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# Effects of Thin Films' Thickness on Radiative Properties of Doped Silicon Multilayer Structures

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**Abstract:** Study of thin film coatings is very important for various industrials. This paper considered effects of thin films' thickness on radiative properties of nano scale multilayer for metal and non metal thin film coatings. 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. Industrial requirements are supported by selecting coating's material and thickness.

**Key words:** Thin Films · Thickness · Metal Coating · Non Metal Coating · Radiative Properties · Coherent Formulation and Doped Silicon

## INTRODUCTION

At temperatures below 600°K the concentration and the type of impurities have important effects on the radiative properties of the film. Moreover, the effects of ions are considerable for the concentrations higher than $1\times10^{16}$ cm$^{-3}$. By increasing temperature, a lattice scattering phenomenon becomes dominant because of increasing the concentration of the phonons [1]. This work uses coherent 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. Doped silicon is used and the coherent formulation is applied. The Drude model for the optical constants of doped silicon is employed. Phosphorus is default impurity for n-type in this work. Silicon dioxide and silicon nitride are used as non metal thin film coatings and gold is used as metal thin film coating. This paper considered effects of thin films' thickness on radiative properties of nano scale multilayer for metal and non metal thin film coatings.

## MATERIALS AND MATHODS

**Coherent Formulation:** When the thickness of each layer is comparable or less than the wavelength of electromagnetic waves, the wave interference effects inside each layer play an important role in accurate prediction of the radiative properties of the multilayer structure of thin films. The transfer-matrix method provides a convenient way to calculate the radiative properties of the multilayer structure of thin films. Assuming that the electromagnetic field in the jth medium is a summation of forward and backward waves in the z-direction, the electric field in each layer can be expressed by

$$Ej = \begin{cases} \left[ A_1 e^{iq1z^{s}} + B_1 e^{-iq1z} \right] e(iq_x x - i\omega t),\ j = 1 \\ \left[ Aj e^{iqjz(z-z_{j-1})} + Bj e^{-iqjz(z-z_{j-1})} \right] e^{(iq_x x - i\omega t)},\ j = 2,3,\ldots N \end{cases} \tag{1}$$

Where, $A_j$ and $B_j$ are the amplitudes of forward and backward waves in the $j_{th}$ layer. Detailed descriptions of how to solve equation (1) for $A_j$ and $B_j$ is given in [2, 3]. Consequently, the radiative properties of the $N$-layer system are given by [2, 3].

$$\rho = \frac{B_1 B_1^*}{A_1^2}, \tau = \frac{\mathrm{Re}(\tilde{n}_N \cos\tilde{\theta}_N)}{n_1 \cos\theta_1}\ \frac{A_N A_N^*}{A_1^2},\ \varepsilon = 1 - \rho - \tau \tag{2}$$

**Optical Constants:** The Drude Model for the Optical Constants of Doped Silicon To account for doping effects, the Drude model is employed and the dielectric function of both intrinsic and doped silicon is expressed as follows [4]:

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$$\varepsilon(\omega) = \varepsilon_{bl} - \frac{N_e e^2/\varepsilon_0 m_e^*}{\omega^2 + i\omega/\tau_e} - \frac{N_h e^2/\varepsilon_0 m_h^*}{\omega^2 + i\omega/\tau_h} \qquad (3)$$

The scattering time, $\tau_e$ or $\tau_h$, depends on the collisions of electrons or holes with the lattice (phonons) and the ionized dopant sites (impurities or defects); hence, it generally depends on temperature and dopant concentration. The total scattering time (for the case of $\tau_e$), which consists of the above two mechanisms, can be expressed as [5]:

$$\frac{1}{\tau_e} = \frac{1}{\tau_{e-1}} + \frac{1}{\tau_{e-d}} \qquad (4)$$

Where, $\tau_{e\text{-}l}$ and $\tau_{e\text{-}d}$ denote the electron-lattice and the electron-defect scattering times, respectively. Similarly, $\tau_h$ can be related to $\tau_{h\text{-}l}$ and $\tau_{h\text{-}d}$. In addition, the scattering time, τ, is also related to mobility, μ, by the following relation:

$$\tau = m^* \mu / e \qquad (5)$$

At room temperature, the total scattering time $\tau_e^0$ or $\tau_h^0$, which depends on the dopant concentration, can be determined from the fitted mobility equations [6]:

$$\mu_e^0 = \frac{1268}{1 + (N_D / 1.3 \times 10^{17})^{0.91}} + 92 \qquad (6)$$

Where, the superscript 0 indicates values at 300 °K and $N_D$ is the dopant concentration of the donor (phosphorus, n-type) in cm$^{-3}$. Because of the relative insignificance of impurity scattering at high temperatures, the following formula will be used to calculate the impurity scattering times:

$$\frac{\tau_{e-d}}{\tau_{e-d}^0} = \frac{\tau_{h-d}}{\tau_{h-d}^0} = \left(\frac{T}{300}\right)^{1.5} \qquad (7)$$

Detailed descriptions of semiconductor devises are given in [6]. The optical constants of silicon dioxide are mainly based on the data collected in [7].

