Ion-Beam Micromachining of Surface Phonon-Polariton Metamaterial Structures in SiC and h-BN

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Metamaterial structures utilizing surface phonon-polariton (SPhP) modes within in polar dielectric crystals, such as SiC and hexagonal-BN (hBN) are attracting interest as promising alternatives to plasmonic media, due to the long scattering lifetimes (i.e., low optical losses) associated with phonons in polar dielectrics in comparison to those of free carrier plasmons in metals and doped semiconductors. This results in exceptionally narrow resonance linewidths, long propagating polaritons and high efficiency metamaterials, albeit in the spectral range between the mid-IR to the single digit THz. Recently we have experimentally demonstrated record quality factors from e-beam patterned localized SPhP resonators in 6H-SiC nanopillar arrays that were 50-200x smaller than the free-space wavelength. [1] In addition, we have more recently demonstrated hBN as the first naturally occurring metamaterial, whereby it exhibits both metallic and dielectric optical response simultaneously along orthogonal optical axes. This type of material is referred to as a hyperbolic metamaterial and is the basis of sub-diffraction imaging and negative refraction.

The focused ion beam microscope (FIB) is an intriguing tool for direct-write, rapid prototyping of novel structures with the unique control in varying the feature depth through dose control. FIB may be used to exploit 3-D resonant modes in SPhP structures in ways that conventional lithography may not. For ion milling of nanoscale features, there is a delicate balance between the writing time, instrument stability, and beam current and control, with the feature fidelity. Mitigation strategies for beam-tail effects and redeposition include the use of hard masks, gas-enhanced etching, and precision beam control.

In this work we present novel metamaterial structures written in 4H-SiC and hBN using an FEI DualBeam Novalab 6 with a Raith Elphy pattern generator. Prior to milling, a 40nm PMMA resist and subsequent 40 nm Cr hardmask were deposited on the surface to mitigate beamtail effects. We explored the impact of ion-assisted etching, using precursors such as XeF_2, water, and iodine-based etchants. Figure 1 is an SEM cross-section on a XeF_2-etched array of 200 nm holes with 600 nm pitch showing vertical sidewalls and the mitigating effects of the Cr layer on reducing beam tailing. We also devised strategies to fabricate chiral metamaterial structures with a polarization dependence using the unique capabilities of the FIB. Figure 2 shows an array of decreasing-slope chiral prototypes that should perform as a mid-IR circular-polarizer using SPhP structures.

References:
1. Caldwell, J.D., et al.,. Nano Letters. **13**(8): p. 3690-3697.

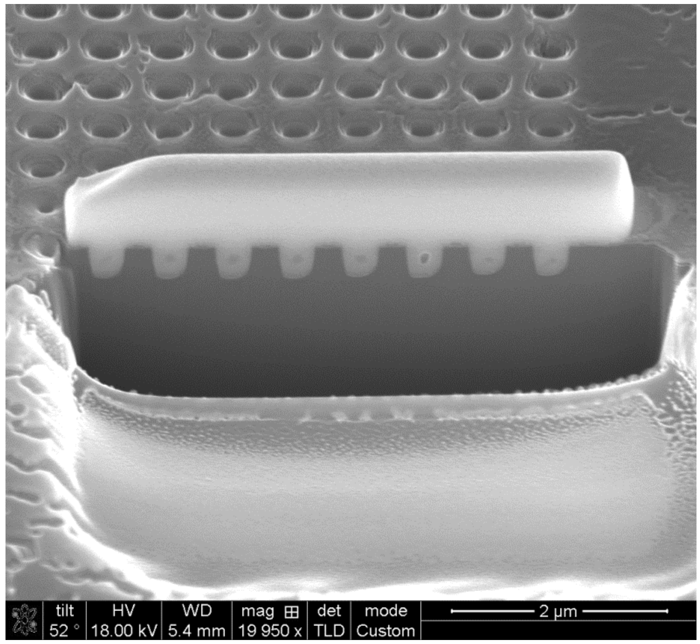

Figure 1: SEM image XeF_2 gas-assisted FIB-etched 200nm circular array through Cr hard mask after Pt-deposition and cross sectioning. Sample is tilted at 52 degrees.

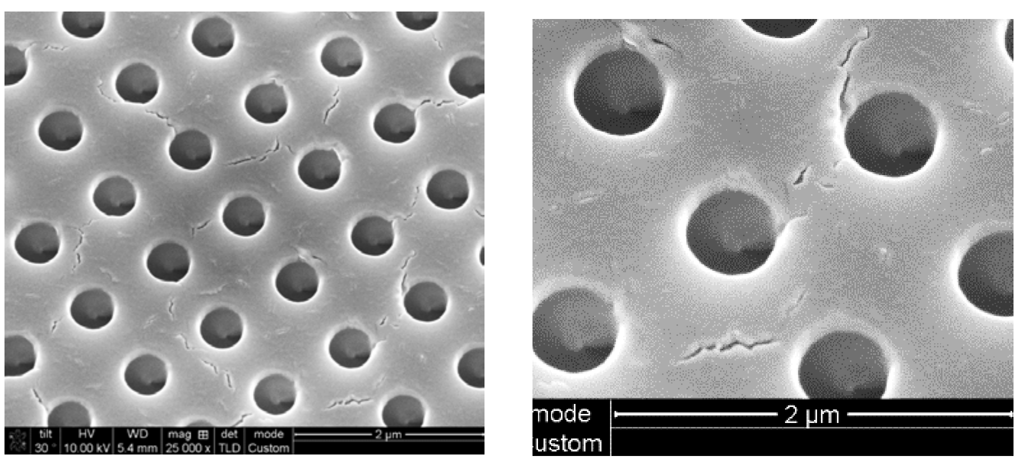

Figure 2. Decreasing slope chiral metamaterial structures in SiC etched using XeF_2-based FIB milling. Samples are designed to demonstrate circularly polarized SPhP phenomena. Image was acquired at 15 degree tilt to show 3-dimensional variation. The features get deeper in counter clockwise direction starting at the 3 o'clock position.

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