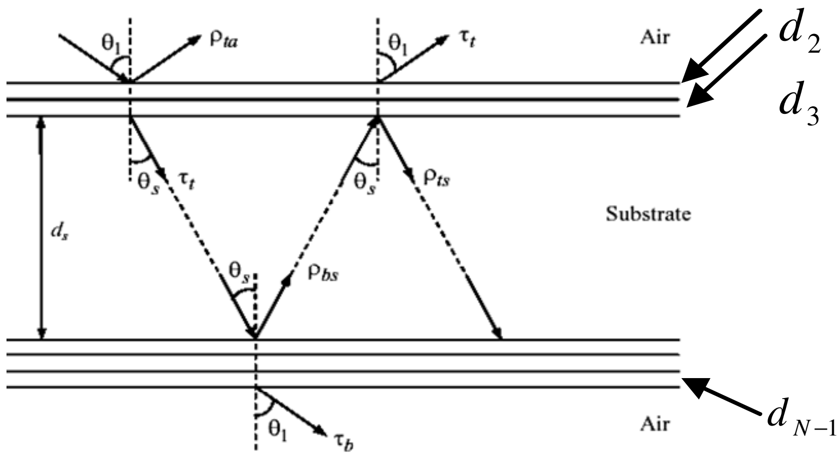

Figure 1. Schematic of thin-film coatings on both sides of a thick silicon.

as metal thin film coating.

MODELING

Incoherent formulation

When the thickness of silicon substrate is much greater than the coherent length and the considered wavelength falls in the semi transparent region of silicon, interferences in the substrate are generally not observable. In this case, the incoherent formulation or geometric optics should be used to predict the radiative properties of the silicon substrate. Two ways to get around this problem are to use the fringe-averaged radiative properties and to treat thin-film coatings as coherent but the substrate as incoherent (Zhang et al., 2003). Figure 1 shows the geometry of the silicon wafer with multi thin-film coatings on both sides. Note that τ_t is the transmittance of the multilayer structure at the top surface (air-coatings-silicon) for rays incident from air. Similarly, ρ_{bs} is for the multilayer structure at the bottom surface for rays incident from the substrate. On the other hand, ρ_{ts} and τ_b are for rays incident from silicon.

The absorption of silicon can be taken into consideration by introducing the internal transmittance

$$\tau_i = \exp\left(-\frac{4\pi k_s d_s}{\lambda \cos\theta_s}\right) \quad (1)$$

Here, k_s is the extinction coefficient of silicon, d_s is the thickness and θ_s is the angle of refraction. The radiative properties of the silicon wafer with thin-film coatings such as reflectance ρ, transmittance τ and emittance ε in the semi transparent region can be expressed as (Timans, 1996):

$$\rho = \rho_{ta} + \frac{\tau_i^2 \tau_t^2 \rho_{bs}}{1-\tau_i^2 \rho_{ts}\rho_{bs}} \quad (2)$$

$$\tau = \frac{\tau_i \tau_t \tau_b}{1-\tau_i^2 \rho_{ts}\rho_{bs}} \quad (3)$$

$$\varepsilon = 1-\rho-\tau \quad (4)$$

Optical constants

The optical constants, including the refractive index (*n*) and the extinction coefficient (κ), of a material are complicated functions of the wavelength and temperature. We need optical constants of materials for calculating the radiative properties of nano scale multilayers.

The Jellison and Modine (J-M) expression of optical constants of silicon for a wavelength between 0.4 µm and 0.84 µm is given in (Jellison et al., 1994):

$$n_{JM}(\lambda,T) = n_0(\lambda) + \beta(\lambda)T \quad (5)$$

$$n_0 = \sqrt{4.565 + \frac{97.3}{3.648^2 - (1.24/\lambda)^2}} \quad (6)$$

$$\beta(\lambda) = -1.864\times10^{-4} + \frac{5.394\times10^{-3}}{3.648^2 - (1.24/\lambda)^2} \quad (7)$$

Li developed a functional relation, for optical constants of silicon that covers the wavelength region between 1.2 µm and 14 µm (Li, 1980):

$$n_L(\lambda,T) = \sqrt{\varepsilon_r(T) + \frac{g(T)\eta(T)}{\lambda^2}} \quad (8)$$

$$\varepsilon_r(T) = 11.631 + 1.0268\times10^{-3}T + 1.0384\times10^{-6}T^2 - 8.1347\times10^{-10}T^3 \quad (9)$$

