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# Optical constants of vacuum evaporated SiO film and an application

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**Abstract** Silicon monoxide films were deposited on silver films on glass substrates and studied by infrared ellipsometry to determine the optical properties in the infrared wavelength range from 1.3 to 40 micrometers. The thicknesses of silicon monoxide and aluminum films were designed to 1 micrometer and 200 nanometers, respectively. The ellipsometric measurements were carried out by using a spectro-ellipsometer attached with an FT-IR. The imaginary part of the refractive index shows a high absorption region which is centered at 10 micrometers, whereas in other wavelength regions it shows rather low absorption. The resultant optical properties of silicon monoxide film are compared with published data. As an application, the spectral reflectance of spectral selective panel heating surface is calculated.

**Keywords** Silicon monoxide · Infrared · Ellipsometry ·
Refractive index · Optical constants

## 1 Introduction

Silicon monoxide (SiO) was first reported by Potter in 1907 [1] and SiO films have been studied for use as protective layers and antireflecting coatings in optical applications [1–4]. SiO films deposited on metallic substrates have also been studied for use as spectral selective radiating materials (SSRMs) for effective nocturnal radiative cooling to low temperatures under clear sky conditions [5, 6]. The origin of the nocturnal radiative cooling is transfer of spectrally selective infrared radiation from SSRMs on the surface of the earth through the atmosphere. Recently SSRMs combined with vanadium oxide thermochromic films [7–9] and spectral selective radiants (SSRs) for panel heating surfaces [10] have been studied. These materials, SSRMs and SSRs, emit infrared radiation only between 8 and 13 $\mu$m. This wavelength region is often called the atmospheric window as the atmosphere has high infrared transmittance here [5].

In these studies of SSRM and SSR, simulations based on thin film optics are often carried out because the function of the thin film systems is largely influenced by atmospheric conditions which can be incredibly unstable. Such model calculations are very useful to obtain repeatable and comparable results in the process of device development.

Accurate spectral optical properties are indispensable for such calculations in the infrared region. However, data of sufficient quality has not been published except for two important data sets published by Hjortsberg and Granqvist [11] in the wavelength range 8 to 33 $\mu$m and by Hass and Salzberg [3] up to 14 $\mu$m. In the far infrared range, there is no published data to the best of our knowledge. From ultraviolet to 14 $\mu$m, Philipp summarized published data [12] including his own data [2].

In this report we present optical properties of SiO films used in SSRM or SSR as determined by spectro-ellipsometry in the wavelength range 1.3 $\mu$m to 40 $\mu$m as well as calculations of a spectral selective radiating surface emitting infrared radiation as an application.

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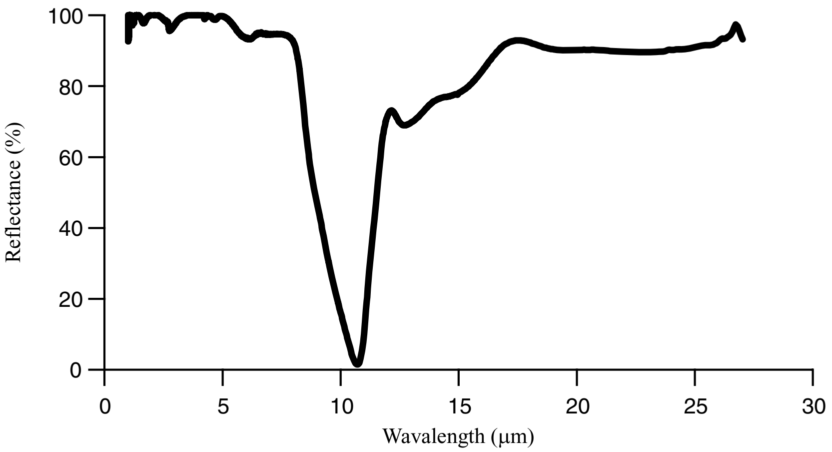


