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CMOS-compatible fabrication of metamaterial-based absorbers for the mid-IR spectral range

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Abstract. A CMOS-compatible approach is presented for the fabrication of a wideband mid-IR metamaterial-based absorber on top of a Si_3N_4 membrane, which contains poly-Si thermopiles. The application is in IR microspectrometers that are intended for implementation in portable microsystem for use in absorption spectroscopy. Although Au is the conventional material of choice, we demonstrate by simulation that near-perfect absorption can be achieved over a wider band when using the more CMOS-compatible Al. The absorber design is based on Al disk resonators and an Al backplane, which are separated by a SiO_2 layer. The fabrication process involves the deposition of Al and SiO_2 layers on top of a Si_3N_4 membrane, lithography and a lift-off process for patterning of the top Al layer.

1. Introduction

Since the introduction of metamaterial-based absorbers in 2008 by Landy *et al.* [1], these structures have been adapted to serve a wide variety of practical applications; including selective thermal emitters [2], wavelength-tunable microbolometers [3], refractive index sensing [4] and microspectrometers [5]. The typical structure of the metamaterial absorber consists of arrays of patterned metallic sub-wavelength structures on top of a dielectric spacer, which is backed by a thick metallic ground plane. The top periodic structure is responsible for the electrical response of the metamaterial absorber. The metallic backplane is thicker than the penetration depth of the incident wave to prevent any transmission. The coupling of two metallic layers results in the magnetic response. Therefore, by selecting the proper geometrical parameters, the effective permittivity ε and permeability μ can be tuned independently, resulting in impedance matching to the free space. Practical structures have been presented that exhibit near-perfect absorption of the incident wave a in certain frequency band can be obtained from microwaves [6], terahertz frequencies [7], the infrared spectral range [5] to the visible spectrum [8].

The essential characteristic of a structure that is to be used as a metamaterial is its sub-wavelength feature size. Consequently, metamaterials designed for microwave frequency range are relatively large and impose no significant requirenenst on the lithography. However for the fabrication of metamaterials operating in the infrared and visible ranges, techniques such as e-beam lithography or focused ion beam (FIB) methods should be used. These methods are capable of making structures with sizes that are in the order of tens of nanometers. However, unlike mask-based photolithography, these methods 'write' the pattern in a point-by-point serial process, which is a significant throughput problem in the fabrication of large-area metamaterials, as required in an absorber. In the part of the mid-IR spectrum that is suitable for absorption spectroscopy on combustible hydrocarbon gas (3-4 μm), the typical feature size of the metamaterial is just within the realms of a conventional lithography system. Such an approach is pursued here; however, the specifications in terms of resolution and step size of such a system on the performance of the metamaterials need to be investigated.

In this paper the fabrication process for a CMOS-compatible wideband metamaterial absorber on top of a Si_3N_4 membrane is presented. The application is the MEMS-based microspectrometer that was already reported in [5]. Three compatibility issues are addressed. The first is the choice of materials. Although Au is the conventional material of choice, near-perfect absorption can be achieved over a wider band when using the more CMOS-compatible Al. The second issue is the dimensions. The absorber design is based on four Al disk resonators in a sub-wavelength unit cell with dimensions in the 500-600 nm range. The third issue is the effect of the limitations of the lithography and other process tolerances on the absorber spectral performance. The fabrication process involves Al and SiO_2. The effects of the lithography and fabrication tolerances, such as the variation in the thickness of deposited dielectric layer, have been investigated using FDTD analysis. Based on the results of these investigations, a fabrication process for wideband absorbers is presented using masked lithography and a lift-off process for patterning of the top Al layer.

2. CMOS-compatibility

Most of the reported metamaterial absorber structures are based on Au, because of its higher electrical conductivity. Higher conductivity of Au results in stronger localized surface plasmon resonance (LSPR) and consequently in stronger magnetic resonance [5]. However, Au is poorly CMOS-compatible. Recently, we have proposed an IR metamaterial absorber using Al circular disks [5]. The FDTD analysis showed that a wide band absorption can be achieved using multiple disk resonators. Figure 1(a) shows the metal-dielectric-metal structure with a circular disk, while Figure 1(b) shows the comparison between the absorption peaks for with Al and Au with an identical geometry. Despite the higher loss of Al in the mid-IR range as compared to Au, the absorption peaks are spectrally shifted but almost identical shape, demonstrating that a near-perfect absorption can also be achieved when using the more CMOS-compatible Al as the plasmonic material.

