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Abstract: A conductive layer of Ti, with a sheet resistance of about 220 Ω sq, was placed in the dielectric spacer of an Al/SiOx/Al metamaterial terahertz absorber at various depths to probe the effect on the absorption of terahertz radiation. For a square size of 15 µm and a periodicity of 21 µm, and dielectric thickness approximately 1.6 µm, maximum absorption was 60%, 88%, and 94% for Ti layers 297, 765, and 1270 nm deep into the SiOx. Finite element simulations of the absorption correlated well with that of the measurements. This indicates that metamaterials with an embedded high temperature coefficient of resistance (TCR) conducting layer can be used for fabrication of microbolometers with tuned spectral sensitivity.

OCIS codes: (040.2235) Far infrared or terahertz; (160.3918) Metamaterials; (310.3915) Metallic, opaque, and absorbing coatings.

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1. Introduction

In recent years, there has been a surge of renewed interest in the terahertz (THz), or far infrared, spectral range. The ability of THz radiation to penetrate dry, nonpolar, low conductivity materials (such as common packaging materials and clothing) makes it a promising candidate for applications such as quality control of food [1], cultural heritage conservation [2], security screening [3], and medical imaging [4,5]. As THz radiation does not penetrate very deep into skin and is nonionizing, it is less harmful and thus potentially safer than X-ray imaging technologies [6]. Detection in the THz range is challenging due to the low photon energy necessitating excessive cooling for optical schemes and the high frequency significantly reducing the effectiveness of electronic schemes; these issues create the well-known ‘Terahertz gap’ [7]. Thermal detectors, such as microbolometers, do not suffer from these difficulties and are thus well suited to THz detection. The THz spectral content in 300 K thermal background is much smaller than higher frequency infrared (IR) radiation; therefore, uncooled imaging systems in the 1-10 THz spectral range typically require an external illumination source [1–5,8–10]. One potential drawback of uncooled microbolometer imaging technology developed for 10 µm IR radiation is that the silicon nitride microbridge is not optimized for high THz absorption [11,12]. Therefore, improving this absorption without adversely affecting other aspects of the sensor would significantly enhance performance.

To achieve high performance in the THz spectral range, it is necessary to consider two significant parameters of thermal detectors, the thermal time constant ($\tau$) and responsivity ($R_{th}$). All thermal detectors rely on a thermally isolated sensitive region which disperses heat to the environment through radiation, convection, and conduction. If the losses can be approximated as linear with respect to the temperature gradient between the thermally isolated sensitive area and the surrounding environment, they can be lumped into a single constant term called the thermal conductance ($G_{th}$). We can then arrive at a formula for the responsivity of a detector under sinusoidal illumination power as [13]:

$$R_{th} = \frac{dT}{P_0} = \frac{\eta}{G_{th} \sqrt{1 + \omega^2 \tau^2}}$$

(1)

where $\eta$ is the absorbance, the fraction of incident power ($P_0$) absorbed by the sensitive region of the detector, and $\omega$ is the modulation frequency of the incident radiation. Typically, thermal detectors operate in a frequency range where $\omega \tau \ll 1$ and the responsivity can be maximized by increasing $\eta$ and reducing $G_{th}$ based on Eq. (1). Practically, minimizing $G_{th}$ is limited by the radiation loss of heat and the size of the legs that connect the sensor to the heat sink. In addition, reducing the thermal capacitance ($C_{th}$) of the sensor (primarily due to the thermal mass of the absorber) is very important for attaining real-time imaging performance by reducing thermal time constant $\tau = C_{th}/G_{th}$. Thus, it is important to make the THz-absorbing layer as thin as possible. This works against improving absorption by simply increasing the thickness of the nitride layer in present microbolometer pixels, given its already poor absorption at THz frequencies.

One possible solution to increase absorption without an appreciable increase in thermal capacitance is using metamaterial absorbing films. These films exhibit optical properties not found in their constituent materials [14]. Of particular interest for THz thermal sensors is the fact that they can absorb nearly 100% of the incident radiation near a tunable resonant frequency, resulting in a very efficient absorbing membrane to be used with narrowband
illumination sources (such as THz-QCLs) [15,16]. Additionally, these metamaterial films can be constructed from materials already used in microbolometer fabrication due to the fact that the absorption characteristics are primarily controlled through the metamaterial geometry rather than the constituent materials. Although not the only possible configuration [14], a periodic array of metal squares, separated from a metal ground plane by a dielectric spacer, can accomplish this in the THz range with fabrication-friendly materials and relatively small dielectric thickness [15]. In addition to THz absorption, the metamaterial absorber should also contain a layer with a high temperature coefficient of resistance (TCR) for measuring temperature change due to the absorption. This layer should not appreciably interfere with the metamaterial absorption mechanism. There are reports on the use of metamaterial absorbers with an integrated TCR layer operating in the infrared wavelengths [17,18]. These approaches include either a metamaterial structure built on the bolometric layer with a dielectric spacer [17] or embedding the bolometric layer within the dielectric of the metamaterial layer and placing the ground plane on the substrate with an air cavity [18]. However, when these approaches extend to THz spectral range, the entire structure becomes relatively thick. This affects the thermal time constant or, in the case of placing the ground plane on the substrate, could reduce the absorption within the membrane [15,16]. Additionally, one could simply attempt to use the bolometric layer as the ground plane of the metamaterial, however, the high resistivity of such materials negatively affects the absorption. In this paper, we experimentally probe the effect of the TCR layer position within the dielectric of the metamaterial on THz absorption.

