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Improvement of uncooled infrared imaging detector by using mesoporous silica as a thermal isolation layer

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Abstract

Thermal-insulation properties of ordered mesoporous silica could possibly improve the efficiency of uncooled infrared imaging detector by introducing a mesoporous silica layer between TiN absorber and Si_3N_4 passivation layer. IR absorption rate of 50% porosity mesoporous silica was simulated and the results showed that above 90% infrared absorptance could be achieved in 8–12 μm wavelength region. Thermal conductivity of mesoporous silica was measured by 3ω method. Finite element modeling was used to simulate thermal isolation effect of mesoporous silica inserted structure. The result shows that an effective thermal-insulation effect could be obtained with 150 nm thick mesoporous silica layer. Also according to the simulation result of time transient temperature variation, it was found that mesoporous silica layer for thermal isolation induced an increase of 30% of residual temperature on TiN absorber. The mesoporous silica film was found to be a good thermal isolation layer for microbolometer.

Keywords: B. Porosity; C. Thermal conductivity; D. SiO_2; E. Sensors

1. Introduction

Uncooled microbolometer provides moderate performance at low cost and has a broader area of commercial and military applications [1]. In general, a microbolometer needs low thermal conductivity and high temperature coefficient of resistance (TCR) materials for resistive film. Because the resistive film changes its electrical resistance with thermal energy emitted from absorber [2]. For an effective control of resistive film, a good conduction of heat from infrared absorber to resistor is necessary. But some of heat flow to resistive film is lost because downstream heat conduction happens from absorber to bottom layer. So, thermal-insulation layer of low thermal conductivity is needed to reduce a heat loss from infrared absorber. By the way, for similar purposes, nano-sized mesoporous silica film with ordered structure and low thermal conductivity has been proposed for thermal insulating layer for micro-electro-mechanical systems (MEMS) [3,4].

In this study, an amelioration of generated heat conduction from infrared absorption at TiN absorber to a-Si:H resistor film was investigated to improve the efficiency of microbolometer. Heat loss, i.e., downstream heat conduction of TiN absorber layer, could be reduced by mesoporous silica thermal insulating layer and an effective heat conduction to upper a-Si:H layer was observed.

2. Experimental procedure

The precursor solution for mesoporous silica was prepared with TEOS, ethanol (EtOH), HCl, H_2O, and Brij-76 surfactant. The molar ratio of catalyst was chosen for minimization of condensation reaction [5]. Porosity of mesoporous silica film was controlled by the amount of Brij-76 as a surfactant. The final composition of TEOS/ethanol/H_2O/HCl/Brij-76 was 1:20:5:0.01:x ($x = 0.03$, 0.05, 0.07). After 1 day aging, silica sol was spin-coated at 3000 rpm for 30 s. The as-prepared film

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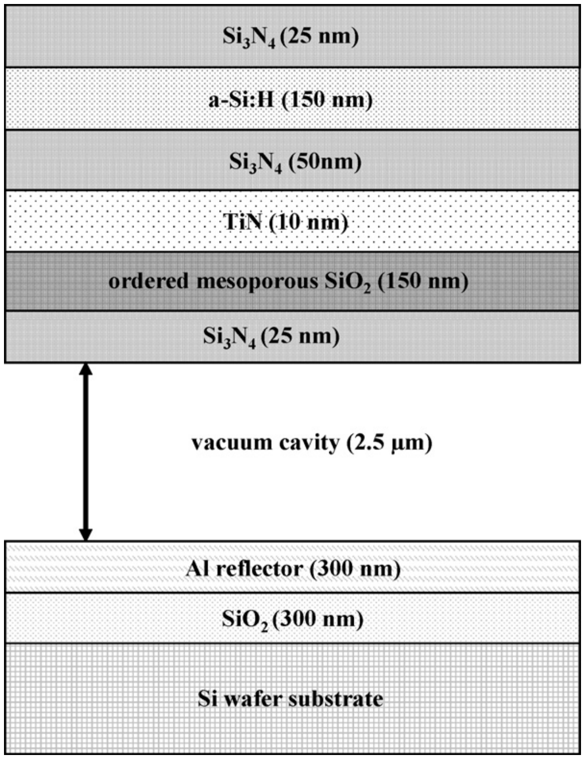

