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Performance Evaluation for Uncooled Microbolometer Using Antireflection Coating of SiO_2/Si_3N_4 Multiple Films on Silicon Window

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In this paper, we have proposed a novel antireflection coating with multilayers of SiO_2/Si_3N_4 on a silicon window, suitable for performance evaluation on a microbolometer thermal sensor in the infrared range of 8–12 μm. The 4-layer coating (2 periods of SiO_2/Si_3N_4) with optimized thickness was designed using the Essential Macleod program developed by Thin Film Center, Inc. On the basis of the proposed long-wavelength infrared (LWIR) silicon-based window by simulation, the samples were also fabricated by physical vapor deposition to characterize and achieve the best possible agreement by Fourier transform infrared (FTIR) spectroscopy. It was found that, in the wavelength range of 8–12 μm, the average transmittance of the double-side-coated sample increases by about 39% compared with that of the uncoated silicon window and its maximum reaches about 98% at 9 μm. We have also demonstrated the performance of an uncooled microbolometer sensor using the coating multilayers of SiO_2/Si_3N_4 on a silicon window, which is compatible with the commonly used germanium window.

1. Introduction

Antireflection coating is required for an infrared window in order to increase transmission for use in high-index IR optical materials. Single-layer antireflection coatings can normally cover only a very small bandwidth. To achieve broad band infrared optical performance, a multilayer stack is usually necessary. Silicon is an infrared optical material with a relatively high refractive index. It is used in infrared devices as windows, lenses, and transmission filters. The high reflection index of silicon causes an important reflection loss from its surface, even in thin film form. Therefore, its surface should be coated with an antireflection coating to reduce the reflectance or increase the optical transmittance. The antireflection coating of the surface is one of the most important methods of reducing the reflection loss of a silicon-based infrared window. In this research, using SiO_2 and Si_3N_4 respectively as low- and high-index coating

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materials deposited on a silicon window (1-mm-thick <100> ± 1° Czochralski silicon substrate, Topsil Semiconductor Materials A/S), the average transmittance of the double-side-coated sample reaches 91.37% in the 8–12 μm atmosphere transmission window range. This is one of the best experimental results compatible with a Ge-based window for long-wavelength infrared (LWIR) optics achieved so far. In this work, using the above-mentioned Si-based multilayer films as an infrared window for the replacement of a Ge-based window, the high performance of a microbolometer sensor is characterized.

2. Design and Preparation of Antireflection Coating

The design of thin-film multilayer coating often specifies the transmittance and reflectance values at various wavelengths, angles, and polarizations of incident light. First, we determine the materials to be used for designing the antireflection coating.(1) For a single-layer antireflection coating, the material used to deposit an antireflection coating must have a refractive index $n = (n_o \times n_s)^{1/2}$, where n_s is the refractive index of the substrate. Silicon is used as a substrate (i.e., an infrared window). For a normal incidence, the reflectance is clearly high without antireflection coating thus, SiO_2 (n = 1.46) and Si_3N_4 (n = 2.03) are respectively used as low- and high-index coating materials to improve the transmittance of a LWIR spectrum. In Fig. 1, the proposed multilayer coating window structure including a four-layer coating (two-period SiO_2/Si_3N_4) is shown. It is suggested that the design has the best arrangement of the layer order and thickness to minimize the reflectance of the silicon window of interest of the LWIR region.(2,3)

In our experiment, a high-transmission (HiTran) silicon window with unique transmission performance across almost the entire infrared band including the far-infrared region is used. The purity of HiTran silicon eliminates all extrinsic impurity-related absorptions over the entire infrared band. However, intrinsic lattice vibrations in silicon reduce the transmission of the

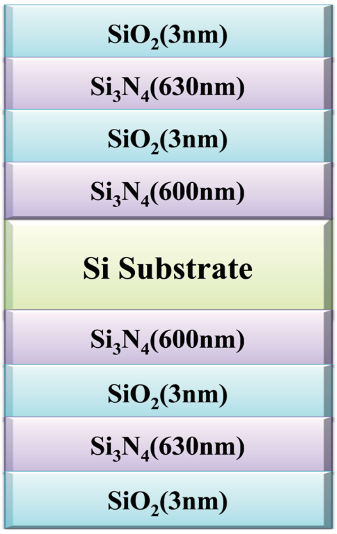


Fig. 1. (Color online) Schematic diagram of the multilayer (consisting of Si_3N_4 and SiO_2) antireflection coating on Si substrate. The thicknesses of the SiO_2 and Si_3N_4 layers were optimized using the Essential Macleod program.

infrared light of thicker HiTran silicon in the extended LWIR wavelength band from 7 to 16 μm, but in this case, cost-efficient HiTran silicon can still replace the other costly infrared materials in this region.