## RESULTS AND DISCUSSION

Figure 1 compares the reflectance and transmittance of thick silicon substrate with 700 $\mu m$ thickness and coated by silicon dioxide thin film with 300$nm$ thickness in two different coating cases and tow different temperatures with the results in [8]. The Electromagnetic waves are incident at $\theta$ = 0. The calculated results are in good

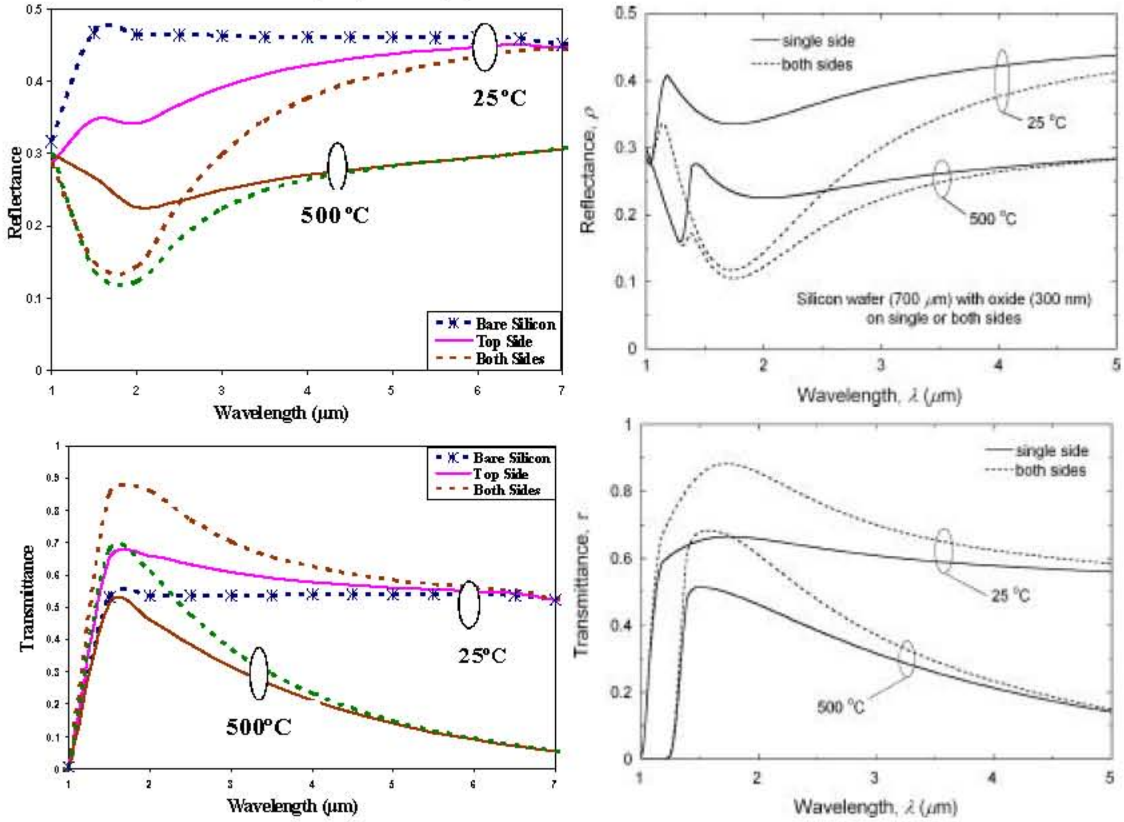

Fig. 1: A comparison of the calculated results (Left side) with results of [8] (Right side)

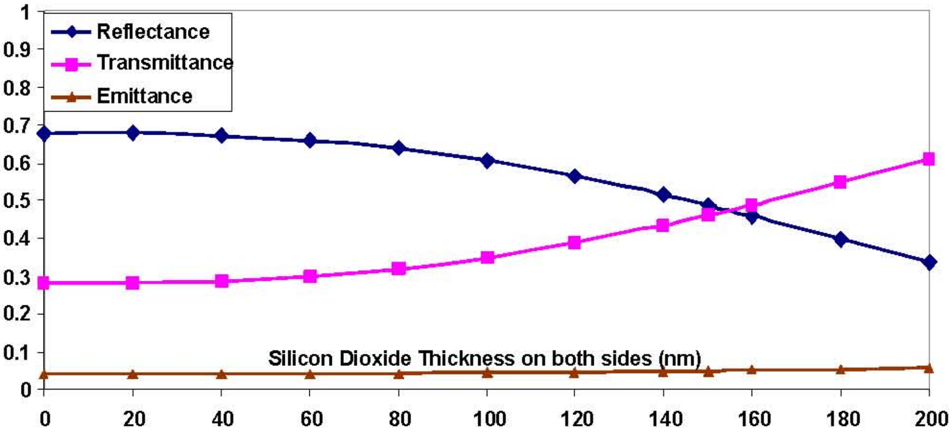

Fig. 2: Radiative Properties of Doped Silicon Sub layer Coated with Silcon Dioxide Coating on Both Sides

