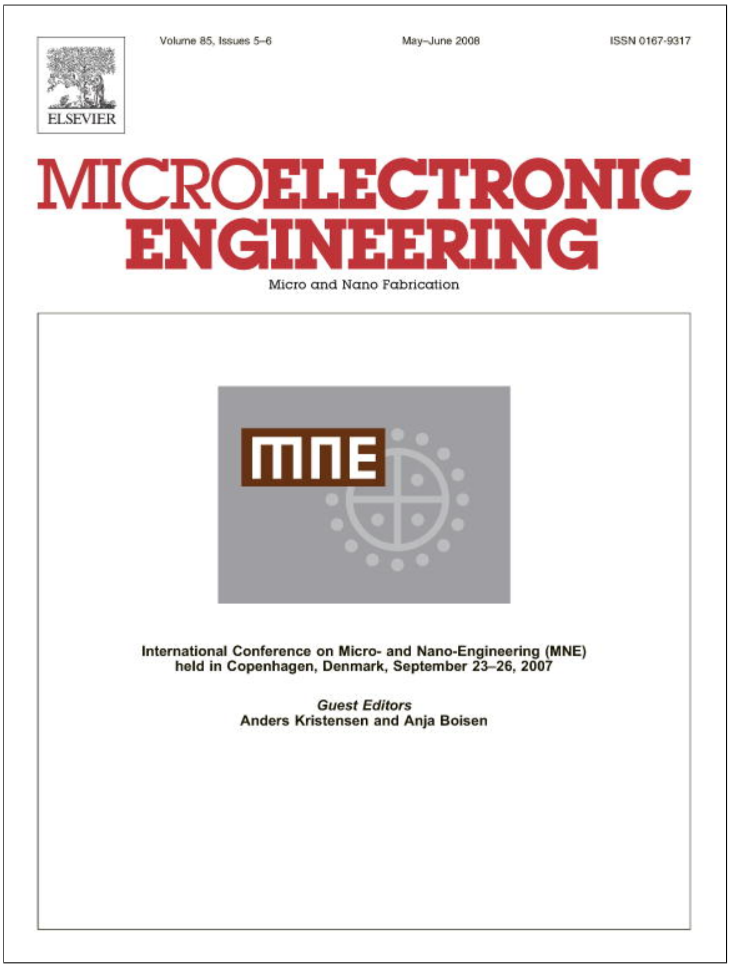

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Efficient infrared emission from periodically patterned thin metal films on a Si photonic crystal

P. Theodoni [a], P. Bayiati [a], M. Chatzichristidi [a], Th. Speliotis [b], V. Em. Vamvakas [a], I. Raptis [a], N. Papanikolaou [a,*]

[a] *Institute of Microelectronics, NCSR "Demokritos", Ag. Paraskevi, Athens GR 15310, Greece*
[b] *Institute of Material Science, NCSR "Demokritos", Ag. Paraskevi, Athens GR 15310, Greece*

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Abstract

We have fabricated a periodic array of holes with diameters of a few microns on thin metal films on a Si substrate by using lithographic techniques, and demonstrate that the structures show extraordinary transmission in the infrared spectrum. Our structures become efficient narrow-band infrared thermal emitters when the hole pattern is transferred to the Si substrate by dry etching using the metal as a mask. The influence of the geometrical parameters, like the hole depth and diameter, on the emission spectra was considered in order to optimize the optical properties.

Keywords: Infrared thermal emitter; Photonic crystal; Optical lithography

1. Introduction

The thermal emission properties of materials can be tuned by structuring the surface in the micro/nano scale. In this direction controlled thermal emission was reported in one dimensional 1D periodic photonic crystals [1], and subwavelength gratings [2] as well as in 2D patterned surfaces [3]. Lately there is a renewed interest in developing novel, efficient infrared (IR) emitters while such structures are promising in thermophotovoltaic applications but also as chemical sensors in the IR [3].