**Fig. 1** Measured spectral reflectance of a SiO/Ag/glass thin film system

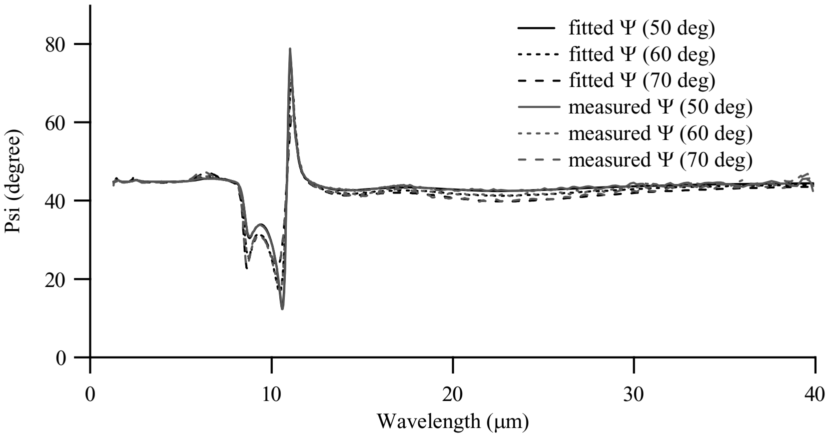


**Fig. 2** Measured ellipsometric parameter $\psi$ and fitted curves at 50, 60 and 70 degrees of incident angle. The agreement between the measured and fitted curves is excellent

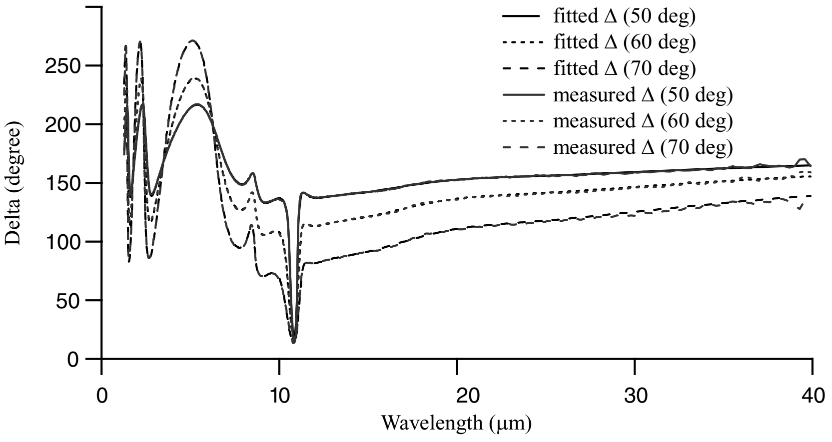


**Fig. 3** Measured ellipsometric parameter $\Delta$ and fitted curves at 50, 60 and 70 degrees of incident angle. The agreement between the measured and fitted curves is excellent

## 2 Experiment and results

### 2.1 Sample preparation

SiO films were deposited on Ag films on glass substrates. To realize the SSRM or SSR, the thickness of the SiO films were designed to 1 $\mu$m. The thickness of the Ag film was 200 nm or more which were large enough so that no infrared light is transmitted through the Ag film. The optical effect of the glass substrate can thus be ignored in the calculations. The films were deposited with a vacuum evaporation technique with the Ag evaporation and the SiO evaporation in this order on a glass substrate.

The spectral reflectance of the samples was measured with an FT-IR (Perkin-Elmer GX) instrument and is shown in Fig. 1. A remarkable absorption is seen around 10 $\mu$m which means this thin film system has high emittance only around 10 $\mu$m, i.e. in the atmospheric window.

