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was etched, using the metal as a mask. The structures have a narrow band absorption spectrum for wavelengths close to the lattice constant of the patterning. Both Al and Au films gave similar infrared response. Our results can be explained by multiple scattering electrodynamic simulations.

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1 Introduction The optical properties of periodic arrays of subwavelength holes on a thin metal film have attracted considerable attention since they show extraordinary transmission, higher than the one expected by normal diffraction [1, 2], for both optical and infrared (IR) frequencies. Additionally, the combination of such patterned thin metal films with photonic crystals can lead to a narrow band thermal emission at a wavelength near the lattice spacing, which differs significantly from the black body spectrum. According to Kirchhoff's radiation law the emission efficiency must equal the absorption efficiency, therefore efficient, narrow band, IR emitters should have narrow band absorption (A) which can be deduced following $A = 1 - R - T$ from reflectivity (R) and transmittance (T) measurements. These structures have interesting applications as thermal emitters for thermophotovoltaic applications but also as chemical sensors in the IR [3].

Extraordinary transmission was attributed to the excitation of surface plasmons which are essentially coupled excitations of the electromagnetic field with the conduction electrons of the metal. Surface plasmons lie outside the light cone and cannot be excited by an incoming electromagnetic wave. The dispersion relation of surface plasmons travelling on a flat metal-dielectric interface is given by:

$$k_{SP} = \frac{\omega}{c} \sqrt{\frac{\epsilon_{met} \epsilon_{diel}}{\epsilon_{met} + \epsilon_{diel}}} \quad (1)$$

The presence of a periodic corrugation like an array of holes modifies the dispersion. For a square array with lattice constant a the surface plasmon dispersion becomes

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

where $|\mathbf{k}_0| = \omega/c$ is the incident wave vector, θ is the angle of incidence, while m, n are integers denoting the scattering order from the array [2].

The thermal emission properties of materials can be modified by micro/nano patterning the surface. One dimensional photonic crystals like Si/SiO₂ multilayers were also used to achieve tuned IR emission, and are considered for possible applications as filters for thermophotovoltaic applications [4]. Directional thermal emission was also reported using SiO₂ subwavelength gratings and was attributed to surface phonon polariton excitation [5]. The aim of this work is to study the IR optical properties of patterned metal films on a Si photonic crystal fabricated with lithographic methods and compare with full electrodynamic simulations.

2 Experimental The photonic devices were fabricated on Si wafers by applying conventional silicon technologies. Square arrays of squares with a lattice constant of 5 μm were transferred in the photoresist with a lithographic mask. In practice, as is also seen in the scanning electron microscopy (SEM) micrographsm, we end up with rounded squares. After the lithographic process a thin, 100nm, metal (Au or Al) layer was sputtered. The layout transfer on the metal layer was accomplished by a lift-off step in acetone in ultrasonic bath revealing the metal 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. In Fig. 1 we present top-down and cross section representative SEM images of the final structures.

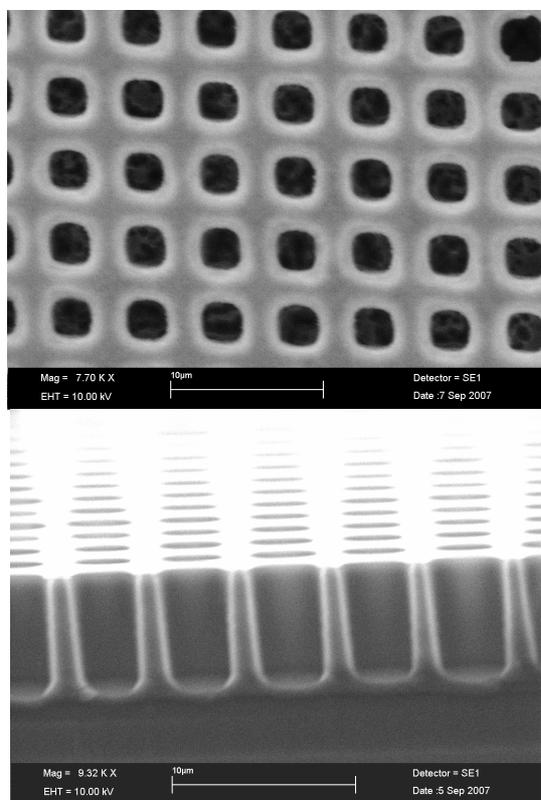


Figure 1 Top-down (upper panel) and cross section (lower panel) of the fabricated structures of periodic array of holes on a Si substrate with a thin metal film on top.

3 Results and discussion We used a Bruker Tensor 27 single beam FTIR spectrometer, reflectance of the fabricated structures was measured almost normal to the surface at an angle 11°. First we measured the infrared reflectance spectrum of a 2D array of holes in the 100 nm metal film on a uniform Si substrate. This was the intermediate structure after the lift-off, and before etching the holes into the Si substrate. Similar structures were demonstrated to show extraordinary transmission, however the absorption in the Si wafer reduces the effect. In Fig. 2a we

show the reflectance for a perforated Au film with holes of diameter $\sim 2.7 \mu\text{m}$ in a tetragonal lattice with lattice constant 5 μm . We observe small drops close to the Si/Au surface plasmon excitation wavelengths close to 17 μm and 13 μm . However the reflectance of the whole patterned wafer is high, around 75% and shows a slight increase for higher wavelengths.