The optical properties of periodic arrays of subwavelength holes on a thin metal film are also intensively studied since they show extraordinary transmission, higher than the one expected by normal diffraction [4]. Such effects were demonstrated for both optical and IR frequencies. The extraordinary transmission was attributed to the excitation of surface plasmons (SP). For a metal film with a square array of holes with lattice constant a the SP dispersion becomes

$$\mathbf{k}_{\mathrm{SP}} = \mathbf{k}_0 \sin\theta \pm n\frac{2\pi}{a}\mathbf{u}_x \pm m\frac{2\pi}{a}\mathbf{u}_y, \qquad (1)$$

where $|\mathbf{k}_0| = \omega/c$ is the incident wave vector, θ is the angle of incidence, $\mathbf{u}_{x,y}$ are unit vectors in the film plane, while m, n are integers denoting the scattering order from the array [5]. The combination of metallic films perforated with subwavelength holes of micrometer dimensions with photonic crystals show thermal emission which is very different from the black body spectrum [3]. Efficient narrow-band IR emitters should have narrow-band absorption (A) which can be deduced following Kirchhoff's law $A = 1 - R - T$ from reflectivity (R) and transmittance (T) measurements. The aim of this work is to fabricate periodically patterned metal films on a Si photonic crystal and study their IR spectra using Fourier-transform IR spectroscopy.

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[*] Corresponding author. Tel.: +30 210 6503245; fax: +30 210 6511723.
E-mail address: N.Papanikolaou@imel.demokritos.gr (N. Papanikolaou).

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2. Fabrication method

The photonic devices were fabricated on Si wafers by applying conventional silicon technologies (optical lithography, sputtering and dry etching). The Si wafers, after cleaning, were coated with 1.0 μm thick AZ-5214 resist and patterned by the image reversal process at a Karl Suss MA6 mask aligner. Square arrays of squares and triangles with a lattice constant of 5 μm were transferred in the photoresist with a lithographic mask. In practice as is also seen in the SEM micrographs we end up with rounded square and rounded triangular (not shown) holes, with the triangles generally covering less surface area compared to the squares. After the lithographic process a thin, 100 nm, Al layer was deposited by DC magnetron sputtering (Ar at 3 mTorr, target power 60 Watt) at deposition rate of ~18 nm/s. The layout transfer on the Al layer was accomplished by a lift-off step in acetone in ultrasonic bath revealing an Al film perforated with a periodic array of holes. Finally, the layout was transferred to Si by dry etching in an inductively coupled plasma (ICP) etcher. The high-density plasma reactor used in this work is an Alcatel (MET, micromachining etch tool), consisted of a load-lock and an ultrahigh vacuum (10^{-6} mbar) main chamber. For the anisotropic Si etching a mixture of 200 sccm SF_6 and 15 sccm O_2 was used. During the etching process, the temperature was −100 °C achieving an etching rate of ~2.5 μm/min. In Fig. 1 we present top-down and cross section representative SEM micrographs of the final structures.

3. Results and discussion

The IR spectra were measured with a Bruker Tensor 27 single beam FTIR spectrometer. Transmission was recorded at normal incidence while reflectance at 12° to the normal. As is shown in Fig. 2 enhanced transmission is observed close to the surface plasmon-polariton wavelengths λ_{SP} predicted for an Al/Si interface, which are obtained from equation

$$\lambda_{SP} = \frac{a}{\sqrt{m^2+n^2}}\sqrt{\frac{\varepsilon_{met}\varepsilon_{diel}}{\varepsilon_{met}+\varepsilon_{diel}}} \tag{2}$$

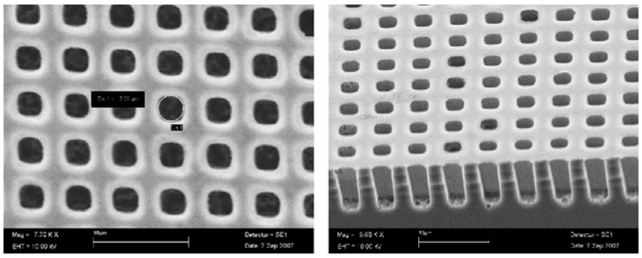

Fig. 1. SEM micrograph of the structures prepared by optical lithography: A square array of holes on a Si substrate covered with a 100 nm thick Al film. The hole diameter is 2.7 μm and the lattice constant 5 μm. The hole depth is ~6 μm.