**Fig. 4** Determined optical constants of an SiO film on an Ag film as determined by infrared ellipsometry

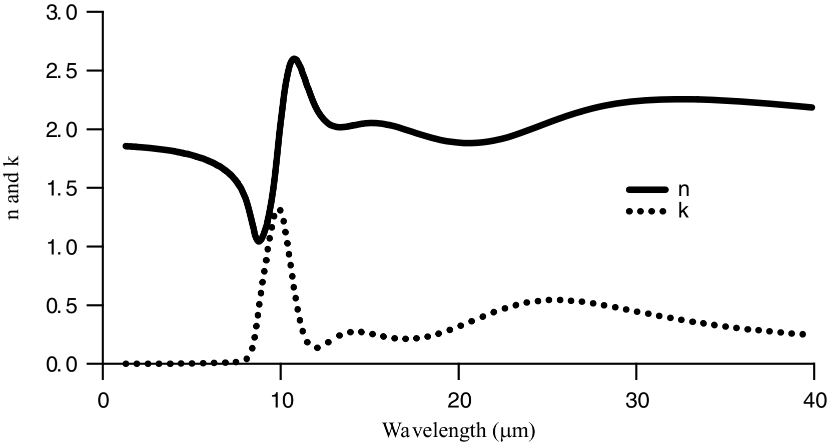
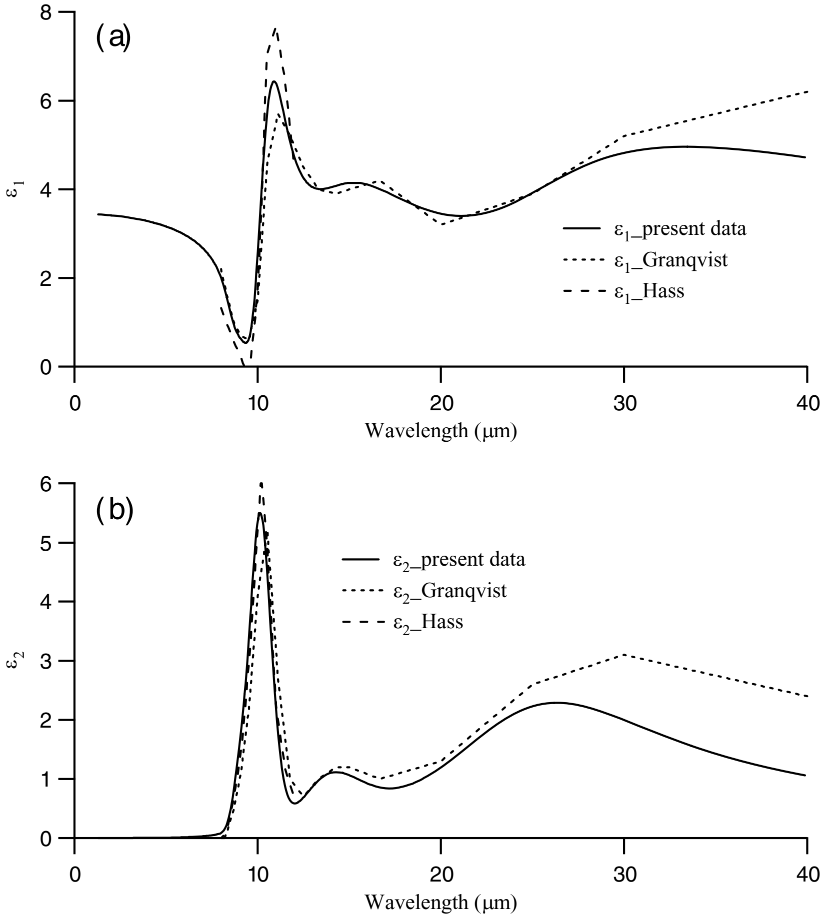


**Fig. 5** Comparison of dielectric functions, (a) $\varepsilon_1$ and (b) $\varepsilon_2$, published by Hjortsberg and Granqvist [11], Hass and Salzberg [11] as tabulated in ref. [13], and those determined in this study. Dotted curves from 33 to 40 $\mu$m are linear extrapolation as shown in ref. [11]



## 2.2 Infrared ellipsometry

Ellipsometry measures the change in the polarization state of light reflected from the surface of a sample. From the ellipsometric data it is possible to determine the optical properties and thickness of thin films by using a fitting process. The measured values are expressed as ellipsometric parameters, psi ($\Psi$) and delta ($\Delta$), which are depending, of course, on the sample and also on the wavelength of the incident light. These values are defined by the ratio $\rho$ of the Fresnel reflection coefficients $R_p$ and $R_s$ for $p$- and $s$-polarized light, respectively, as follows.

$$\rho = \frac{R_p}{R_s} = \tan(\Psi)\exp(i\Delta) \tag{1}$$

In this expression $i$ is the imaginary unit. In the fitting process, we initially assume the optical properties, that is the

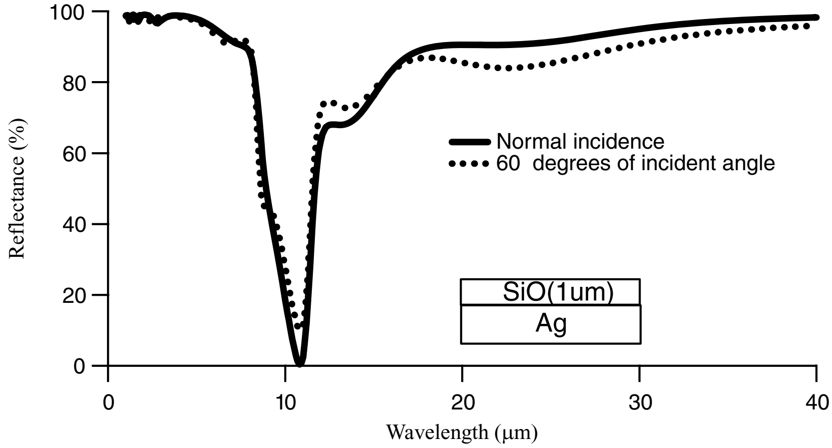


**Fig. 6** Calculated spectral reflectance of SiO (1 $\mu$m)/Ag at normal incidence and 60 degrees incident angle

angle.