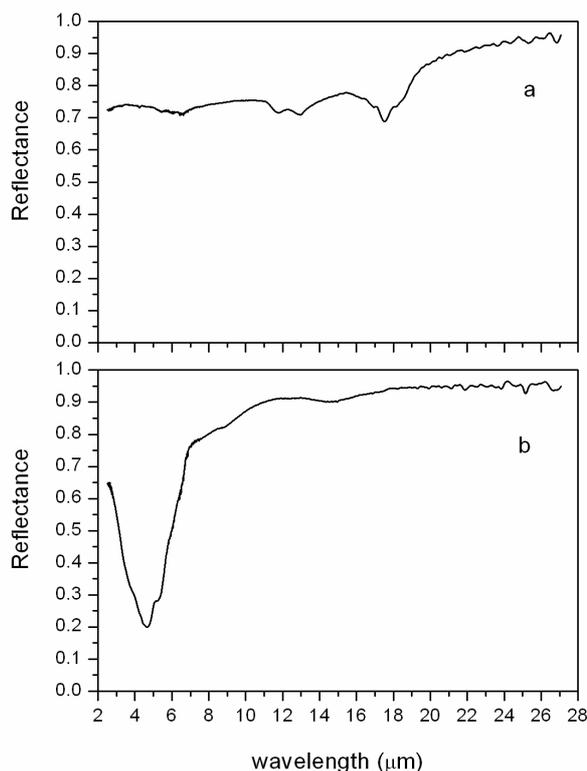


Figure 2 a) Reflectance spectra of a 100 nm Au thin film perforated with a square array of square holes of transverse dimension 2.7 μm , on a $\sim 380 \mu\text{m}$ Si substrate. The lattice constant is 5 μm . b) Reflectance spectrum of the same structure after Si was etched up to a depth of $\sim 5 \mu\text{m}$.

The perforated metallic films were etched using the Au as mask up to a depth of $\sim 5 \mu\text{m}$ the final structure is shown in the lower panel of Fig. 1. The infrared transmittance through the whole, patterned, 380 μm thick Si wafer is small, less than 1%, while the reflectance is shown in Fig. 2b. 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. The fabricated systems are expected to have a narrow band thermal emission spectrum, narrower than the black body spectrum. Emission will be more efficient for temperatures where the maximum of the black body spectrum coincides with the maximum absorption of the structure. This can be tuned for different temperatures by changing the geometrical parameters of the patterned films.

We have also studied structures with Au instead of Al as metallic coating. The reflectance spectra are shown in Fig. 3, apart from a small shift to lower wavelengths for Au compared to Al the spectra are very similar. Additionally recent work on similar structures using Pt metallic films gave similar results [3, 6]. This observation is important since different metals can be chosen depending on the application.

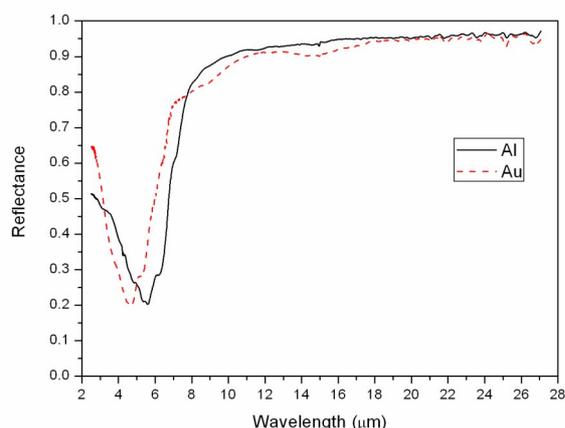


Figure 3 Reflectance spectra for the structures shown in Fig. 1 with a lattice constant $a = 5 \mu\text{m}$, hole diameter $\sim 2.7 \mu\text{m}$, and depth $\sim 5 \mu\text{m}$. The different spectra correspond to Al (full line) and Au (dashed line).

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 remain unchanged for holes deeper than $2.5 \mu\text{m}$. The diameter of the hole is a more important parameter and requires optimization. For larger holes reflectance drops further but it does not reach values close to one away from the resonance, additionally the absorption band becomes broader. For holes of smaller diameter, the reflectance drop is smaller. In order to gain more insight we have also performed full electrodynamic simulations.

4 Theoretical We used a multiple scattering method for the calculation of the optical response of the hole array. The present methodology is an extension of the method which was originally developed for spherical scatterers [7]. Spherical harmonic expansions of the field around each scatterer are used. In the current implementation the scattering T matrix of the non spherical particles (cylinders in this work) were calculated using the extended boundary condition approach. The scattering events are summed in each plane of periodic scatterers and the wave field is transformed in a plane wave representation. Here we should also note that the scattering events are summed up in real space in case of holes in the metal while the standard 2D Kambe sum is used for the layer of holes in Si.