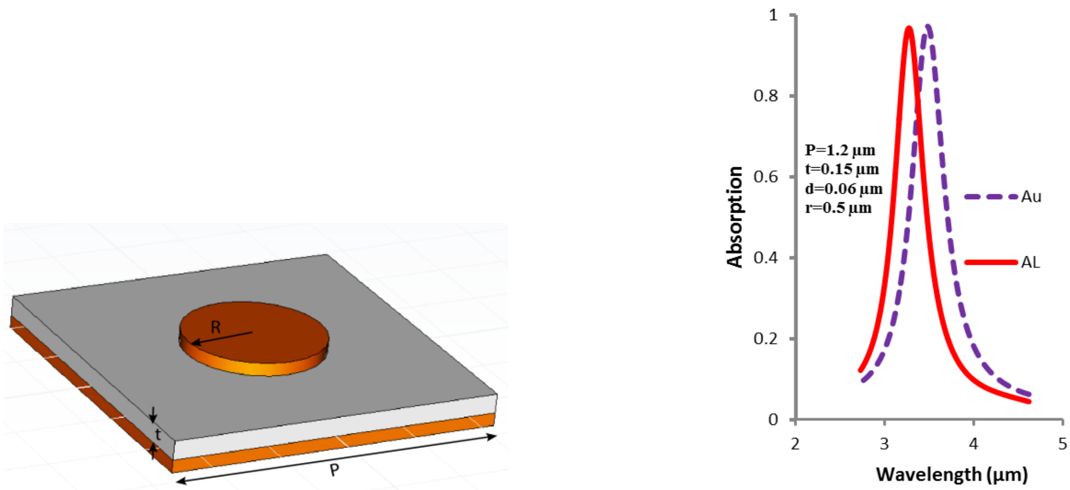

Figure 1. (a) Unit cell of metal-dielectric-metal with a single resonator. (b) Absorption peak for an identical single-resonator absorber when using two different metals; Al and Au.

2. Device operation and tolerances

Arranging differently sized Al disk resonators in a single unit cell results in a broadband absorption spectrum, if the different disks are tuned to different parts of the spectrum to be absorbed in such a way that the spectra do overlap. A design is presented here with four differently sized Al disks in one unit cell of the structure, as presented in Figure 2 (a). Wideband operation over the spectral range can be achieved by staggered tuning of four Al disk resonators in one 1.5 × 1.5 μm^2 unit cell. By using different values for the radius for the Al disks, between 0.50 µm and 0.63 µm, and tuning the thickness of the SiO_2 spacer (150 nm, in this design) wideband absorption over the 3-4 µm range was obtained (Figure 2). The simulations reveal an average absorption of about 95% with a ±4% ripple at normal incidence.

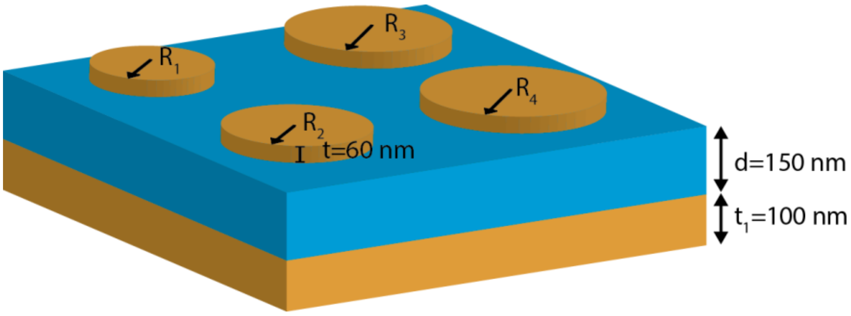

Figure 2. (a) The unit cell schematic of the multi-resonator (wideband) absorber. Periodicity (p) =1.5 µm. R_1=500 nm, R_2=540 nm, R_3=580 nm, R_4=630 nm

