SAND2020-10800C

14th International Congress on Artificial Materials for Novel Wave Phenomena – Metamaterials 2020
New York, USA, Sept. 28th – Oct. 3rd, 2020

Three-Dimensional Meta-films – A Discovery Platform for Structured Electromagnetic Materials

D. B. Burckel [1], K. M. Musick, P. J. Resnick, M. B. Sinclair, and M. Goldflam [2]

[1] Sandia National Laboratories, P. O. Box 5800, 87185, Albuquerque, NM, USA

***Abstract* – A wall-first variant of membrane projection lithography (MPL) is introduced which yields three-dimensional meta-films; mm-scale structures with micron-scale periodicity and 3D nm-scale unit cell structure. These meta-films combine aspects of photonic crystals, metamaterials and plasmonic nano antennas in their infrared scattering behavior. We present the fabrication approach, and modeling/IR characterization results.**

I. INTRODUCTION

Optical devices using structured materials have played a central role in optical components at least since the wire diffraction gratings of Rittenhouse and Fraunhofer. Nevertheless, the last 35 years of optical physics has been especially affected by the impact of structuring materials on the scale of the wavelength of light and the subsequent application of the electronic crystal solid state analogy to the treatment of Maxwell's equations. Photonic crystals [1] are characterized by a periodicity of ~ $\lambda/4$, while metamaterials [2] can have a characteristic size/periodicity of $\lambda/10$ or smaller. Meanwhile, optical antennas, scattering elements which have similar wavelength scale dimensions, have brought RF and microwave antenna concepts to micro and nano-photonics. Here we present 3D meta-films as a platform where these varying structured media can all be combined into a single device with optical behaviors which demonstrate a coupling and hybridization of these concepts. These meta-films are fabricated on the millimeter scale with periodicity on the order of micrometers and sub-unit cell structure on the order of 10s-100s of nanometers. Recent work has highlighted the potential design benefits of combining periodic arrays of structures with "designer" scattering elements [3].

II. WALL-FIRST MEMBRANE PROJECTION LITHOGRAPHY

Membrane projection lithography [4-7] is a three-dimensional (3D) fabrication approach capable of making complex lattice + basis materials. The approach is generic but is especially relevant for infrared metamaterials

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

and photonic structures where many complementary metal oxide semiconductor (CMOS)-compatible materials

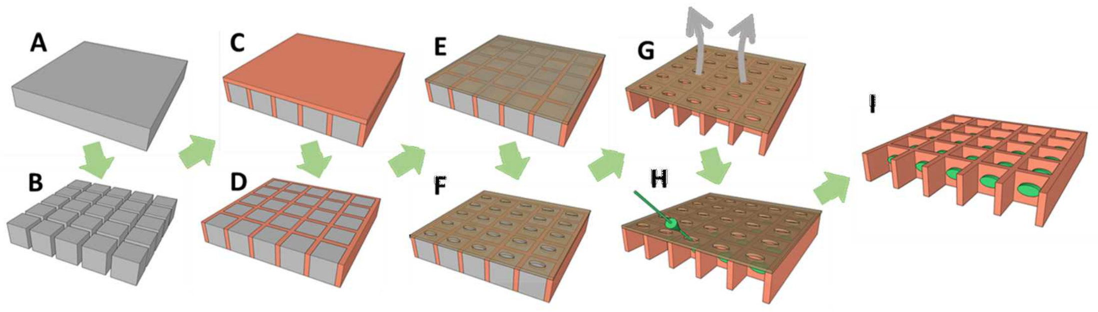

Fig. 1. Schematic depiction of the "wall-first" membrane projection lithography approach.