Fig. 1. A schematic cross-sectional diagram of mesoporous silica added bolometer structure.

was exposed to air for 1day and the mesoporous silica film was fabricated after the calcination at 400 °C for 2 h with a heating rate of 1 °C/min [6]. Ordered structure of mesoporous silica thin film was checked by using an X-ray diffractometer (XRD). Infrared absorption characteristic of mesoporous silica thin film was analyzed by using Jasco Fourier transform infrared (FT-IR) 300E. Thermal conductivity of mesoporous silica layer was measured by 3ω method and 300 nm gold electrodes were realized using a standard photolithographic procedure and lift-off process [7]. Infrared absorption of mesoporous silica inserted structure was simulated using Essential Macleod optical simulation software and a cross-sectional diagram of bolometer structure with mesoporous silica thin film is given in Fig. 1. Thermal conduction was also simulated by using a finite element modeling (FEM) 2-dimension transient thermal conduction simulation tool.

3. Results and discussion

The ordered structure of mesoporous silica thin film was checked by XRD. Fig. 2 shows the XRD pattern of ordered mesoporous silica films with different porosity. Among three films with different porosity, mesoporous film with 30% porosity (Fig. 2(a)) shows a diffraction peak at the highest value of two-theta. There is a decrease in diffraction angle as an increase in the porosity of mesoporous film. The porosity was increased by an increase of amount of surfactant and larger size of pores could be generated [8]. So a distance between pore center and silica wall center was lengthened with the increased porosity and diffraction angle was getting lower.

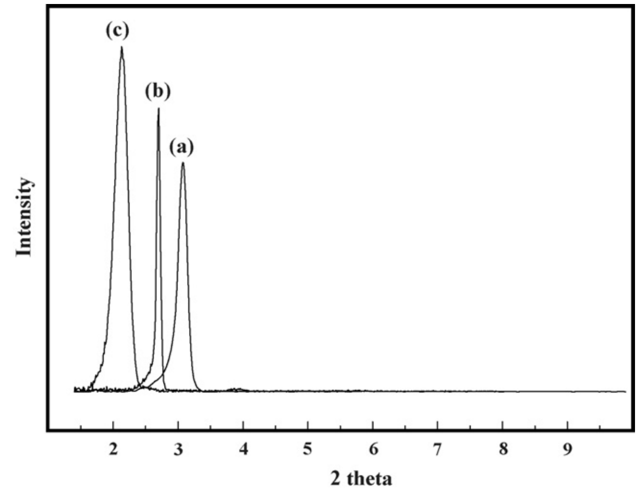

Fig. 2. XRD pattern of ordered mesoporous silica films of (a) 30%, (b) 40% and (c) 50% porosity.

To use mesoporous silica thin film for a thermal insulating layer of microbolometer, mesoporous silica should not reduce the absorption property of IR sensor. Fig. 3 shows FT-IR spectrum of 150 nm mesoporous silica thin films with three different porosities. Porous films show a similar absorption behavior in 750–1250 cm^{-1} independent on the porosity. This absorption corresponds to Si–O–Si bond [6]. Microbolometer infrared absorption should be maintained above 80%, because a degeneration of sensor capability is observed with absorption below 80% [9]. Therefore, prior to insert mesoporous silica layer between TiN absorber and Si_3N_4 passivation layer, infrared absorption loss should be considered to prevent a lowering of infrared absorption at TiN absorber.

