Effects of Incidence Angle on Thermal Radiative Properties of Nanoscale Semiconductors

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Abstract: Thin film coatings play an important role in the semiconductor industries and micro electromechanical and nano electromechanical equipments. This work uses transfer-matrix method for calculating the radiative properties. Lightly doped silicon is used. The considered wavelengths are 0.9 µm and 2.7 µm. Results showed that at high temperatures, transmittance becomes negligible. At low temperatures, the emissivity of silicon is a complex function of wavelength. The change in reflectivity and emittance with the angle of incidence is very small from 0° to 70° and they change significantly beyond 70° in the wavelength of 0.9 µm. The transmittance is considerable in the wavelength of 2.7 µm. The transmittance decreases with increasing of temperature in this wavelength. Results also showed that the change in transmittance with the angle of incidence is very small from 0° to 70° and the transmittance decreases rapidly beyond 70° in the wavelength of 2.7 µm. The reflectance increases when incidence angle increases and the emittance decreases with increasing in incidence angle for lightly doped silicon wafer coated with a silicon nitride film on both sides at 500ºC.

Key-Words: Incidence Angle, Emittance, Transmittance, Lightly Doped Silicon, Nanoscale.

1 Introduction

Radiative properties of semiconductors play an important role in radiation thermometry and radiative heat transfer during thermal processing. The detailed understanding of them is critical for monitoring and controlling temperature in semiconductor processing techniques, such as rapid thermal processing (RTP), molecular beam epitaxy (MBE), and chemical vapor deposition (CVD), and many devices, such as semiconductor lasers, radiation detectors, tunable optical filters, waveguides, solar cells, selective emitters and absorbers, etc.

For lightly doped silicon, silicon dioxide coating has higher reflectance than silicon nitride coating for visible wavelengths. In visible 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 [1, 2].

This work uses coherent and 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 nitride is used as non metal thin film coating. This paper considered effects of incidence angle on thermal radiative properties of nanoscale semiconductors.

2 Modeling

2.1 Coherent Formulation

The transfer-matrix method provides a convenient way to calculate the radiative properties of the multilayer structure of thin films (Figure 1). Assuming that the electromagnetic field in the j_{th} medium is a summation of forward and backward waves in the z-direction, the electric field in each layer can be expressed by [3, 4]

$$E_j = \begin{cases} \left[A_1 e^{iq_{1z}z} + B_1 e^{-iq_{1z}z}\right] e^{(iq_x x - i\omega t)}, & j=1 \\ \left[A_j e^{iq_{jz}(z-z_{j-1})} + B_j e^{-iq_{jz}(z-z_{j-1})}\right] e^{(iq_x x - i\omega t)}, & j=2,3,...N \end{cases} \quad (1)$$

here, A_j and B_j are the amplitudes of forward and backward waves in the jth layer. Detailed

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descriptions of how to solve Eq. (1) for A_j and B_j is given in [3, 4].

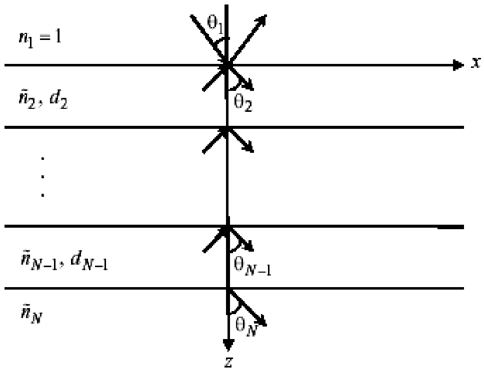

Figure 1: The geometry for calculating the radiative properties of a multilayer structure

Consequently, the radiative properties of the *N*-layer system are given by [3, 4]

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

2.2 Incoherent Formulation

When the thickness of silicon substrate is much greater than the coherent length, and the considered wavelength falls in the semitransparent region of silicon, interferences in the substrate are generally not observable from the measurements. 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 [4]. (Figure 1)

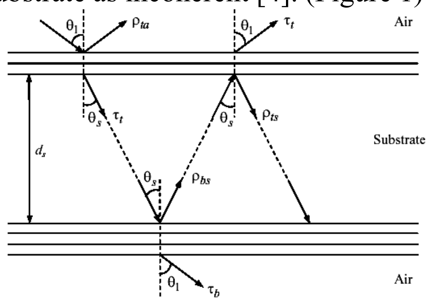

Figure 1: Schematic of thin-film coatings on both sides of a thick silicon

Consequently, the radiative properties of the silicon wafer with thin-film coatings in the semitransparent region can be expressed as [3, 4]

2.3. Optical Constants

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 [5]. Li developed a functional relation, for optical constants of silicon that covers the wavelength region between 1.2 µm and 14 µm [6]. 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. The optical constants of silicon dioxide, silicon nitride and gold are mainly based on the data collected in Palik [7].