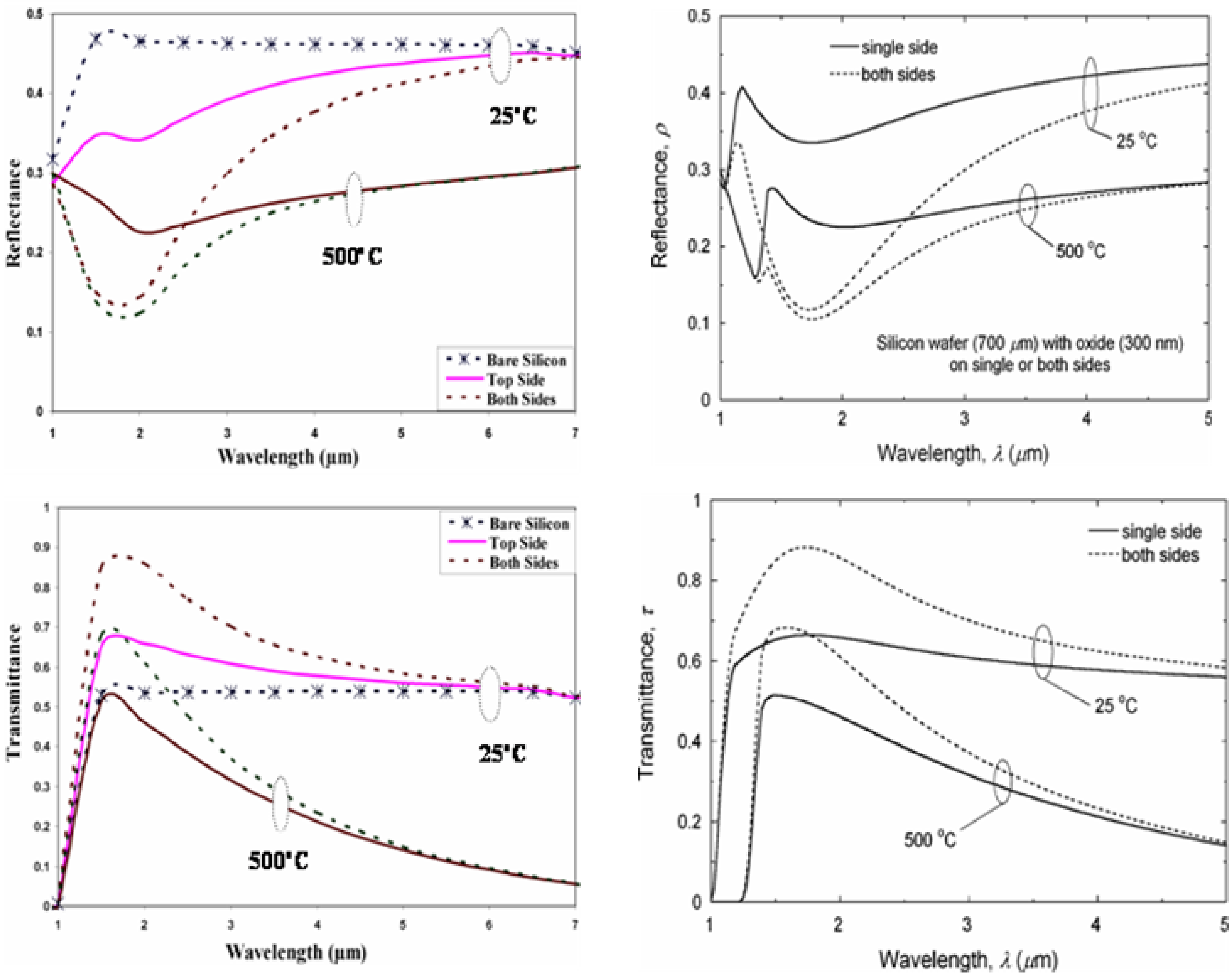

Figure 2. A comparison of the calculated results (left side) with results of (Lee et al., 2005) (right side).