![Fig. 1. Schematic (a) and top view micrograph (b) of a metamaterial absorber with a bolometric layer embedded in the dielectric. The square size and pitch were selected to have an absorption peak within the 1-10 THz band.](image)

2. Fabrication and measurement

The approach used in this work involves a metamaterial structure with a bolometric layer embedded in the dielectric layer as schematically illustrated in Fig. 1. The aim of the work is to determine the optimal location of the bolometric layer within the dielectric to achieve the highest possible THz absorption. Three wafers containing metamaterial absorbers with Ti as the bolometric layer located in the dielectric spacer at varying depths along with one without a bolometric layer were fabricated using standard MEMS microfabrication techniques, similar to those used in [15]. The fabrication sequence includes deposition of an 85 nm thick layer of Al on 4” Si substrates using e-beam evaporation. Following this, a layer of low stress nonstochiometric silicon-rich silicon oxide (SiOₓ) with different thicknesses was deposited using plasma enhanced chemical vapor deposition (PECVD). Wafers A-D possessed 1270 nm, 765 nm, 297 nm, and 1590 nm of SiOₓ, respectively, confirmed through optical interferometry. Then, a Ti layer was sputter deposited using Ar plasma onto wafers A-C and a Si test wafer with a SiNₓ isolation layer to measure conductivity. The measured thickness of
Ti was found to be about 10 nm and confirmed to have a sheet resistance of about 220 $\Omega$/sq, which corresponds to conductivity of $4.45 \times 10^5$ S/m. Following the deposition of Ti, an additional SiO$_x$ layer with thicknesses of 297 nm, 765 nm, and 1270 nm were deposited using PECVD on wafers A-C, respectively. This resulted in nearly equal total spacer thicknesses, including Ti layer, of 1577 nm, 1540 nm, 1577 nm, and 1590 nm for wafers A-D. A second 85 nm thick layer of Al was then deposited onto wafers A-D using e-beam evaporation and was then patterned using photolithography and sputter-etched with Ar plasma to form an array of squares as in [15], with the absorption characteristics of the 15 $\mu$m side and 21 $\mu$m pitch configuration shown here. Square size mainly influences the resonant absorption frequency, while dielectric thickness and periodicity strongly affects absorption magnitude [15]. This particular configuration was chosen for its resonant frequency in the 1-10 THz range, and other configurations with varying resonant frequencies can be found in [15]. All wafers were intentionally overetched approximately 150 nm into the SiO$_x$ to assure complete insulation between square elements. The composition of layers of wafers A-D are summarized in Table 1. To determine the optical properties of these metamaterial absorbing layers in the THz spectral range, reflection measurements were taken using a Thermo-Nicolet Nexus 870 Fourier Transform Infrared Spectrometer (FTIR) with a globar source and PIKE Technologies MappIR accessory. An Au-coated Si wafer was used to establish the background for the reflectance measurements. The two 85 nm thick Al layers block any significant transmission due to the 40 nm skin depth at around 4.7 THz, resulting in over two orders of magnitude reduction of power due to exponential attenuation. The periodicities used are less than one third of the free space wavelength [15], resulting in negligible higher order scattering [19].

This allows $A + T + R = 1$ to be simplified to $A = 1 - R$. The resulting absorption spectra for samples A-C are plotted in Fig. 2(a).

| Wafer | Top SiO$_x$ | Bottom SiO$_x$ | Total Spacer | Max. Absorption |
|-------|-------------|----------------|--------------|----------------|
| A     | 297         | 1270           | 1577         | 62%            |
| B     | 765         | 765            | 1540         | 88%            |
| C     | 1270        | 297            | 1577         | 94%            |
| D     | —           | —              | 1590         | 98%            |

