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Strong terahertz absorption using SiO_2/Al based metamaterial structures

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Metamaterial absorbers with nearly 100% absorption in the terahertz (THz) spectral band have been designed and fabricated using a periodic array of aluminum (Al) squares and an Al ground plane separated by a thin silicon dioxide (SiO_2) dielectric film. The entire structure is less than 1.6 mm thick making it suitable for the fabrication of microbolometers or bi-material sensors for THz imaging. Films with different dielectric layer thicknesses exhibited resonant absorption at 4.1, 4.2, and 4.5 THz with strengths of 98%, 95%, and 88%, respectively. The measured absorption spectra are in good agreement with simulations using finite element modeling. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3693407]

Terahertz (THz) imaging has gained increased attention because of its many distinctive properties, which makes it attractive for security and medical applications.[1] Despite the availability of some terahertz sources and detectors, highly sensitive THz imaging systems are still restricted to the research domain. THz imaging has been demonstrated using conventional, microbolometer-based imagers optimized for infrared (IR) wavelengths (8-12 μm) paired with an external THz illumination source.[2,3] Potential limitations of this approach are the low sensitivity in the THz region of microbolometer cameras optimized for IR imaging and the relatively low output power of commonly available THz sources such as quantum cascade lasers (QCLs). Bi-material based uncooled infrared imaging technology[4,5] is another possible candidate for THz imaging using the same principle as microbolometers, but it suffers the same limitations in performance.[6] In both cases, the absorbed energy heats the sensing element, changing its resistance in case of microbolometers and deforming its structure in case of bimaterial sensors. To increase the sensitivity of these devices, it is necessary to modify the pixel membrane structure with layers with high THz absorption, without compromising the thermal proprieties of the sensors.[6] Thus, relatively thin (less than 2 μm) THz absorbing membranes are required, ideally with absorption tuned to the QCL illuminator frequency. One approach is to replace the pixel membrane with a metamaterial structure, tuned to the QCL frequency, to achieve resonant absorption and, thus, high sensitivity. One constraint is that the materials used should have structural and thermal properties compatible with fabrication of microelectromechanical system (MEMS) based bi-material sensor pixels.[5] Several groups have reported the fabrication and analysis of metamaterial structures operating in THz spectral band using a variety of configurations including resonant elements and periodic arrays of metallic squares and rings.[1,7–11] The common theme was to place a capacitive mesh close to a conducting plane with a dielectric spacer in between to form an artificial structure that exhibits electromagnetic properties such that its impedance matches with the surrounding media (free space in our case) at a specific frequency.[12] In this situation, ideally, there is no transmission and no reflection resulting in total absorption. By controlling shape, thickness, and properties of metallic and dielectric layers, it is possible to tune the frequency and absorption amplitude of the resonance. This concept was employed to tune absorption characteristics of microbolometers working in the IR range.[13] High absorption in THz range and even multiband capabilities have been achieved with thicker polyimide and SiO_2 dielectric layers.[8,14]

In this letter, we report the design and fabrication of highly absorbent, thin metamaterial structures (less than 1.6 μm thick), using SiO_2 and Al. The favorable combination of thermal, mechanical, and optical properties of SiO_2 and Al[6] make them highly suitable to build membrane structures with high absorption as well as large bi-material deflection. The metamaterial structures are comprised of an array of Al squares separated from an Al ground plane by a SiO_2 layer as schematically illustrated in Fig. 1(a). Each Al layer is about 100 nm thick, and the thickness of the SiO_2 layer is varied from 1 to 1.4 μm. The entire structure was grown on a high resistivity Si wafer for testing purposes. They were designed to absorb frequencies in the 4–4.5 THz spectral region to take advantage of the availability of high power QCLs in this frequency range.[3] The absorption characteristics of the structures were simulated with 3D finite element modeling using COMSOL multiphysics software. Due to the periodicity of the metamaterial structures, a unit cell as schematically shown in Fig. 1(a) was used in the simulation. The field distribution is calculated for a normally incident plane wave polarized along one of the edges of the square and perfect electric and perfect magnetic boundary conditions. The reflection spectrum of 1 W incident power is calculated by integrating the power flow on the layer boundary, while transmission is considered to be zero since the ground plane thickness is greater than the skin depth of aluminum in this range of frequencies (80 nm for aluminum at 4 THz). The index of refraction of SiO_2 at THz frequencies was taken from[15,16] as $2.0 + 0.025i$ and conductivity of 1×10^7 S/m was used for Al.