Finally the scattering matrices of consecutive planes are combined to obtain the total solution. The details of the method can be found elsewhere [8]. The high aspect ratio of the fabricated structures causes convergence problems in the calculation. However our calculations show that scaling down the structures to smaller sizes up to $1.3\text{--}1.5 \mu\text{m}$, where the optical constants of Si remain almost constant, just causes a scaling of the spectra. Detailed calculations will be published elsewhere. For this reason we considered structures with smaller aspect ratio where convergence problems are less crucial, since the conclusions of the theoretical study are relevant and can be used to understand the optical properties of the fabricated structures. We considered a 300nm Au film with an array of cylindrical holes in a square lattice with lattice constant $1.5 \mu\text{m}$ on a $380 \mu\text{m}$ thick Si wafer. The hole depth was chosen $1.3 \mu\text{m}$ so that the hole pattern was transferred in the Si substrate. We used a constant dielectric function for silicon $\epsilon_{\text{Si}} = 11.9$ and tabulated data from the literature [9] for Au. Convergence was reached for an angular momentum expansion $\ell_{\text{max}} = 13$ and 137 plane waves, the scattering matrix for the non spherical objects (cylinders) required $\ell_{\text{cut}} = 20$ to achieve convergence [8].

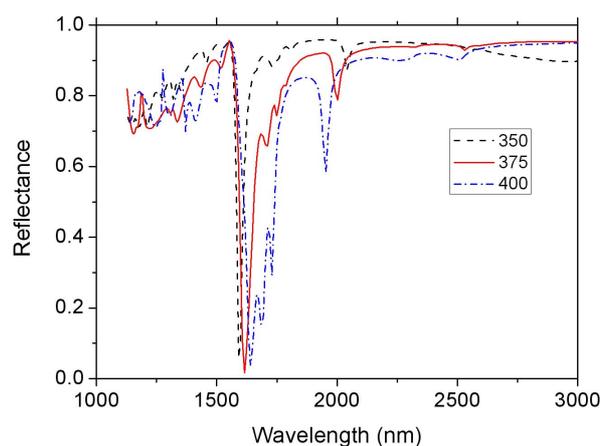


Figure 4 Calculated reflectance spectra for a tetragonal lattice of cylindrical holes in Si covered with a thin Au film. The lattice constant is $1.5 \mu\text{m}$, the hole depth $1.3 \mu\text{m}$ and the Au thickness 300nm . The three spectra are for different radii of the holes, dashed line 350nm , full line 375nm , and dash-dotted line 400nm .

We considered the influence of the hole diameter on the reflectance keeping all other parameters the same. The results are shown in Fig. 4. One important result is that the reflectance drop becomes narrower with reducing diameter of the holes, in accordance with the experimental results. For smaller diameters there is no reflectance drop. Moreover we also observe a smaller drop for higher wavelengths around $2 \mu\text{m}$ which becomes deeper for increasing hole diameters and also shifts to lower wavelengths. This

is due to a surface plasmon excitation between the metal and an effective medium of Si with holes.

5 Conclusion In conclusion we studied both experimentally and theoretically a narrow band IR emitter by introducing a periodic array of holes in Si coated with Au or Al. The structure is highly reflective and shows absorption in a narrow band for wavelengths close to the lattice constant of the periodic structure. Our simulations show that the width of the absorption band can be tailored by controlling the size of the holes.

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References

- [1] T.W. Ebbesen, H.J. Lezec, H.F. Ghaemi, T. Thio, and P.A. Wolff, *Nature* **391**, 667 (1998),
- [2] W.L. Barnes, A. Dereux, and T.W. Ebbesen, *Nature* **424**, 824 (2003),
- [3] R. Biswas, C.G. Ding, I. Puscasu, M. Pralle, M. McNeal, J. Daly, A. Greenwald, and E. Johnson, *Phys. Rev. B* **74**, 045107 (2006).
- [4] F. O’Sullivan et al., *J. Appl. Phys.* **97**, 033529 (2005); D. L.C. Chan et al., *Phys. Rev. E* **74**, 016609 (2006).
- [5] N. Dahan, A. Niv, G. Biener, V. Kleiner, and E. Hasman, *Appl. Phys. Lett.* **86**, 191102 (2005).
- [6] I. Puscasu, M. Pralle, M. McNeal, J. Daly, A. Greenwald, E. Johnson, R. Biswas, and C.G. Ding, *J. Appl. Phys.* **98**, 013531 (2005).
- [7] N. Stefanou, V. Yannopapas, and A. Modinos, *Comp. Phys. Commun.* **132**, 189 (2000).
- [8] G. Gantzounis and N. Stefanou, *Phys. Rev. B* **73**, 035115 (2006).
- [9] E.D. Palik (Ed.), *Handbook of Optical Constants of Solids* (Academic Press, 1998).