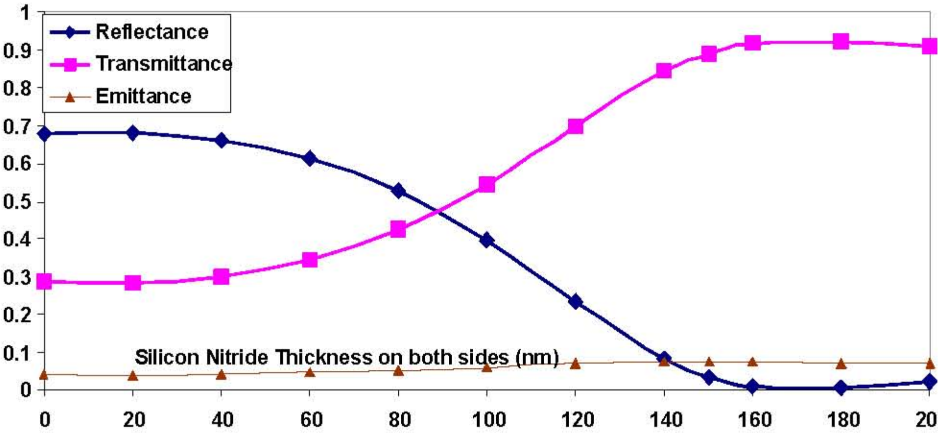

Fig. 3: Radiative Properties of Doped Silicon Sub layer Coated with Silcon Nitride Coating on Both Sides

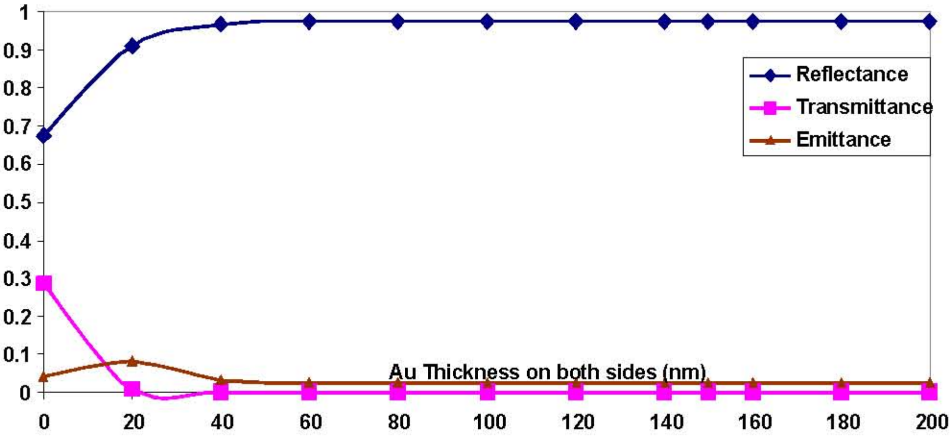

Fig. 4: Radiative Properties of Doped Silicon Sub layer Coated with Gold Coating on Both Sides

agreement with results in [8]. 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 1). 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 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 [9].

This paper considered effects of thickness of thin film coating on radiative properties. The silicon sub layer thickness is 500 $\mu m$ and layers' temperature is 25°C. Doped silicon with donors and concentration of 1e18 ($cm^{-3}$) is used. Radiative properties of nano scale multilayer such as reflectance, transmittance and emittance are shown in Figures 4 to 6 for different thin film coatings. These properties are compared in wavelength of 1.55 $\mu m$. Thickness of thin film coating changed from 0 nm to 200 nm for silicon dioxide coating, silicon nitride coating and gold coating. Silicon dioxide coating and silicon nitride coating are used as metal thin film coatings and gold coating used as non metal thin film coating.

**From the Results:**

- The emittance in this wavelength and at room temperature is negligible.
- Silicon dioxide and silicon nitride coating act as anti reflector and these coatings reduce reflectance toward bare silicon.
- If thickness of silicon dioxide coating and silicon nitride coating increases, reflectance of multilayer decreases and transmittance increases.
- Gold thin film coating is a metal coating and it increases reflectance.
- The reflectance of multilayer that coated with gold thin film coating increases by increasing the thickness of gold thin film coating.
- Increasing thickness of thin film coating up to 50 nm has not any important effect on the radiative properties of multilayer for non metal coatings.
- If non metal thin film coating thickness increases to 50 nm then transmittance increases and reflectance decreases rapidly.
- For gold coating, increasing thin film thickness up to 40 nm causes increasing reflectance of multilayer and decreasing transmittance rapidly and then these properties remain constant.
- When silicon nitride thin film coating thickness increases to 160 nm then reflectance of multilayer decreases about 99%.
- When silicon dioxide thin film coating thickness increases to 200 nm then reflectance of multilayer decreases from 0.676 to 0.334.
- If gold thin film coating thickness increases to 40 nm then reflectance of multilayer increases from 0.676 to 0.967.
- Industrial requirements are supported by selecting coating's material and thickness.

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