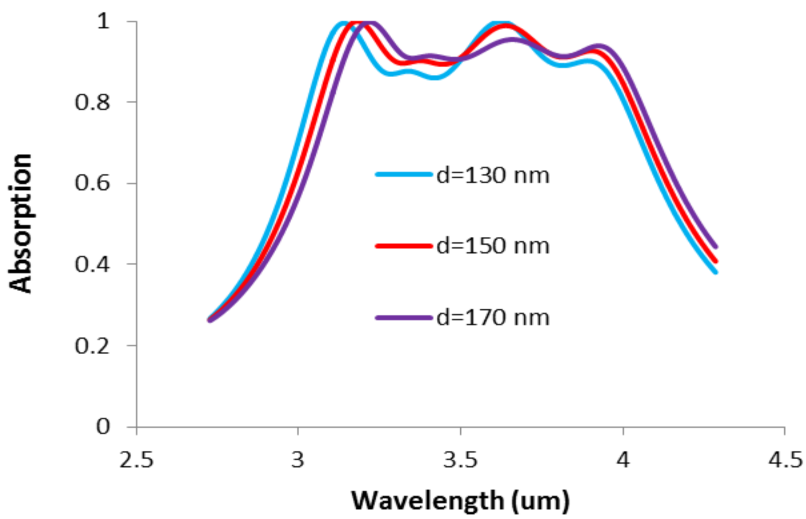

Figure 2. (b) Simulated absorption spectra of the multi-resonance absorber with dielectric thickness (d)=150 nm and ±20 nm tolerance.

The tolerances in the thickness of the deposited SiO_2 could affect the absorber performance. Simulation results when considering a ±20 nm variation in the dielectric layer thickness are shown in Figure 2 (b). This result demonstrates that the spectral performance of absorber is not significantly affected.

The resolution of the e-beam lithography is in order of less than ten nanometers and would enable the precise definition of the Al disks in the 500-600 nm range. Therefore, e-beam has been used for the fabrication of reference structures, but the limitations of masked lithography for fabrication are also considered. Figure 3, shows the spectral performance in case of: octagonal structures, inner squares (inscribed polygon) and outer squares (circumscribed polygon), as compared to circular structures. This result confirms that the metamaterial is actually rather robust for deviations from the circular shape of the top structures. This can be explained by the magnetic plasmonic resonance mechanism of the absorption. The length or diameter of the top metallic pattern determines the resonance frequency, because it defines the LSPR. The results indicate a limited susceptibility to shape deformation. The resonance wavelengths vary within the band, but the wideband absorption remains acceptable. It should be noted that the inner square design is basically tuned to a significantly shorter plasmonic resonance wavelength.

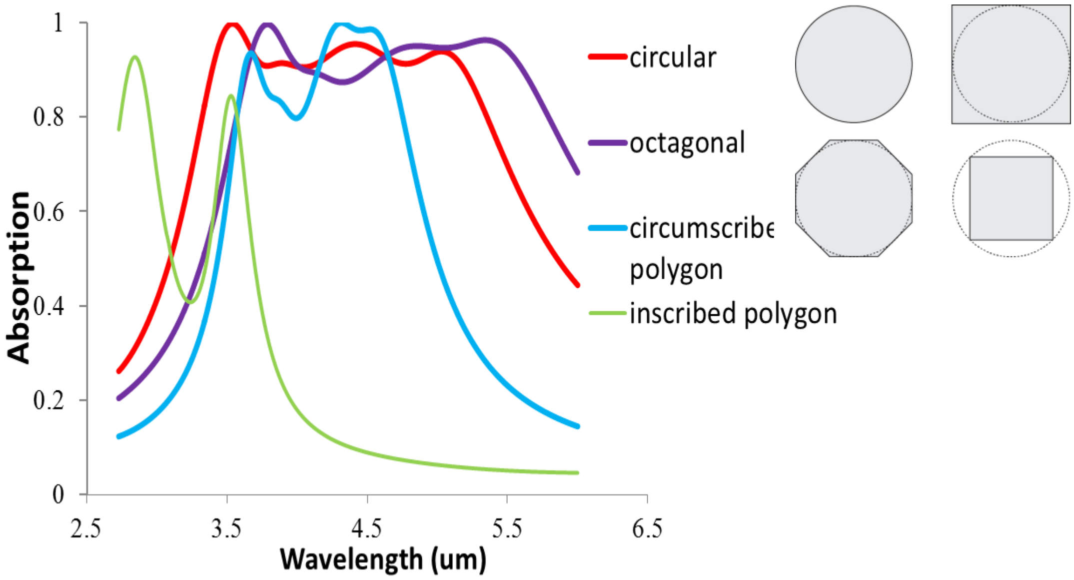

Figure 3. Simulated absorption spectra for different metallic patterns. The various shapes are shown in the inset.

3. Device Fabrication

This absorber is intended for use in combination with polysilicon thermopile based detector arrays fabricated on Si_3N_4 freestanding membranes as shown in Figure 4 [9].

