3D metamaterials for thermal-IR applications

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Membrane-projection lithography enables fabrication of true out-of-plane resonators at a 3D resolution of tens of nanometers, and can be scaled to full-wafer processing.

Metamaterials are artificially structured components that enable control of electromagnetic radiation through engineered permit-tivities ($\varepsilon$) and permeabilities ($\mu$) that can be spatially inhomogeneous and frequency dependent. This is achieved through design and fabrication of structures smaller than the wavelength of the radiation targeted. For example, they can be small metallic resonators, such as split-ring resonators (SRRs) and their variants, or high-dielectric-constant spheres embedded in lower-dielectric-constant media.

With some limitations (mostly caused by metallic ohmic losses and fabrication resolution), the design and performance of this new class of materials is scalable over most of the electromagnetic spectrum. Scaling to optical and IR frequencies requires fabricating metallic traces with widths and gaps on the order of 100 nm and tens of nanometers, respectively. While this resolution can be readily attained using a number of techniques, it is more difficult to obtain a metamaterial exhibiting magnetic activity. The latter typically requires magnetic-field excitation of out-of-plane oscillating currents, which implies fabrication of resonators with out-of-plane geometries (see Figure 1). Here, we present IR metamaterials fabricated using a novel technique—membrane-projection lithography (MPL)—that allows construction of true out-of-plane resonators, has a resolution of tens of nanometers in all three directions, and can be scaled to full-wafer processing in a parallel fashion.

Figure 2 shows three different MPL variants. A membrane, patterned with the desired resonator shape, is suspended over a cavity of the required shape. A series of directional evaporations through the patterned membrane results in deposition of replicas of the membrane pattern on the interior cavity face(s). These directional evaporations do not cause any significant spreading of the line widths defined on the membranes. The resulting material can be thought of as composed of a lattice of unit cells containing a basis that consists of the suite of resonators. Using MPL, each of these components, as well as the lattice morphology (such as face-centered cubic or hexagonal), unit-cell geometry (cubic, cylindrical, triangular), and basis (resonator number, shape, and symmetry) can be designed independently to maximize performance. In addition, in applications with relaxed requirements, MPL can be simplified.

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Figure 3. (a) Four SRRs in a quasi-hemispherical cavity formed with self-aligned MPL (SAMPL) in polyimide. (b) Four SRRs in a pyramidal cavity formed with SAMPL in silicon. (c) Five SRRs (only three shown) in a cubic unit cell of SU-8 photoresist polymer formed with MPL. Au: Gold.

to two self-aligned variants, thus drastically reducing process complexity.

Figure 3 displays scanning-electron-microscopy (SEM) images of three different structures created using MPL, as well as some possible unit-cell geometries. Each structure was formed in a different material and using a different process to create the suspended patterned membrane and underlying cavity. We formed the self-aligned unit cell in Figure 3(a) by depositing a poly(methyl methacrylate) (PMMA) membrane on top of a base-developable polyimide. We patterned the PMMA layer with e-beam lithography and placed the sample in commercial photoresist developer. The patterned PMMA allowed the developer to dissolve the polyimide immediately below, thus forming a roughly hemispherical cavity. A single, normally directed evaporation step deposited the gold SRRs after liftoff of the membrane in acetone. The SRRs lie on a best-fit plane (20 degrees out of plane). The self-aligned unit cell of Figure 3(b) was formed by patterning a nitride membrane on top of (100) silicon using e-beam lithography and dry etching. The sample was then placed in a potassium hydroxide bath, where the characteristic crystallographic etch delineates the <111> planes, yielding a pyramidal cavity with 54° side walls. A single, normally oriented evaporation again deposited the gold SRRs, after removal of the nitride membrane. Finally, Figure 3(c) is a SEM image of a cleaved cubic unit cell with five SRRs located on each of the cube’s inner faces (only three are visible). We used the most general MPL approach (not self-aligned) to create this structure.

We then generated a rectangular array of open, cubic unit cells (boxes) using contact lithography in SU-8 (a photoresist polymer). The SU-8 boxes were overfilled with polyimide and planarized. We deposited PMMA on top of the boxes and patterned them with e-beam lithography. We used tetramethylammonium hydroxide-based developer to dissolve out the polyimide backfill through the patterned membrane. Five directional evaporations and liftoff completed the process. This structure contains SRRs (oriented 90° out of plane) aligned along each of the coordinate axes. Figure 4 shows a larger area of a similar sample as that shown in Figure 3(c).

We have confirmed that resonators similar to those shown in Figures 3(c) and 4 show magnetic activity when illuminated at normal incidence to the sample plane. In addition to the isolated responses of the individual resonators, we are exploring intra- and intercell coupling to combine permittivity and permeability effects to yield spatial control of ε and μ, and potentially double negative behavior. This process can be repeated after planarization to yield truly optically thick, 3D metamaterials at IR frequencies.

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