are transparent to IR wavelengths and mature silicon and CMOS processing tools can be used. Starting from a 3 μm thick-film of poly-silicon (Fig 1A), 300 nm wide trenches are etched (Fig. 1B),and backfilled with a conformal chemical vapor deposition (CVD) silicon nitride (Fig. 1C). The filled trenches will become the walls of the unit cells. This step also results in nitride deposition on the tops of the unit cells, which is etched off (Fig. 1D). A stencil membrane material is deposited (Fig. 1E) and patterned using e-beam, optical stepper, interferometric lithography or contact lithography with the desired shape of the unit cell inclusion (F.g 1F). The patterned membrane is then used to dissolve out the polysilicon inside the unit cell cavity using XeF_2, yielding a suspended, patterned membrane (Fig. 1G). Angled deposition through the patterned membrane results in deposition of one (or more) instances of the pattern on the interior walls of the unit cell (Fig. 1H). After liftoff, a patterned 2D array of decorated unit cells with 3D inclusions is left. This process can be performed on bulk silicon wafers in cases where the device is expected to operate in reflection mode. If high transmission is of interest, the polysilicon layer of step A can be deposited on a lower silicon nitride layer and the supporting substrate beneath the array can be removed leaving a suspended meta-film with total thickness ~ 4μm, and lateral dimensions of millimeters.

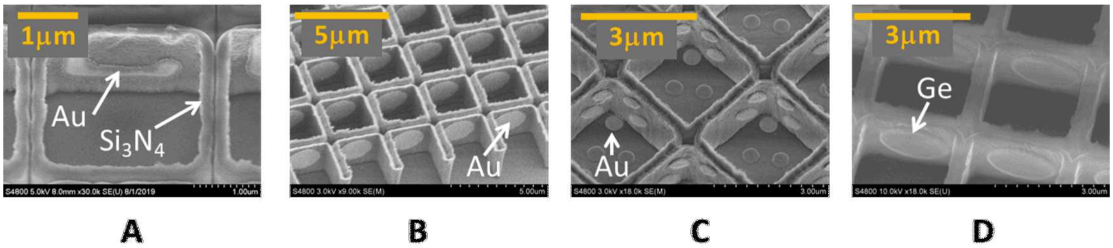

Fig. 2. Scanning electron micrograph images of representative structures created using the MPL approach from Fig. 1 A. Vertically oriented gold SRR in a silicon nitride unit cell; B Vertically oriented gold disks; C Gold pentamer deposited on both the floor and adjacent walls of the unit cell; D Vertically oriented germanium disks.

Fig. 2 contains scanning electron micrograph (SEM) images of some sample structures created using the MPL approach from Fig. 1. The visible seam noticeable in A-C is due to rounding at the top of the high aspect ratio wall etch. This feature is mostly cosmetic and has very little impact on the scattering behavior of the structure.

III. MODELING RESULTS

Consider the unit cell in Fig. 3A, a nominally cubic unit cell with a vertically oriented metallic ellipse in meta-film with the backside substrate removed. The supporting nitride slab and unit cell walls form a slab photonic

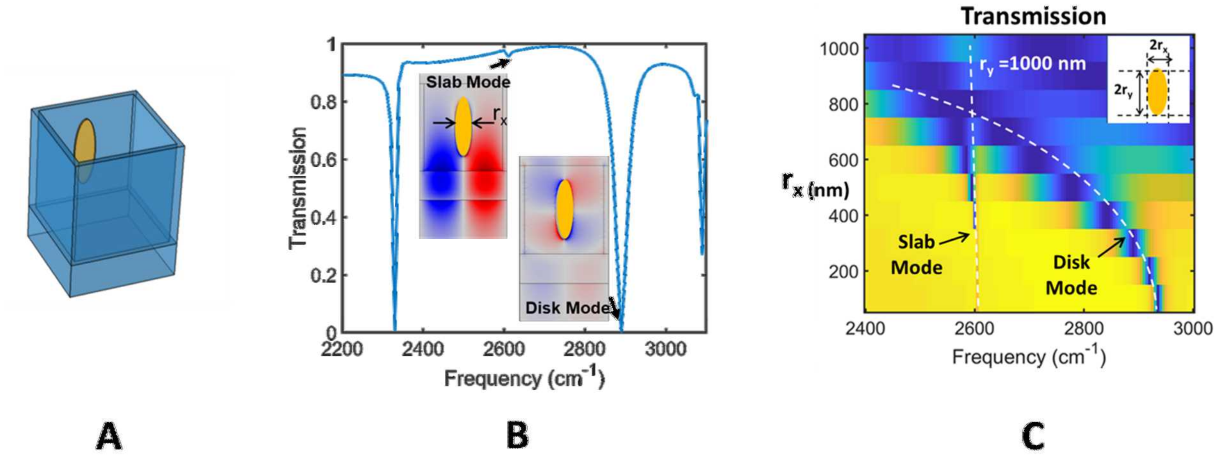

Fig. 3. A. Schematic diagram of cubic silicon nitride unit cell matrix with a gold ellipse deposited on one vertical wall; B. Simulated transmission spectrum. The slab mode at 2600 cm-1 is very narrow and not resolved well at this resolution. Inset cross-section field plots show the location of the field being localized to either the slab or the particle; C. Reflection map created by varying the lateral width of the ellipse from 100 nm to 1000 nm.