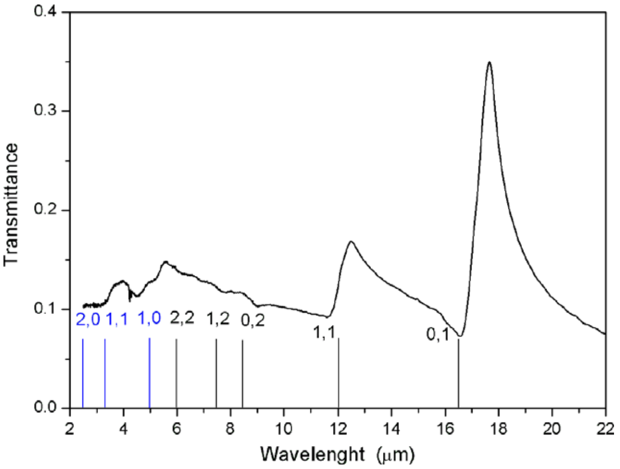

Fig. 2. Transmission spectra of 100 nm Al films patterned with a periodic array of square holes (lattice constant $a = 5$ μm, hole diameter $d = 2.7$ μm). The film lies on a uniform Si substrate, the horizontal lines denote SP frequencies for Si/Al (black lines), and Si/air (blue lines) obtained from Eq. (2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and are marked with the vertical lines, while smaller peaks corresponding to Al/air SPs are also seen below 5 μm. Transmittance more than 35% is observed around 17.5 μm at wavelengths larger than the hole size for the first (1,0) scattering order. The wavelengths of the measured transmittance peaks are in good agreement with the theoretical prediction that gives the surface plasmon wavelengths at normal incidence. We used a constant dielectric function for silicon $\varepsilon_{Si} = 11.9$ and tabulated data from the literature [6] for Al. There is a small but systematic red shift of the observed values compared to the theoretical prediction. This can be attributed to possible dielectric function variation in our samples compared with the optical constants reported in the literature for Al. Our results are in accordance with results obtained by other groups who reported similar enhanced transmittance from hole arrays in the IR spectrum [7,8].

The perforated metallic films were etched using the Al as mask up to a depth of ~6 μm, the final structure is shown in Fig. 1. The IR transmittance through the whole, patterned, 380 μm thick Si wafer is small, less than 1%, while the reflectance is shown in Fig. 3. The observed drop in reflectance means that our samples strongly absorb in a narrow-band. Ideally the thermal emission should have the black body spectrum, in practice the emissivity is lower and the bodies are referred to as gray bodies. By virtue of Kirchhoff's law we conclude that the fabricated structures have a thermal emission band narrower than the black body spectrum. The thermal emission obtained from the absorption spectrum for temperatures 300 and 500 K is shown in Fig. 4.

The peak emissivity mainly depends on the lattice constant, and our structures are optimized for efficient narrow-band thermal emission around 500 K since for this temperature the black body spectrum has a maximum

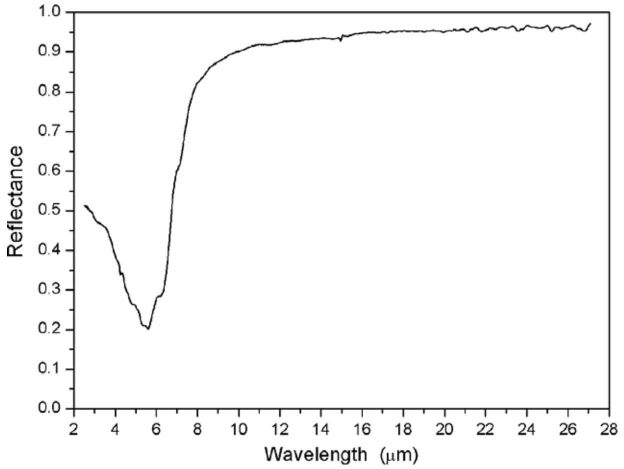

Fig. 3. Infrared reflectance spectrum of the structure shown in Fig. 1, the lattice constant is 5 μm the hole diameter is ~2.7 μm, with hole depth ~6 μm.

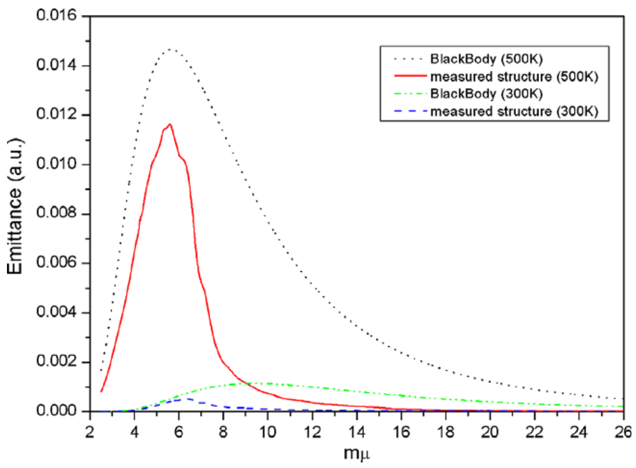

Fig. 4. Emmitance of the structures appearing in Fig. 1, which is obtained from the absorption appearing in Fig. 3 for two different temperatures, 300 K and 500 K. The ideal black body spectra are also shown for comparison.