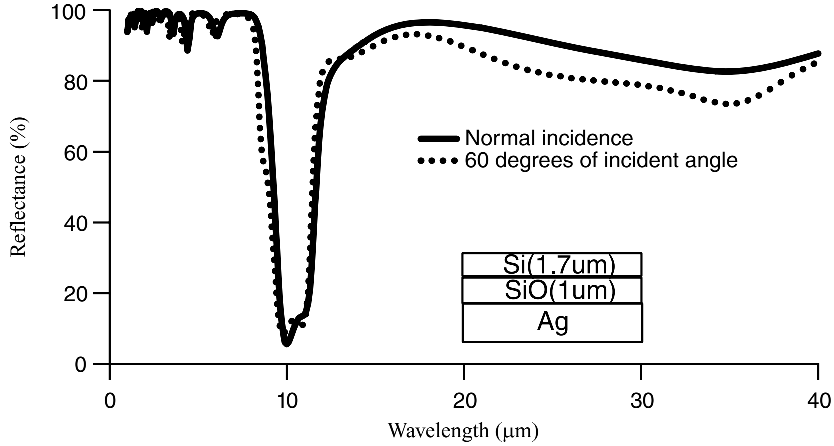


**Fig. 7** Calculated spectral reflectance of Si (1.7 $\mu$m)/SiO (1 $\mu$m)/Ag at normal incidence and 60 degrees incident angle

refractive indices and thicknesses of the films in the sample. We then calculate $\Psi$ and $\Delta$ and compare the calculated and experimental data, and repeat the process to obtain best fit for optical properties and thicknesses.

$\Psi$ and $\Delta$ were measured using a J. A. Woollam variable angle spectroscopic ellipsometer (IR-VASE) with incident angles 50, 60, and 70 degrees. Measured data from a SiO film on Ag are shown in Figs. 2 and 3. The fitting results are also shown in Figs. 2 and 3, and the experimental and model calculated curves are very close. Figure 4 shows the obtained complex-valued refractive index $n + ik$ of the SiO film. The thickness was determined 1117 nm simultaneously. The optical properties of the Ag film which were indispensable to reconstruct the model calculated $\Psi$ and $\Delta$, were determined by ellipsometry on a Ag film on a glass substrate deposited by the same vacuum evaporation technique. In the model fitting we assumed four oscillators in this spectral region for the SiO film. As seen in Fig. 4, there is a high $k$ region around 10 $\mu$m, which is the origin of high emittance only in the atmospheric window. Figure 5 shows the complex dielectric function $\varepsilon = \varepsilon_1 + i\varepsilon_2 = (n + ik)^2$ and a comparison with published data [11, 13]. The correspondence among the curves in Fig. 5 shows the validity of our optical properties.

## 3 An application to panel heating surface

The determined optical constants can be used for simulations in thin film systems. Here as an example, we estimated the reflectance of a spectral selective panel heating surface at normal and oblique incident angles to evaluate spectral emittance to the oblique angle.

Figure 6 shows the calculated spectral reflectance of an SiO film (1 $\mu$m in thickness) on an Ag substrate at normal incidence and at 60 degrees of incidence angle. The spectral reflectance at normal incidence agrees with Fig. 1. As the incident angle increases from 0 to 60 degrees, the spectral reflectance changes slightly due to the change of the optical path length in SiO film. At the minimum at about 11 $\mu$m, the reflectance increases with the incident angle, which means the thermal emission to the normal is larger than at oblique incidence.

Figure 7 shows the calculated reflectance of an Si and an SiO film stacked on Ag substrate. The thicknesses of the Si and SiO films are 1.7 and 1 $\mu$m, respectively. The thickness of the Si film was selected not to change the reflectance at about 10 $\mu$m even when the incident angle increased. The constant reflectance of emittance allows us to calculate thermal emission from the surface by only Lambert's cosine law at least between 0 and 60 degrees.

## 4 Conclusions

The optical properties in terms of the complex refractive index of silicon monoxide films deposited by vacuum evaporation on silver films on glass has been determined by infrared ellipsometry and compared with published data. As an application example, we calculated spectral reflectance of spectral selective radiating panel surfaces at normal and oblique incidence.

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