IR absorption of microbolometer was calculated in 1–14 μm wavelength region by using an optical simulation software [10]. Fig. 4(a) shows the calculated results of IR absorption of microbolometer including nonporous silica layer and it was about 80% in 8–12 μm until the introduction of 150 nm thick of nonporous silica thin film. This means that there is not an

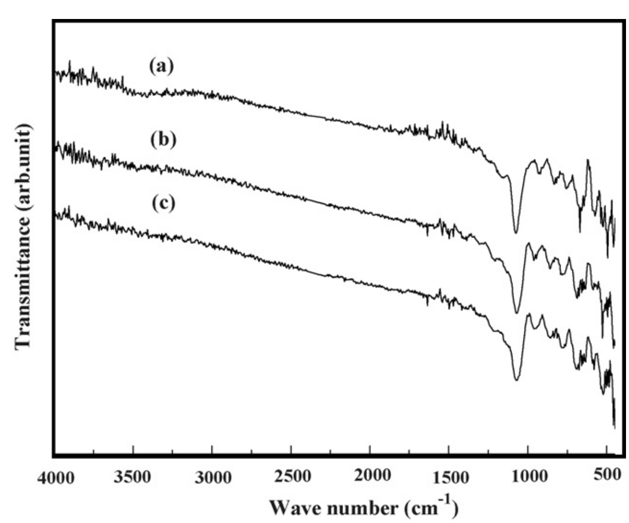

Fig. 3. FT-IR spectra of ordered mesoporous silica films of (a) 30%, (b) 40% and (c) 50% porosity.

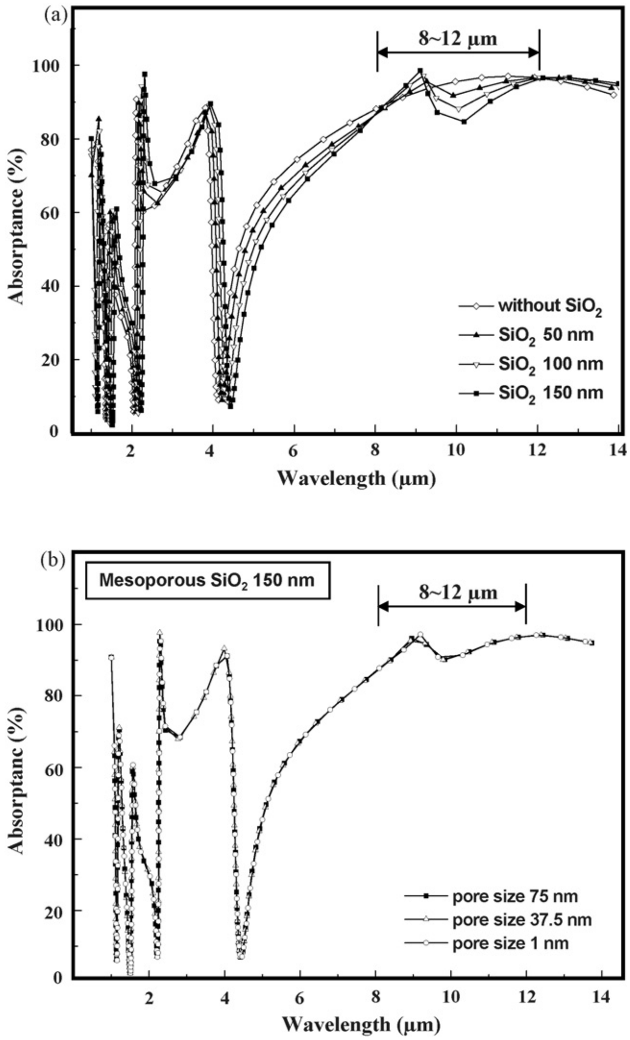

Fig. 4. Calculated absorption spectra versus wavelength for (a) nonporous and (b) mesoporous SiO_2 thermal isolation layer added bolometer structure.

important loss of IR absorption efficiency with an introduction of silica layer between absorber and passivation layers.

To simulate infrared absorption of microbolometer with mesoporous silica film, it needs to assume that mesoporous film structure is constructed as layer by layer structure of pore and silica. Fig. 4(b) corresponds to the calculated IR absorption of microbolometer with 50% porosity of mesoporous silica thin film. Though the variation of the thickness of pore and silica layers from 1 to 75 nm, IR absorption was not changed. Furthermore a microbolometer with 50% porosity of mesoporous silica thin film shows above 90% of infrared absorption, so it was confirmed that mesoporous silica thin film of 150 nm thick does not degenerate IR absorption of microbolometer in 8–12 μm region.