around 6 μm. In principle optimizing the geometrical properties of the structures can lead to narrower absorption spectrum. Our results show that the hole depth is not a crucial factor if the holes in Si are not very shallow. Only small modification in the spectra was found (not shown) and the main features do not change much for holes deeper than 2.5 μm and up to 8 μm.

The size of the hole is a more important parameter and requires optimization. We have fabricated arrays with holes of different diameters keeping the same lattice constant. The dependence of the reflectance spectrum is shown in Fig. 5. Generally smaller holes lead to shallower reflectance minima moreover for larger holes reflectance drops further but the structures are less reflective for wavelengths away from the resonance, while the absorption band becomes broader. There is an optimum diameter around 3 μm in order to obtain high absorption in a narrow-band.

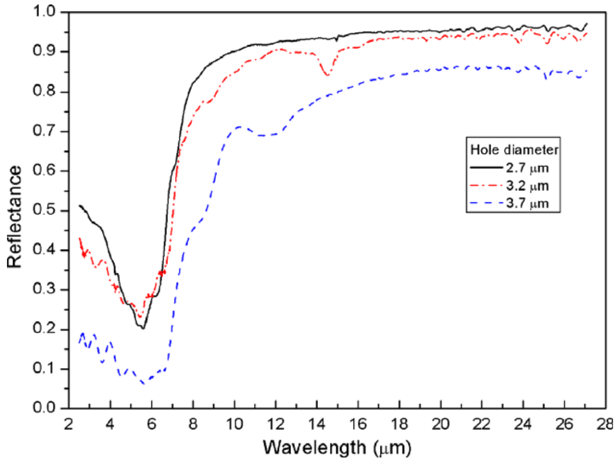

Fig. 5. Measured IR reflectance of a 100 nm, Al thin film patterned with a square array (lattice constant 5 μm) of holes with different diameters on top of a silicon substrate.

We have also studied the dependence of the reflectance spectra on the angle of incidence and only a small variation was observed.

Numerical electromagnetic simulations are currently under way in order to explain the optical properties and achieve more optimized structures. To clarify the role of the thin metal film we have prepared photonic crystals with holes on Si only, using the same geometry. The spectra are shown in Fig. 6, transmittance is small, around 20%, and drops at wavelengths just bellow the lattice constant (5 μm), simultaneously, the reflectance shows a minimum just above 5 μm. It is clear that the reflectance drop is not as abrupt as in the case of the metal-coated structures, moreover the metal makes the structure highly reflective for wavelengths larger than ~10 μm.

In conclusion we have fabricated a narrow-band IR emitter by introducing a periodic array of holes in Si coated with Al. The structure shows absorption in a narrow-band

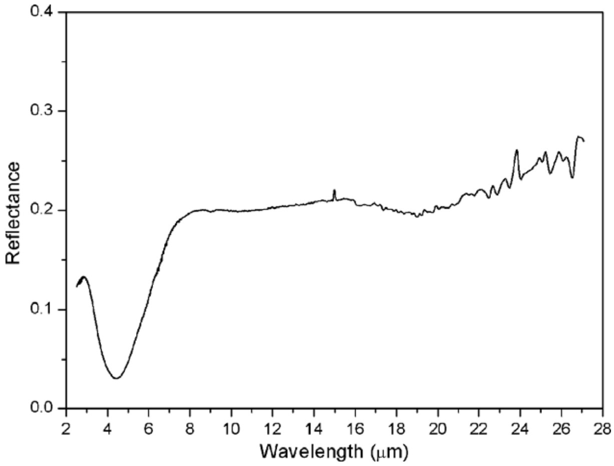

Fig. 6. Measured IR reflectance spectra for a Si photonic crystal with an array of 2D holes with lattice constant $a = 5$ μm and diameter ~3 μm.

for wavelengths close to the lattice constant of the periodic structure. Moreover the emission peaks are expected to scale to smaller wavelengths for smaller structures. We also note that the optical properties remain essentially unchanged for different metal films. We have replaced Al with Au and obtained similar IR spectra.

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