Plasmonic Lithography Utilizing Epsilon Near Zero Hyperbolic Metamaterial

Xi Chen[1], Cheng Zhang[2], Fan Yang[2], Gaofeng Liang[2], Qiaochu Li[2] and L. Jay Guo[1, 2]
[1]Applied Physics, [2]Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109, USA

Hyperbolic metamaterial (HMM)[1-4] is a type of uniaxial metamaterial whose tangential and vertical permittivities have the opposite signs $\epsilon_{\parallel} \cdot \epsilon_{\perp} < 0$. HMM has been widely exploited for various proposes, particularly as filters in ultraviolet (UV) lithography[1-4]. In HMM lithography, sub-wavelength patterns were produced based on interference effect. However, due to the strong attenuation of the light propagating in the HMMs, the field intensity in the light-sensitive photoresist (PR) layer is several orders of magnitude weaker than that of the incident light, which increases the exposure time and lowers the throughput[1,2]. Furthermore, the 1:1 patterning approach using hyperlens is challenging because the difficulty of making the mask[3]. To address these issues, a system which can create interference patterns while maintaining high light transmission is desired. In this work, we proposed to utilize epsilon-near-zero (ENZ) HMM[4] to produce period reduction patterns with improved field strength in the PR layer.

Aluminum (Al) and aluminum oxide (Al_2O_3) films were used to construct a type II ENZ HMM ($\epsilon_{||} \to 0$ and $\epsilon_{\perp} > 0$)[4]. The scheme of the ENZ lithography is shown in Figure 1A. One-dimensional Al grating is used as the photomask with the period of 700 nm, and duty cycle of 0.75. The type II ENZ HMM is placed in contact with an index-matching layer, followed by the PR layer to record the imaged patterns. TM polarized light with the wavelength of 405 nm was used for illumination. The simulated electric field intensity distribution $|E|^2$ of the latent image in the PR layer is shown in Figure 1B for one mask period. 6X pattern size reduction from the mask was achieved, due to the 3rd diffraction of the grating and the interference of two counter-propagating waveguide modes. The field contrast is calculated to be ~ 0.915, as illustrated in Figure 1C, which shows uniform $|E|^2$ distribution at different depths in the PR film. The scanning electron microscopy (SEM) images of the resulting patterns are shown in Figure 2. Subwavelength patterns with half-pitch of 58.5 nm, which is 1/7 of the light wavelength, with aspect ratio of around 2:1 were achieved, matching simulation results.

Due to the low loss and high anisotropy of type II ENZ HMM, we demonstrated that sub-wavelength patterns can be created in PR while maintaining strong field intensity, high aspect ratio, and good uniformity. It is worth noting that the printed patterns are also smaller than that on the masks, which also alleviate the difficulty in mask fabrication and improve the throughput of plasmonic lithography.

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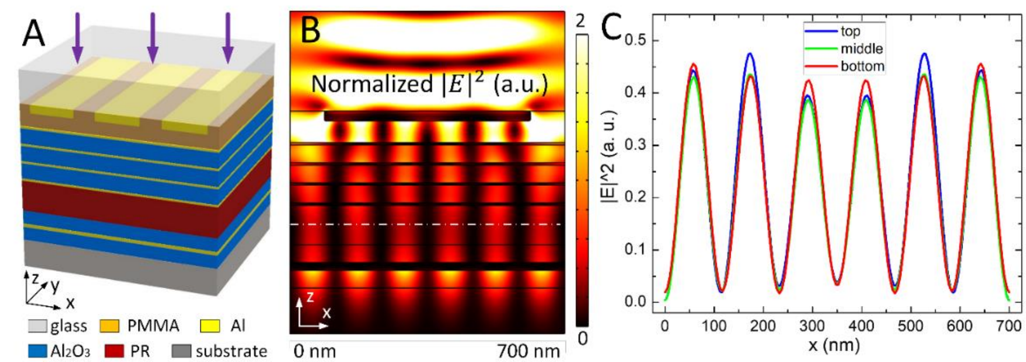

Figure 1 Lithography design using ENZ HMM.

(A) Schematic of the ENZ lithography design in Cartesian coordinates. (B) Normalized $|E|^2$ distribution in the xz plane with the wavelength illumination for 7 layers of 6 nm Al and 47 nm Al_2O_3 ENZ HMM and the white dashed line indicates the middle position in the PR. (C) Normalized electric field distribution $|E|^2$ along horizontal dashed lines at the top, middle and bottom positions in the PR.

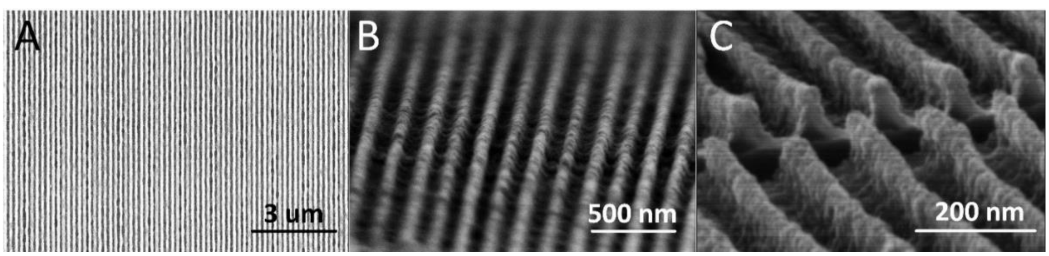

Figure 2 The SEM of the patterns made by the Al/Al_2O_3 ENZ HMM.

(A) top view (B) angled view and (C) Cross-section view of the patterns with period around 117 nm and height of 100 nm.