3 Results

In Figure 2, radiative properties of lightly doped, 700-µm-thick Si is plotted as a function of angle of incidence for λ = 0.9 µm and λ = 2.7 µm, respectively. As can be seen in figures, the change in reflectivity with the angle of incidence is very small from 0° to 70°. The reflectivity changes significantly beyond 70° (figure 2.a). The change in emissivity with the angle of incidence is very small from 0° to 70°. The emissivity changes significantly beyond 70° (figure 2.c). This is once again illustrated in figure. 2.c for three specific temperatures. At high temperatures, the emissivity of silicon reaches its intrinsic value of 0.7 and remains independent of wavelength in the 1–20-µm range. At shorter wavelengths, close to the absorption edge of silicon, the transmittance is negligible. However, for λ=2.7 µm, the transmittance becomes significant, as can be seen in figure. 2.b. At high temperatures, transmittance becomes negligible. At low temperatures, the emissivity of silicon is a complex function of wavelength. The calculated results are in good agreement with results of [8].

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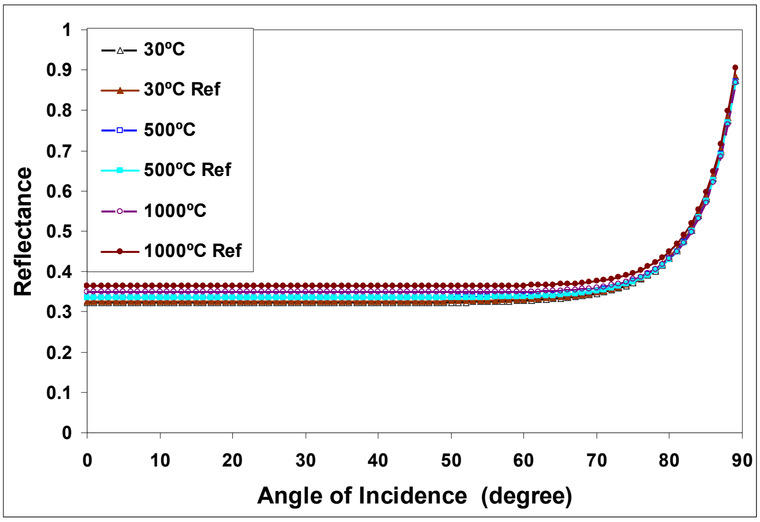

Figure 2.a (λ = 0.9 µm)

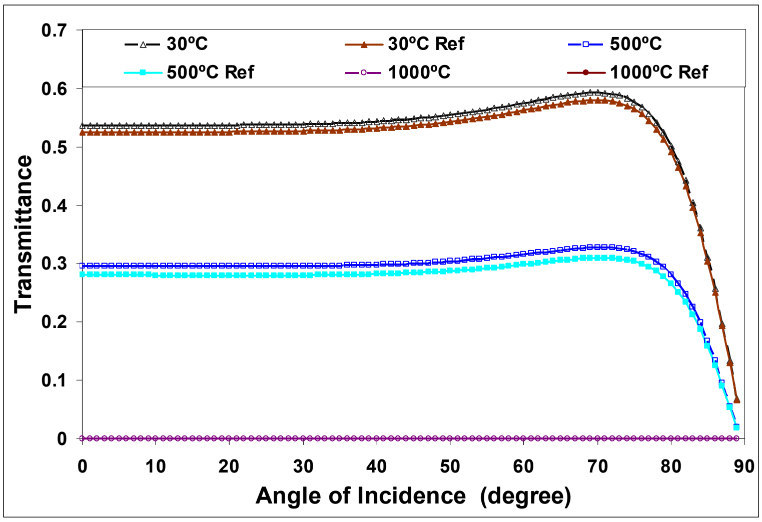

Figure 2.b (λ = 2.7 µm)

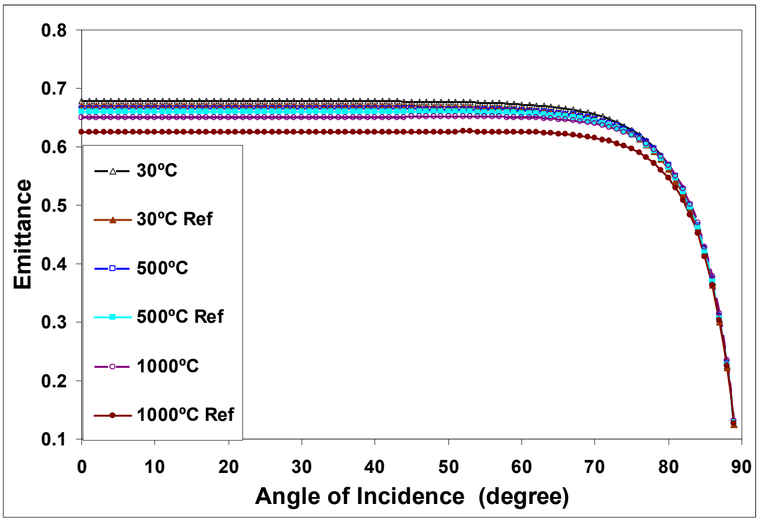

Figure 2.c (λ = 0.9 µm)

Figure 2. A comparison of the calculated results with results of [8]

Now consider the case in which the silicon wafer is coated with thin film on both sides at 500ºC temperature. Si_3N_4 is used as thin film coating. The thickness of silicon wafer is 500 μm and the Electromagnetic wave incident differs from 0º to

89º. The considered wavelengths are 0.9 μm and 2.7 μm. The thickness of Si_3N_4 is 400 nm.