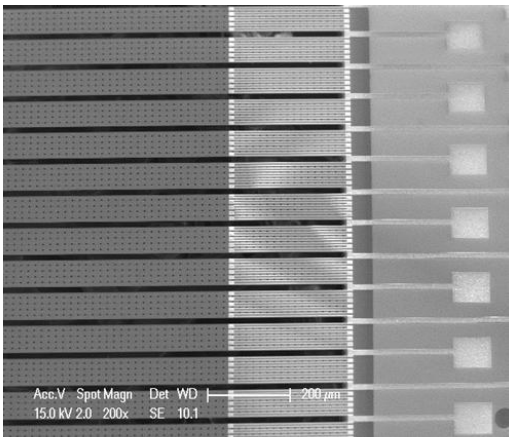

Figure 4. Released thermopile array without absorber.

After completion of the detector array fabrication and before the sacrificial release, a 100 nm thick Al film is sputtered on the detector array. This layer serves as the metallic back plane of the metamaterial absorber. Subsequently, a 150 nm thick SiO_2 layer is deposited on the Al layer by Atomic Layer Deposition (ALD). Several techniques are available for low-temperature SiO_2 deposition on top of the Al backplane, such as PECVD, sputtering and ALD. Althougth ALD is a very slow deposition technique it is the most sutaible technique for the kind of flexible expremtation that is needed at this stage. Afterwards, a layer of resist (PMMA) is spin-coated on the SiO_2 dielectric layer and lithography is used to define the pattern of the top Al structures. The technique that is considered for transferring the pattern is based on a lift-off process, which is a method of patterning using a sacrificial material (photoresist). Figure 5 shows the schematics of the fabrication process. After EBL exposure and development, an inverse pattern of the disks is made in the resist layer. Subsequently, the second Al layer is deposited on the samples. The remaining resist layer with the Al on top of it, are removed. The remaining structure layer will have the desired metallic pattern. Finally, a set of sacrificial openings is patterned and etched through the membrane and absorber layers. The sacrificial layer (TEOS) is etched in a high concentration HF solution (73% to avoid Al attack) and the samples were subjected to the supercritical CO_2 drying.

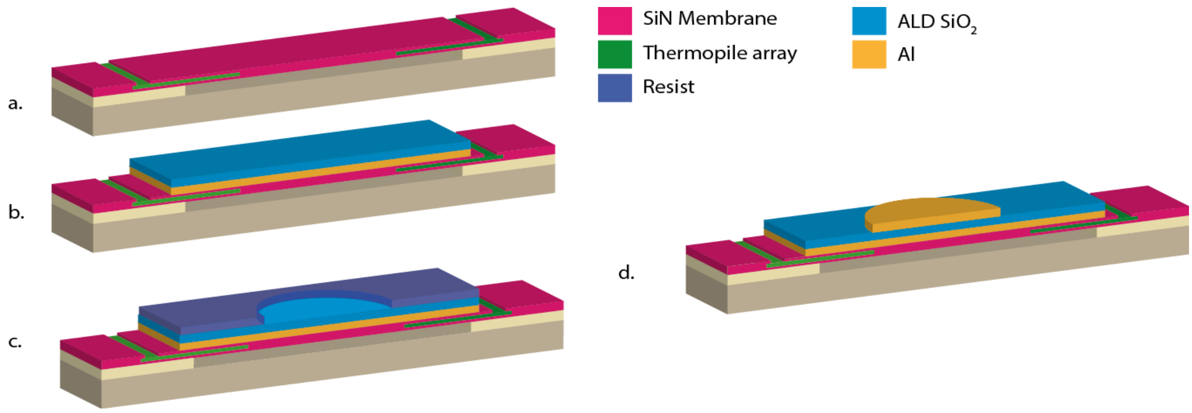

Figure 5. A cross-sectional view of the fabrication flow with lift-off: a. Substrate with detector array (thermopile) on a 0.9 μm Si_3N_4 membrane; b. Deposition and patterning of Al and SiO_2; c. Resist coating and e-beam lithography and development of patterns; d. Deposition of Al and lift-off.

4. Conclusion
The CMOS-compatible fabrication of mid-IR metamaterial-based absorbers was studied. This process involves deposition of Al-SiO_2-Al stack on top of a Si_3N_4 membrane using a lift-off process. Simulations indicate a 95±4 % absorption in the 3-4 μm mid-IR spectrum range using Al. It was also shown that the performance of the absorber structure is not significantly affected by variations in the the dielectric layer thickness. Although e-beam lithography is used in the first experiments, the relatively large disk dimensions (500-600 nm) and the limited susceptibility of the spectral absorption to shape distortion by limitations in the lithography would allow conventional lithography to be applied to the large-area absorbers. On-going experimentation should validate the robustness of the technique for variations in the circular shape. The masked lithography would be a significant advantage for high-volume wafer-level fabrication.

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