$$g(T) = 1.0204 + 4.8011\times10^{-4}T + 7.3835\times10^{-8}T^2 \quad (10)$$

$$\eta(T) = \exp(1.786\times10^{-4} - 8.526\times10^{-6}T - 4.685\times10^{-9}T^2 + 1.363\times10^{-12}T^3) \quad (11)$$

The J-M expression is used in this study to calculate the optical constants of silicon for the wavelength region from 0.5 µm to 0.84 µm but Li's expression is employed for wavelengths above 1.2 µm. For a wavelength range of 0.84 µm to 1.2 µm, we use a weighted average based on the extrapolation of the two expressions.

$$n_{AVG} = \frac{(1.2-\lambda)n_{JM} + (\lambda-0.84)n_L}{1.2-0.84} \quad (12)$$

The optical constants of silicon dioxide, silicon nitride and gold are mainly based on the data collected in Palik (1998).

RESULTS AND DISCUSSION

Figure 2 compares the reflectance and transmittance of thick silicon substrate with 700 µm thickness and coated by silicon dioxide thin film with 300 nm thickness in two different coating cases and two different temperatures with the results in (Lee et al., 2005). The electromagnetic waves are incident at θ = 0°. The calculated results are in good agreement with results in (Lee et al., 2005). Because the refractive index of silicon dioxide (around 1.45) is smaller than that of silicon, the reflectance with a coating is always lower than that of bare silicon for non metal thin film coatings (Figure 2). The oscillation in the reflectance is due to interference in the silicon dioxide coating. The free spectral range is determined by $\Delta\lambda/\lambda^2 = (2n_f d_f)^{-1}$, where $\Delta\lambda$ is the separation

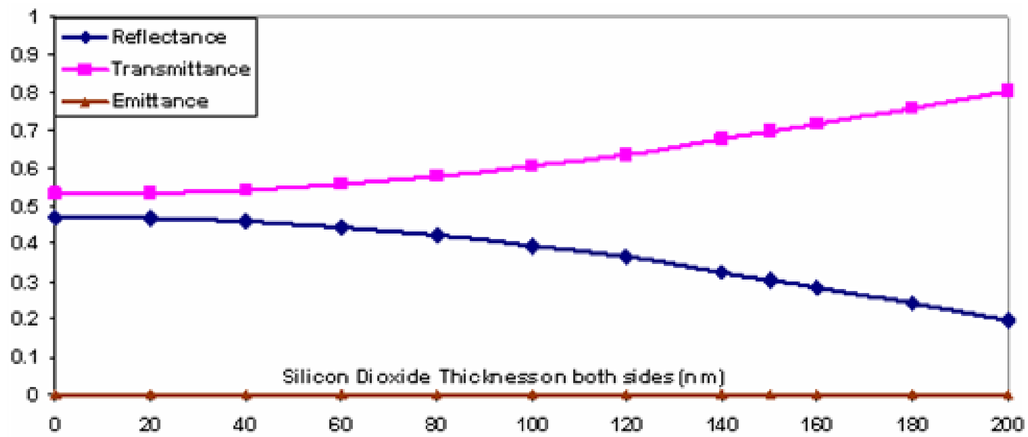

Figure 3. Radiative properties of silicon sub layer coated with silcon dioxide coating on both sides.

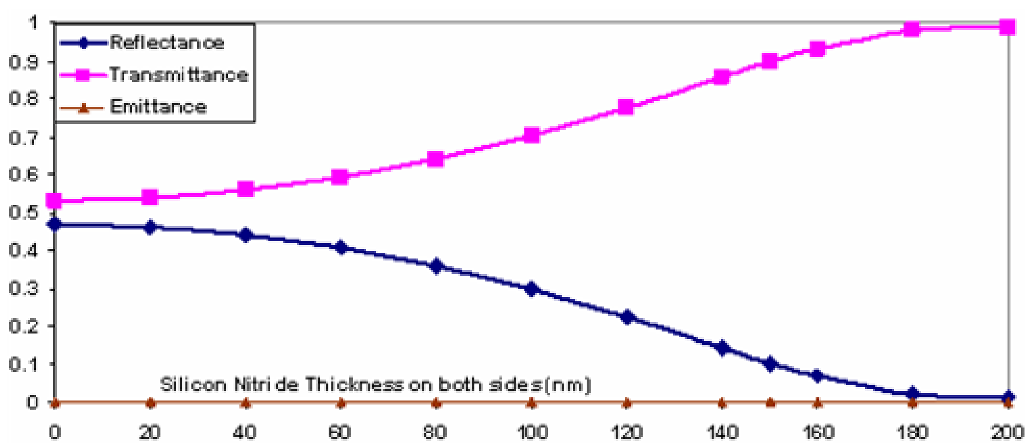

Figure 4. Radiative properties of silicon sub layer coated with silcon nitride coating on both sides.