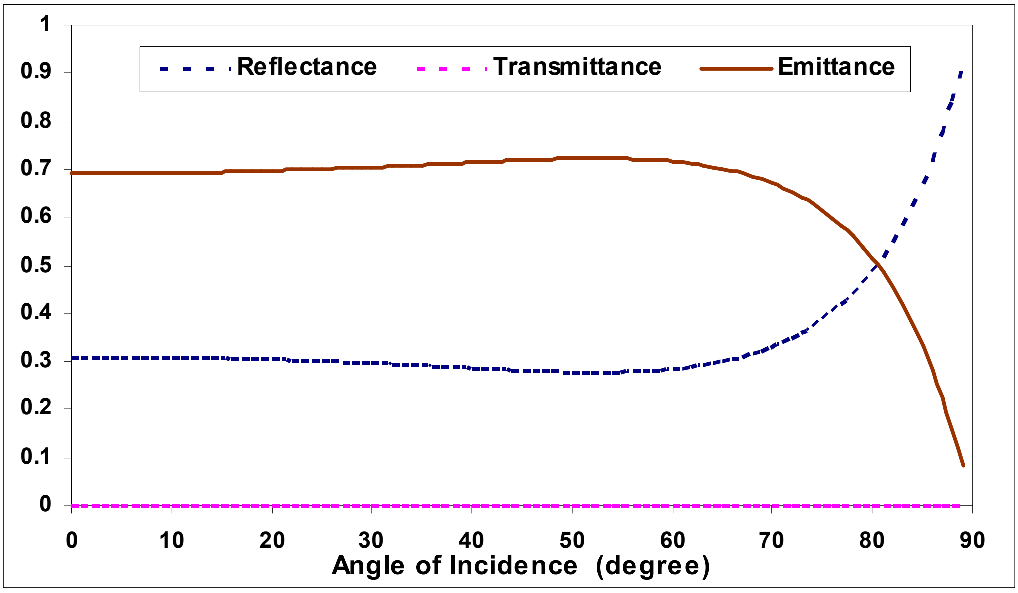

Figure 3. The radaitive properties of lightly doped silicon wafer coated with a silicon nitride film on both sides at 500ºC in wavelength of 0.9 μm

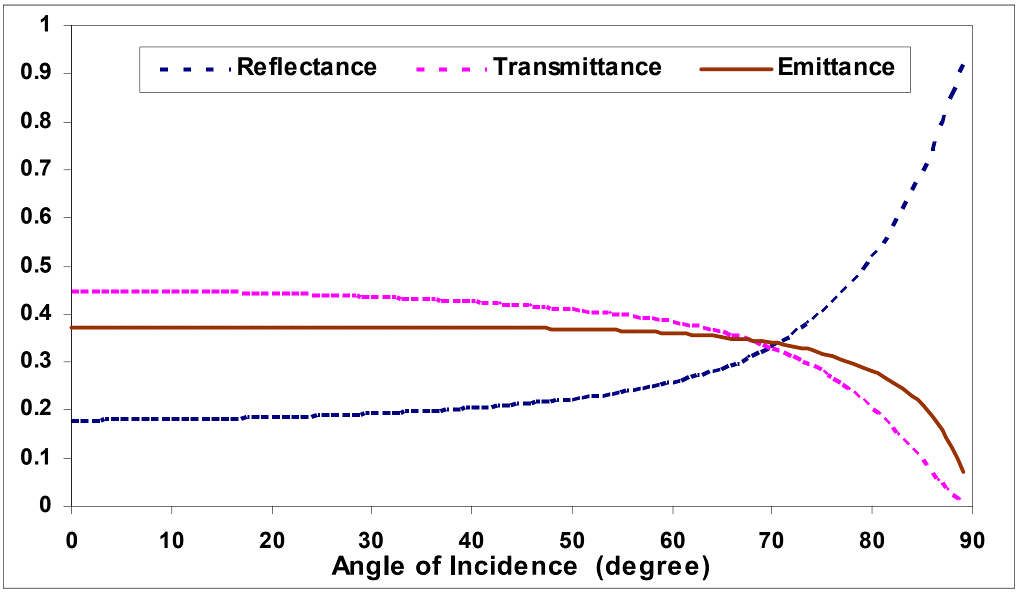

Figure 4. The radaitive properties of lightly doped silicon wafer coated with a silicon nitride film on both sides at 500ºC in wavelength of 2.7 μm

Lightly doped silicon is used and coherent formulation is applied. The results are shown in figures 3 and 4. For this case, the reflectance increases when incidence angle increases and the emittance decreases with increasing in incidence angle.

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