An inserted thermal isolation layer must have low thermal conductivity to block thermal conduction from absorber to bottom layer. To measure thermal conductivity of mesoporous silica thin film, 150 nm thick mesoporous silica film of 30% porosity and 2–3 nm thick chemical oxide of Si was prepared on Si substrate. Fig. 5 shows measured thermal conductivity of mesoporous silica film of 30% porosity by 3ω method [11].

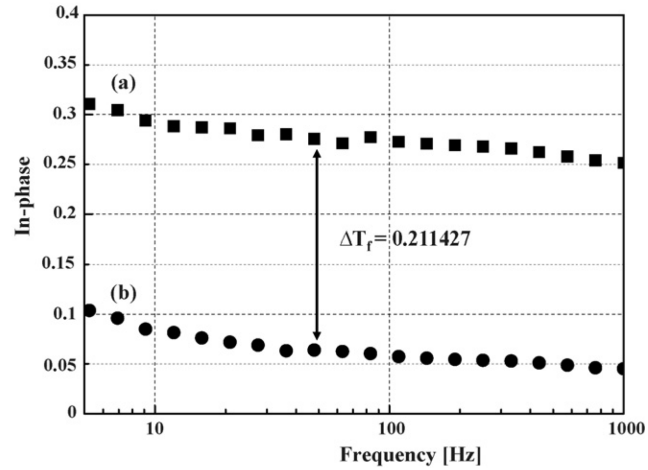

Fig. 5. In-phase signals of (a) mesoporous silica film and (b) chemical oxide on Si substrate for measuring thermal conductivity of mesoporous silica film of 30% porosity.

Calculated ΔT_f was 0.211427 and thermal conductivity was 0.214 W/m K. It is about one order smaller than that of nonporous silica (1.1 W/m K) [12]. Therefore, mesoporous silica thin film can be used as a thermal isolation layer due to its high thermal isolation capability.

The thermal isolation effect of mesoporous silica thin film with 50% of porosity, minimizing heat flow from TiN to Si_3N_4 passivation layer, could be obtained by finite element computer simulation. The parameters of thermal properties of each layer used in the simulation were given in Table 1 [13]. Fig. 6 shows FEM result of 2-dimesional thermal conduction in bolometer structure without (a) and with (b) mesoporous silica thin film. The simulated structure of Fig. 6(b) was a-Si:H (150 nm)/Si_3N_4 (50 nm)/TiN (10 nm)/mesoporous silica (150 nm)/Si_3N_4 (25 nm). Thermal distribution of bolometer was simulated by measuring temperature distribution when 1 °C was applied on the top of a-Si:H layer. The 2-dimensional time transient thermal conduction process was used as an analyzing tool. Fig. 6(a) shows an uniform thermal distribution in a whole layer due to high thermal conductivities of Si_3N_4 and TiN. The heat from top hydrogenated amorphous silicon layer conducts fast to bottom layer. Fig. 6(b) shows an effective thermally insulated structure by using 150 nm mesoporous silica layer. Because there is almost no downstream of heat to lower part, there is a large thermal-insulation region of near 0 °C. It was due to 150 nm thick mesoporous silica film of very low thermal conductivity and high heat capacity.