between adjacent interference maxima and n_f and d_f are the refractive index and thickness of the thin film. The spectral separation $\Delta\lambda$ increases toward longer wavelengths. As the film thickness increases, the free spectral range decreases, resulting in more oscillations with the thicker silicon dioxide film. Therefore oscillations increased toward longer wavelengths. Interferences in the substrate are generally not observable in the incoherent formulation. This is the major difference between coherent and incoherent formulations (Oloomi et al., 2009b). The silicon sub layer thickness is 500 µm and layers' temperature is 25°C. Radiative properties of nano scale multilayer such as reflectance, transmittance and emittance are shown in Figures 3 to 5 for different thin film coatings. These properties are compared in wavelength of 1.55 µm. Thickness of thin film coating changed from 0 to 200 nm for silicon dioxide coating, silicon nitride coating and gold coating. Silicon dioxide and nitride coatings are used as metal thin film coatings and gold coating used as non metal thin film coating.

The results in Figures 3 to 5 show that the emittance in this wave length and at room temperature is negligible. Therefore SiO_2 and Si_3N_4 layer can be considered as a good anti reflector layer because they reduce reflectance toward silicon surface. Meanwhile, thin gold layer increases reflectance. It is shown that for non metal thin film coating, the reflectance decreases as the thickness increases, because of increasing transmittance, but for metal thin film coating, transmittance decreases as the thickness increases, because of increasing reflectance. From the Figures 3 and 4, it was concluded that increasing the thickness of thin film coating up to 100 nm has no important effect on the radiative properties of multilayer for non metal coatings.

Figures 3 and 4 show that increase of non metal thin film coating's thickness greater than 100 nm causes increase of transmittance and decrease of reflectance rapidly. Reflectance increases and transmittance decreeses rapidly till thickness of gold thin layer reaches to 60 nm and then the properties remain constant (Figure 5).

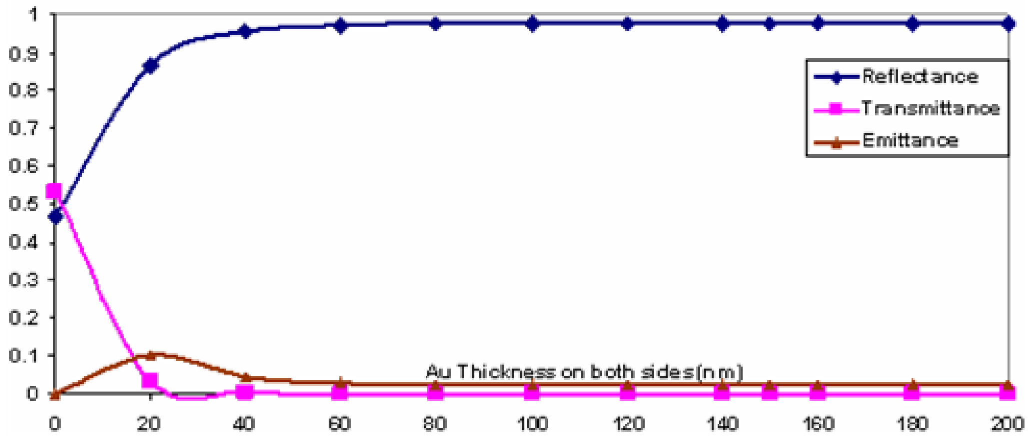

Figure 5. Radiative properties of silicon sub layer coated with gold coating on both sides.

From the results, it was observed that the reflectance decreases 97% by increasing the thickness of silicon nitride layer to 200 nm. The reflectance changed from 0.469 to 0.198 by increasing thickness of silicon dioxide layer to 200 nm (Figures 3 and 4). It was also observed that increasing thickness of gold layer to 60 nm causes increase in the reflectance from 0.469 to 0.972 (Figure 5). From the results, it may be concluded that industrial requirements are supported by selecting coating's material and thickness.

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