3. Discussion

It is clear that in Fig. 2(a), as the Ti conductive layer gets closer to the patterned top Al layer, the THz absorption of the metamaterials is reduced and slightly red shifted. This is expected conceptually as the Ti layer would function as a poor ground plane if the lower SiO$_x$ and Al layers were removed. The redshift in the resonant absorption frequency is larger than the frequency shifts observed in [15] for thinner dielectric thicknesses, suggesting that a simple reduction of dielectric thicknesses will not explain these absorption spectra. To model the THz absorption characteristics of the metamaterial film with an embedded bolometric layer, finite element (FE) simulations were performed using the RF module of COMSOL multiphysics software explained in greater detail in [15].
Fig. 2. (a) Experimental (solid) and FE model (dashed) absorption spectra for samples A (black), B (red), and C (green). (b) Theoretical absorption curves for sample A for a set of sheet resistivities in the bolometric layer. Square size is 15 μm with 21 μm periodicity for both plots.

The periodic geometry of the metamaterial absorbing film allows for a single unit cell to be modeled with periodic boundary conditions. Internal ports or scattering boundary conditions allow incoming plane waves at specific frequencies to enter the model. The THz absorption can be calculated by subtracting off reflection and transmission coefficients calculated from the S parameters. Alternatively, resistive heating can be used to calculate absorption. This method is especially useful for calculating the absorption of elements that are not thermally linked, such as a ground plane disconnected from a bolometer microbridge. The aluminum layers were modeled using a conductivity of $1 \times 10^7$ S/m, confirmed through four-point probe and stylus profilometer measurements. SiO$_x$ was modeled as a dielectric with a complex index of refraction of $1.95 + 0.025i$, adjusted from the SiO$_2$ values used in [15] based on the experimental results therein. Ti was modeled as having a sheet resistance of 220 Ω/sq based on four-point probe measurements. The exact thickness of the Ti is irrelevant as long as the sheet resistance is well known [20] and was estimated as 10 nm from previous depositions. As in [15], the overetching of SiO$_x$ is included in the models, producing a slight blue shift in the resonant absorption frequency due to an effectively smaller index of refraction. Figure 2(a) shows the comparison of simulated and measured data for the three samples. The simulated data is able to capture the effect of the location of Ti layer on the absorption reasonably well. E-field magnitude plots for these simulations are shown in Fig. 3, all using the same color scale for E-field intensity. It is clear that the E-fields do penetrate the Ti layer but not the ground plane in all cases, and that the Ti is indeed acting as a poor ground plane. The E-fields also become less intense as the Ti layer nears the square array, indicating that it is negatively affecting the resonance. In addition, absorption of sample A is also simulated for a set of conductivities of the bolometric layer as shown in Fig. 2(b). It can be seen that, if the conductivity of this layer is reduced, the influence of the layer on the absorption of the metamaterial decreases, as expected. Since typical high TCR bolometric layers have sheet resistances in the kΩ range, we should expect that a spacer of 300 nm of SiO$_x$ between the bolometric layer and the patterned Al layer will be sufficient for achieving high THz absorption. The results indicate that the two most important parameters that affect the absorption peak height are the conductivity and position of the bolometric layer between the patterned Al layer and ground plane of the metamaterial. Therefore, if these metamaterials are to be incorporated into a microbolometer pixel, we have to determine the location of the high temperature coefficient of resistance (TCR) bolometric layer within it. Fortunately, the high resistivity of most practical continuous bolometric layers should render them relatively easy to integrate, from an optical point of view, into a THz metamaterial absorber. The data in
Fig. 3. E-field magnitude plots from COMSOL FE simulations at 4.7 THz for samples A (a), B (b), and C (c). All plots use the same color scale, with warmer colors indicating more intense E-fields. Material types of different regions are labeled in (a). E-field, H-field, and propagation vectors of the incident THz waves are shown on (b).

Fig. 2 also seems to show that within the range of parameters used, there is some equivalence in the effects of sheet resistance and position of a thin bolometric layer on the absorption spectrum. Qualitatively, less conductive layers should allow for greater penetration of E-fields and thus more of the desirable resonance between the square array and the ground plane. Also, a high conductivity layer near the ground plane or a low conductivity layer near the square array should both converge to the original absorption spectrum.

4. Conclusion

We fabricated THz-absorbing Al/SiOx/Al metamaterial layers with a thin Ti conductive layer inserted into the dielectric spacer to be used as bolometric layer. The introduction of Ti reduced the magnitude of the absorption peak strongly when placed near the patterned Al layer in addition to a small redshift. The measured absorption spectra are in reasonably good agreement with those of the simulations. The results indicate that the bolometric layer should be placed near the ground plane for achieving maximum absorption. The simulations of the effects of the conductivity of the bolometric layer on absorption reveal weak sensitivity to its position when the sheet resistance of the bolometric layer exceeds about 1 kΩ/sq.

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