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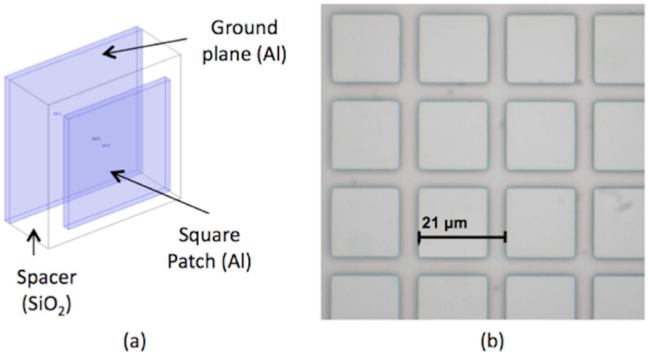

FIG. 1. (Color online) (a) Simulated metamaterial unit cell: the square patch and ground plane are aluminum 100 nm thick and the dielectric spacer is 1–1.4 mm thick SiO_2; (b) Scanning electron micrographs of the fabricated metamaterial absorber.

Three samples were fabricated using standard microfabrication techniques. Al ground planes, 95 nm thick, were deposited using e-beam evaporation. Dielectric SiO_2 films of 1430 nm, 1235 nm, and 1035 nm thick were deposited using plasma enhanced chemical vapor deposition (PECVD) for samples A, B, and C, respectively. The dielectric film deposition was followed by e-beam deposition of another layer of Al film, 95 nm thick. Finally, square arrays were patterned, using wet etching, on the top Al layer with sides 16.3 μm, 16.5 μm, and 15.3 μm for samples A, B, and C, respectively. The periodicity of the squares is 21 μm for all of the samples. Actual dimensions of the squares and periodicity of the samples were measured using optical microscopy. Note that the variation of the squares dimensions was obtained by varying the time in the etchant. The thicknesses of the layers were measured using conventional stylus profilometry.

The three samples were characterized using a Fourier transform infrared spectrometer (FTIR) extended to THz range. The reflectance spectra were measured with FTIR beam incident at 30° from the normal of the absorber arrays. The details of the measurement can be found in Ref. 17. Figure 2 shows the measured reflection spectra of the three samples.

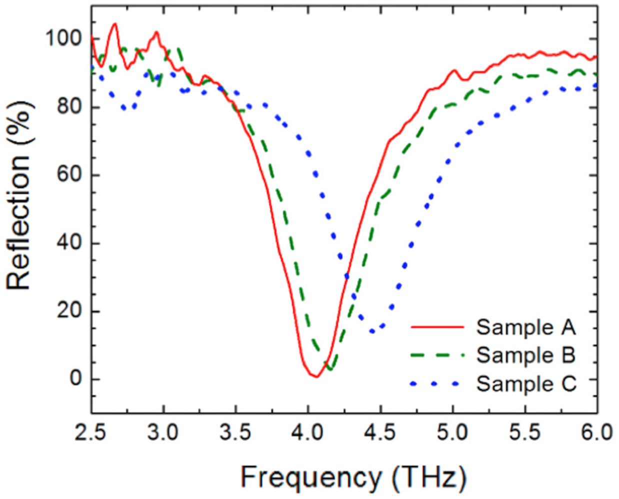

FIG. 2. (Color online) FTIR measurement of the reflection spectra for sample A (solid), sample B (dashed), and sample C (dotted) and simulated absorption spectra of the fabricated films A, B, and C.