Table 1
Parameters of the materials used in FEM simulation

	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)	Density (kg/m^3)
a-Si:H	0.9	681	2230
Si_3N_4	13	710.6	3100
TiN	16.72	522.5	5430
Mesoporous SiO_2 (50% porosity)	0.13	780	1320

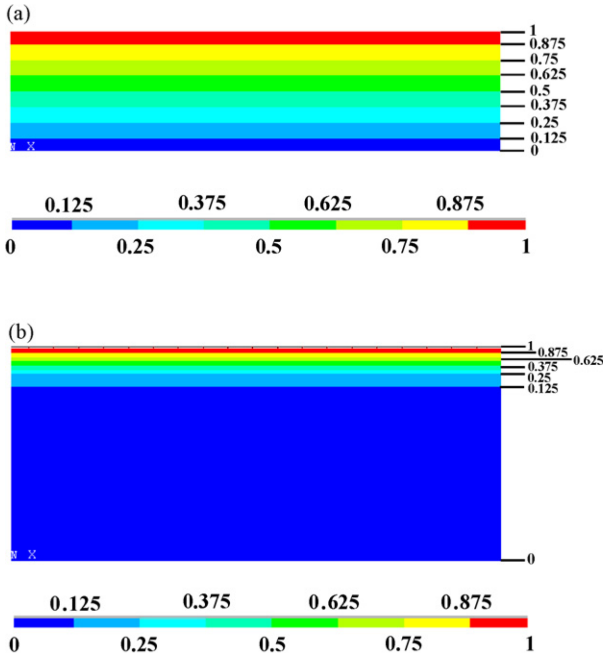

Fig. 6. FEM results of 2-dimensional thermal conduction of bolometer structure (a) without and (b) with mesoporous SiO_2 thermal isolation layer.

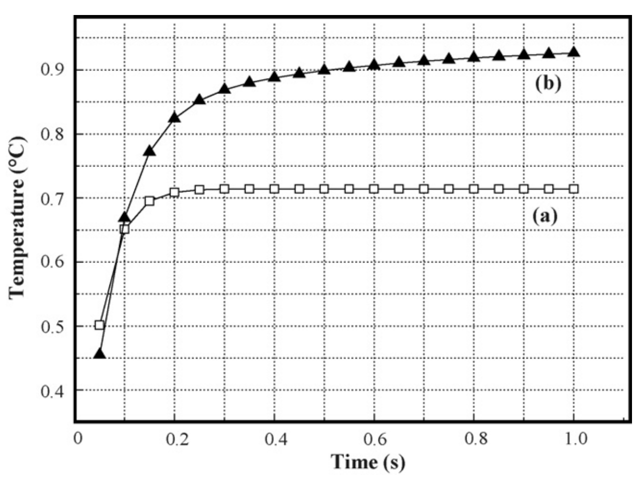

Fig. 7. Time transient temperature variation result of bolometer structure (a) without and (b) with mesoporous SiO_2 thermal isolation layer.

Fig. 7 shows temperature variation result depending on time of mesoporous silica added bolometer structure to verify more critical temperature distribution. The simulated structure of Fig. 7(a) is TiN (10 nm)/Si_3N_4 (25 nm) and (b) is TiN (10 nm)/mesoporous silica (150 nm)/Si_3N_4 (25 nm). Temperature difference under TiN absorber was calculated during 1 s. Fig. 7(a) is a type of only Si_3N_4 passivation layer under TiN absorber, it shows saturated temperature of 0.713 °C. But Fig. 7(b) shows temperature of mesoporous silica inserted structure and it was increased to 0.925 °C. Temperature of TiN absorber could be increased about 30% than that of without mesoporous silica thin film. It means that mesoporous silica blocks heat flow from TiN absorber to bottom layer and returns the downstream of heat to upper resistor layer very effectively.

4. Conclusions

An absorption decrease at 750–1250 cm^{-1} was not important with 30–50% porous silica thin films of 150 nm thick. Thermal conductivity of mesoporous film could be measured by 3ω method as 0.214 W/m K. IR absorption of 50% porosity mesoporous silica added bolometer structure was simulated and it was above 90% in 8–12 μm region. FEM simulation results showed that an effective thermally insulated bolometer structure was possibly constructed by using 150 nm mesoporous silica layer. Through the transient temperature variation result depending on time of mesoporous silica added bolometer structure, 30% TiN absorber temperature increase was obtained with inserted 150 nm thick mesoporous silica thin film. It was revealed that mesoporous silica film could be a good thermal isolation layer for microbolometer.

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