crystal which has a complex in-plane band structure. The ellipse can enhance or suppress scattering into this band structure. In Fig. 3B, COMSOL was used to simulate the structure. In the frequency range from 2400 cm-1 to 3000 cm-1, there are two noticeable scattering features. The inset field plots show that these two features correspond to a predominately slab waveguide mode with the field largely confined to the supporting slab and a higher frequency "disk" mode with the field localized around the disk. The slab mode is a very high-Q resonance and is hence very narrow. The resolution of the plot is only able to show a small dip indicated by the arrow. By varying the ellipse minor axis dimension, these two modes can be forced to overlap, as seen in the transmission map in Fig. 3C, where the vertical axis corresponds to increasing r_x, while r_y is fixed at 1000 nm. The ability to control the coupling between these two disparate resonances

VI. Conclusion

We presented a new variation of membrane projection lithography capable of creating suspended patterned meta-films with micron-scale periodicity and total thickness. These meta-films possess characteristics of photonic crystals, plasmonic nano-antennas and metamaterials. We show that by varying the structure of the unit cell interior, dramatic changes in the scattering behavior can be engineered.

While the structures shown here employ simple unit cell scattering elements, the approach is general, and capable of fabricating much more complex unit cell designs which result from numerical optimization approaches [8,9].

Acknowledgement

This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. Partially supported by the Defense Advanced Research Projects Agency Defense Sciences Office (DSO) Program: DARPA/DSO EXTREME; Agreement No. HR0011726711.

References

[1] J. D. Joannopoulos, R. D. Meade, J. N. Winn, *Photonic Crystals – Molding the flow of light,* 2nd ed, Princeton University Press, 1995.
[2] C. M. Soukoulis and M. Wegener, "Past achievements and future challenges in the development of three-dimensional photonic metamaterials," *Nat. Photon.*, vol. 5, pp. 523-530, 2011.
[3] Y. Radi, D. L. Sounas and A. Alu, "Metagratings: beyond the limits of graded metasurfaces for wave front control," *Phys. Rev. Lett*, vol. 119, 067404, 2017.
[4] D. B. Burckel, J. R. Wendt, G. A. Ten Eyck, J. C. Ginn, A. R. Ellis, I. Brener, and M. B. Sinclair, "Micrometer-scale cubic unit cell 3D metamaterial layers," Adv. Mater. vol. 22, pp. 5053-5057, 2010.
[5] D. B. Burckel, P. J. Resnick, P. S. Finnegan, M. B. Sinclair, and P. S. Davids, "Micrometer-scale Fabrication of complex three-dimensional lattice+basis structures in silicon," Opt. Mater. Express vol. 5, pp. 2231-2239, 2015.
[6] D. B. Burckel, S. Campione, P. S. Davids, and M. B. Sinclair, "Three dimensional metafilms with dual channel unit cells," Appl. Phys. Lett., vol. 110, 143107, 2017.
[7] K. M. Musick and D. B. Burckel, "Refinements in membrane projection lithography: a route to fabrication of 3D metamaterials," Proc. SPIE 10930, Advanced Fabrication Technologies for Micro/Nano Optics and Photonics XII, 1093005 (2019); https://doi.org/10.1117/12.2513632.
[8] B. M. Adomanis, D. B. Burckel, and M. Marciniak, "3D plasmonic design approach for efficient transmissive Huygens metasurfaces," Optics Express, vol. 27, pp. 20928-20937, 2019.
[9] D. Z. Zhu, E. B. Whiting, S. D. Campbell, D. B. Burckel, and D. H. Werner, "Optimal high efficiency 3D plasmonic metasurface elements revealed by lazy ants," ACS Phot., vol. 6, pp. 2741-2748, 2019.