The deposition of antireflection coating on the surface of the HiTran silicon window was performed by physical vapor deposition (PVD) in a vacuum chamber by using an electron gun and a thermal boat at a pressure of 1×10^{-5} Torr. A 1-mm-thick polycrystalline silicon wafer was used as a substrate. Before deposition, the substrate was polished and thoroughly washed with detergent in an ultrasonic bath. To completely remove pollution from the two-sided surfaces of the polished silicon substrate before deposition, the inside of the vacuum chamber was subjected to glow discharge for 10 min. SiN_x (99.99%) and SiO_x (99.999%) were evaporated using the electron gun and thermal boat, respectively. During deposition, the silicon substrate temperature was kept at 150 °C. The layer thickness and deposition rate were measured using a piezoelectric crystal. The deposition rates were 1.5 and 0.5 nm/s for SiN_x and SiO_x, respectively.(4) Figure 1 shows the structure of the layers. The IR transmission spectrum was measured using a Fourier transform infrared (FTIR) spectrometer (PerkinElmer, Spectrum One).

Figure 2 shows the schematic experimental setup for the characteristic evaluation of the microbolometer sensor. Using the testing system, sensor parameters such as thermal response, noise power spectral density (PSD), (5) thermal time constant (τ),(6) noise equivalent, specific detectivity (D^*),(7) and temperature difference (NETD)(8) are measured and extracted. The microbolometer sensor is mounted on a copper cold finger and then sealed in a vacuum chamber with pressure kept at 10 mTorr, and temperature at 22 °C using a highly precise throttle valve with pumping by a Pfeiffer mechanical pump and a thermoelectric (TE) cooler by temperature-controlled electronics, respectively. For the measurement of the spectral response and thermal time constant, a CI cavity-hole-like black-body radiation source with a temperature of 500 K through the chopper of low and high modulation frequencies is emitted to the microbolometer sensor and then response signals are obtained from the SR-570 preamplifier and SR-830 lock-in amplifier synchronously.(9–11)

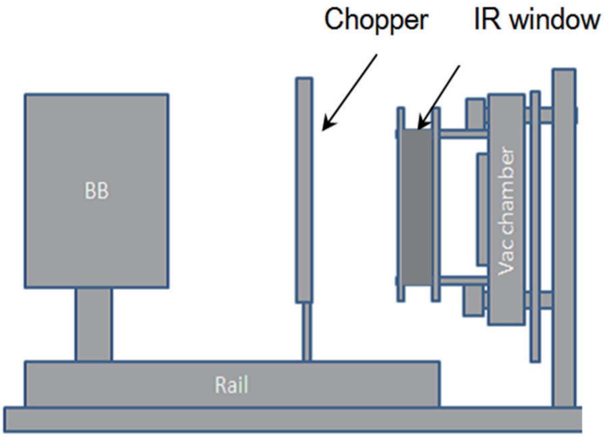


Fig. 2. Schematic experimental setup for the characteristic evaluation of microbolometer sensor.

3. Results and Discussion

In this work, we apply an approach that depends on needle optimization as the synthesis method and a characteristic matrix to design a broadband-pass filter for LWIR light. Consequently, the optimization was performed by above simple method at a reference wavelength of 10 µm. The arrangement and optimized thickness of the layers in the designed antireflection coating are shown in Fig. 1. The total thickness of the antireflection coating is 2.472 µm.

Figure 3 shows the curve simulated using the Essential Macleod program and that measured by FTIR with two-sided coating compared with that of the uncoated sample. We have considered the striking contrast between the two cases: uncoated Si substrate and four-layer antireflection coating on both sides of the substrate. However, for the uncoated high-quality Si substrate,(3) the average of transmission is 52.37%. It is clear that the two-sided coating case greatly enhances the LWIR transmission between 8 and 12 µm. With the deposition of four-layer antireflection coating on both sides of the substrate, the maximum transmittance reaches 98% (occurs about 9 µm). The average transmittance increases by 39% and reaches 91.37%, which is closer to the simulated data of 95.16%, in the wavelength range of 8 to 12 µm. As seen from Fig 3, there is good agreement between the simulated and experimental results, especially for the wavelength of 9.5 µm. In this study, note that the best possible agreement is firstly obtained using the tooling factor (thickness of film on substrate/thickness displayed on monitor) for Si_3N_4 and SiO_2. Then, after repeating the deposition process several times and by using the "reverse engineering" mode of the Essential Macleod software, the best choice for the monitor thickness was obtained. The discrepancy may be attributed to tooling factor-calibrating errors,(4) monitoring errors during layer deposition, and the packing density of deposited coating materials.(12)