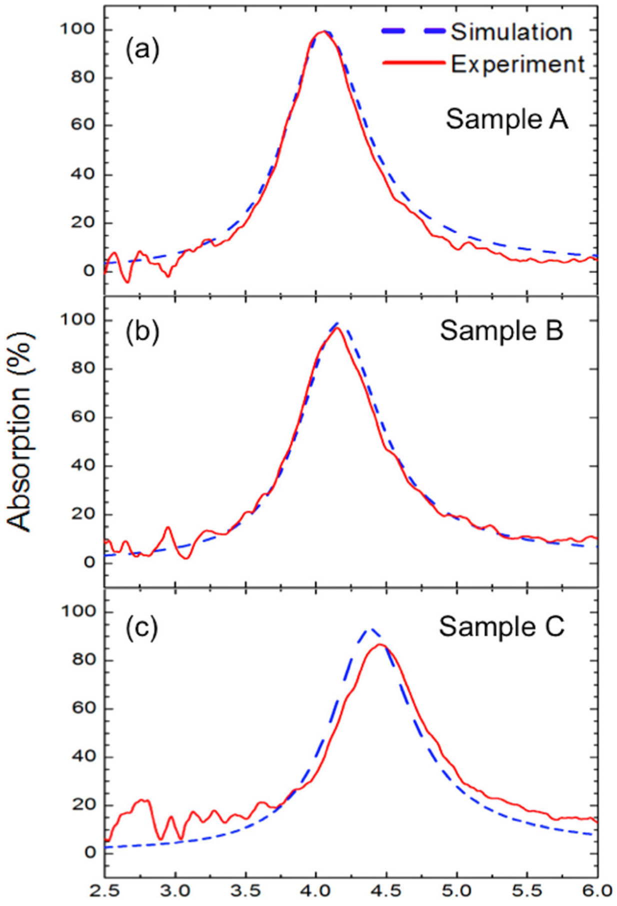

FIG. 3. (Color online) Experimental (solid line) and simulated (dashed line) absorption spectra of the fabricated films A, B, and C.

Reflection minima of 2%, 5%, and 12% were found at the frequencies of 4.1, 4.2, and 4.5 THz for samples A, B, and C, respectively. The absorption spectrum of each sample was obtained by evaluating (100 – T – R), where T is the transmission coefficient (zero in this case) and R is the reflection coefficient. Figure 3 shows the estimated absorption of each sample compared to the simulations. There were no adjustable parameters used in the simulations except the use of actual dimensions and corresponding material parameters. The close agreement between the measured and simulated spectra validates the accuracy of the simulation. The measurements indicate that small squares with a thicker dielectric layer give resonances at higher frequencies. This is expected since the combination of a small area and a thicker dielectric layer reduces the unit cell capacitance resulting in increase of the resonance frequency.[1]

The overall results show that relatively simple metamaterial structures can be fabricated using standard MEMS and microelectronics materials such as SiO_2 and Al and achieve nearly 100% absorption at a targeted frequency. Moreover, the high degree of accuracy of the simulation indicates that it is possible to design metamaterial structures tuned to the available QCL sources. In addition to the location of the resonance peak, its magnitude was determined by the parameters of the metamaterial structure. The thinner dielectric films tend to reduce the absorption as seen in the measured data in Fig. 3(c). In order to determine the effect of thinner layers on absorption, the structure in sample A was simulated

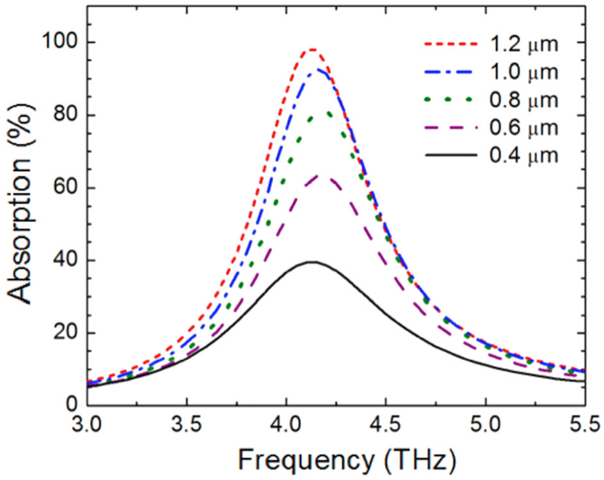

FIG. 4. (Color online) Finite element simulations (sample A) with dielectric thickness from 0.6 μm to 1.2 mm.

with various SiO_2 layer thicknesses ranging from 1.2 μm down to 0.4 μm while keeping the rest of the dimensions the same. It is clear from Fig. 4 that the strength of the absorption decreases rapidly as the thickness of the SiO_2 layer is reduced. This is primarily due to an increase in impedance mismatch between the air and the structure resulting in higher reflection.[13] Note that a slight blue shift of the absorption spectra was observed for thicker dielectric layers due to the decrease in capacitance. Simulations with the thickness of the dielectric layer beyond 1.4 μm were also found to decrease absorption. A good description of this behavior is given by Chen *et al.*[18]

In conclusion, thin metamaterial structures were fabricated using MEMS compatible SiO_2 and Al layers for applications in bi-material THz sensors.[19,20] The fabricated films showed the possibility of achieving nearly 100% absorption by controlling the thickness of the dielectric layer and size of the squares. The measured THz absorption spectra showed good agreement with that of the simulations indicating the accuracy of the finite element models developed. Tunability of the response was also demonstrated by controlling the dimensions of the metamaterial structure. The small thickness and high absorption coefficient of these films make them very suitable for integration into bi-material and microbolometer focal plane arrays as absorbing layers for achieving high sensitivity THz imaging.

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