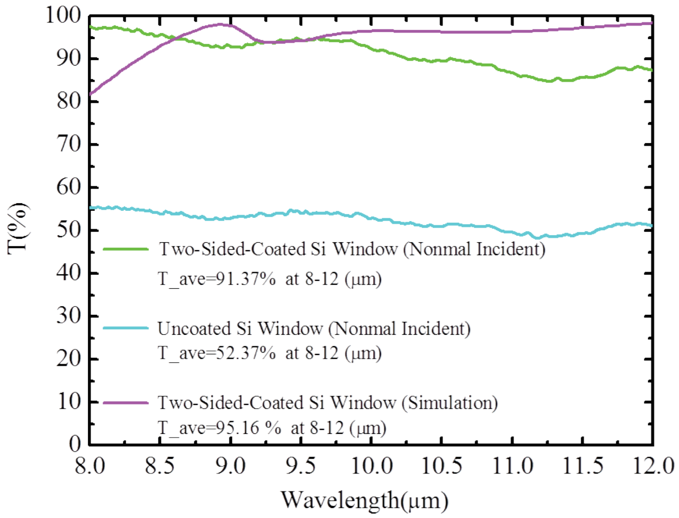
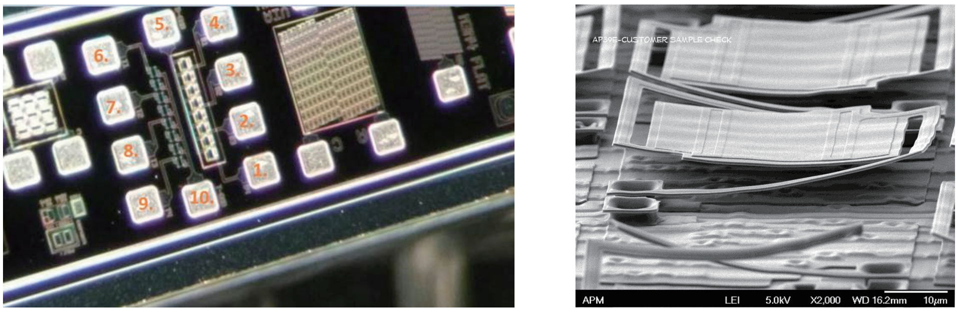


Fig. 3. (Color online) Calculated and experimental infrared optical transmission spectra for uncoated and coated Si substrates.

In addition, a set of test microbolometers (testkey structure) identical to those in the array was also fabricated in close proximity to the focal plane array (FPA) to be used for the measurement of thermal parameters. Figure 4(a) shows an optical microscopy image of a testkey for wire bonding used in this experiment, and a scanning electron microscopic image of two 52-µm-pitch active pixels in the 160′120-pixel microbolometer array is displayed in Fig. 4(b). Owing to imprints of readout integrated circuit (ROIC) layout mapping to the surface of the microbolometer sensor after the MEMS process and, the moderate stress on the interlayers of the sensor structure, the surface topography results in slight bending. The testkey structure pattern in Fig. 4(a) consists of 16 pixels of microbolometers (eight active pixels for the extraction of thermal parameters: Nos. 1–4 signal pads and flat pixels for monitoring the temperature of substrate, Nos. 6–9 signal pads, and Nos. 5 and 10 are common grounding pads).

Table 1 shows the key thermal parameters of the microbolometer sensors measured and extracted from the testkey illuminated through our proposed infrared silicon window coated with the multiple layers of SiO_2/Si_3N_4 films and through a germanium window, respectively. The thermal parameters of the microbolometer sensors in this study using the Si-based window in the LWIR detection range are almost compatible with those of the Ge-based one. Undoubtedly, it is noted that the high-performance and cost-effective Si-based window has a great possibility for the replacement of an expensive Ge-based window.



(a) (b)

Fig. 4. (Color online) (a) The optical microscopic image of testkey structure pattern consisting of 16 pixels of microbolometers, where eight active pixels are identical to those in the array, was also obtained in close proximity to the FPA. (b) SEM image of two microbolometer active pixels (floating pixels) in a section of FPA.

Table 1
Key thermal parameters from the microbolometer sensors illuminated through the infrared silicon window coated with the antireflection multiple layers of SiO_2/Si_3N_4 films and through germanium window.

Items	R_b (kΩ)	Γ (ms)	Res. (V/W)	G (W/mK)	C ($J{\cdot}K^{-1}$)	V_{nT} (V)	NEP (W)	Detectivity (cm-$Hz^{1/2}$/W)	η	NETD (mK)
Testkey1 with Si-Window	47.59	18.8	7775.9	$9.78 \times 10E{-8}$	$1.39 \times 10E{-9}$	$1.74 \times 10E{-7}$	$2.23 \times 10E{-11}$	$2.24 \times 10E8$	0.6612	86.28
Testkey2 with Si-Window	46.95	20.1	8744	$9.69 \times 10E{-8}$	$1.95 \times 10E{-9}$	$2.22 \times 10E{-7}$	$2.53 \times 10E{-11}$	$1.97 \times 10E8$	0.7368	87.85
Testkey with Ge-Window	51.1	16.2	10025	$8.87 \times 10E{-8}$	$2.28 \times 10E{-9}$	$4.56 \times 10E{-7}$	$4.55 \times 10E{-11}$	$2.49 \times 10E8$	0.8627	76.78

4. Conclusions

We have studied the design, fabrication, and characterization of the multiple layers of antireflection coating consisting of Si_3N_4 and SiO_2 on a Si substrate. The obtained results show that, by depositing 4 layers of $Si_3N_4/SiO_2/Si_3N_4/SiO_2$ on both sides of the substrate, the average IR transmittance increases by about 39% and its maximum reaches 98% in the wavelength range of 8 to 12 μm. This is one of the best experimental results compatible with a Ge-based window for LWIR optics achieved so far. The usage of the cost-effective Si-based optic material as the LWIR window will increase the popularity of commercial thermal imaging in the future.

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