Fabrication of Wafer-Scale Nano-split-ring Metamaterials By Nanoimprint without Direct-write in Mold Making

Wen-Di Li, Can Peng, Shufeng Bai and Stephen Y. Chou
NanoStructure Laboratory, Dept of EE, Princeton University, Princeton, NJ 08544, USA

Metamaterials based on patterned nanostructures, such as split-ring array, critically hinge upon our ability in nanopatterning over large area with low cost. Nanoimprint is considered as one most promising method for such application. However, nanoimprint requires a mold, which, for complex patterns (e.g. split-rings), needs "direct-write" patterning (e.g. EBL or FIB). Due to a point-by-point serial writing manner, direct-write of nanostructures has a low-throughout and is currently limited to small area. Here we report and demonstrate an approach that allows us to fabricate nanoimprint molds with complex patterns (e.g. split rings) on wafer scale without using any direct-write.

The novel approach is based on (i) fabrication of a scaffold-mold with simple scaffold patterns *without* direct-write; and (ii) fabrication of a final "composite" mold using nanoimprint with the scaffold-mold, plus other processing steps that modify the scaffold structures into the desired nanopatterns. Here we show how this approach being used for making single-split ring array and double split ring array on wafer scale.

In making a single split ring array mold, the scaffold-mold was a wafer-scale pillar array mold, fabricated by either interference lithography or double cycles of imprinting and processing with a grating mold. As shown in Fig. 1, an imprint with the scaffold mold plus etching created a SiO_2 pillar array on the final mold substrate. Deposition of LPCVD SiNx and selectively etching formed a SiNx ring surrounding each SiO_2 pillar [1]. During consequent oblique Cr deposition, the pillar is used as a shadow mask to block Cr from being deposited into its shadow, forming Cr ring with a cut (Fig. 1d). RIE etching with the Cr as mask created a single cut on the SiNx ring. Then HF removed the SiO_2 pillar, completing the single-cut SiNx ring mold fabrication. The single split ring array molds with 40 nm cut, 120 nm outer diameter, 80 nm inner diameter, and 200 nm pitch have been achieved (Fig. 2).

In making a double split ring array mold, two scaffold molds and two imprinting were used. The first scaffold mold was a square pillar array mold. An imprint (with the first scaffold mold) and etching patterns SiO2 square pillars on the second scaffold surface (Si substrate). A conformal LPCVD SiNx was deposited and etched by RIE to remove both top and bottom SiNx. Then the SiO2 pillars are wet etched by HF solution, leaving only square SiNx rings on the second scaffold mold surface (Fig. 3a-d). The second scaffold mold was used to imprint square ring array in the resist coated on the final composite mold substrate (Fig. 3e). Three different Cr oblique shadow evaporations and lift-offs created a Cr square ring with two breaks (splits) (Fig. 3f). The Cr mask creates double split ring structures on the final composite mold surface during following RIE etching (Fig. 3g-h). Imprinting with the final composite mold and an Au lift-off created wafer-scale double-split square-ring array with 750 nm side, 180 nm width, and 1 μm pitch (Fig.4). The measurements of transmission spectra demonstrated magnetic resonance modes of negative magnetic permeability.

The methods open up a viable path to manufacture wafer-scale meta-material with high-throughput and low cost.

[1] Shufeng Bai, Stephen Y. Chou, to be published

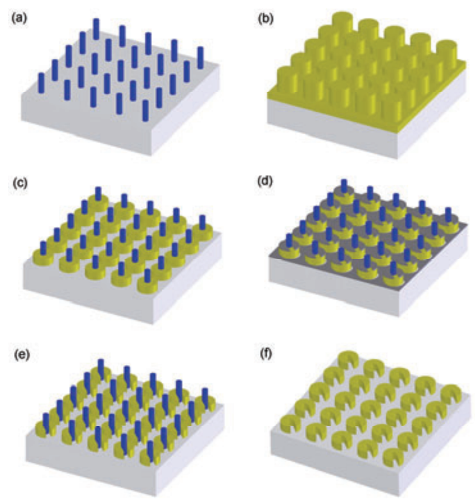

Fig. 1. Fabrication process of nanoimprint mold for split-ring devices: (a) SiO_2 pillars fabricated by interference lithography (or nanoimprint); (b) conformal SiNx growth over the pillars fabricated in (a); (c) etching down SiNx by reactive ion etching to expose the SiO_2 pillar; (d) oblique evaporation of Cr using the SiO_2 pillar as shadow mask; (e) use of Cr as mask to etch into SiNx forming SiNx ring with a cut; (f) removal of SiO_2 pillar. by

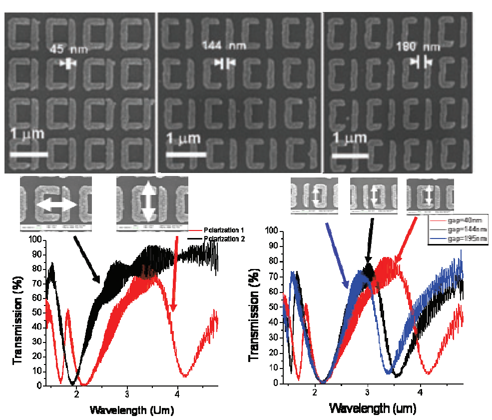

Fig. 4. (top) SEM image of fabricated Au double split rings with different split sizes; (bottom left) measured transmission spectra of double split ring arrays under two orthogonal polarizations, when the polarization is along the split magnetic resonance is observable; (bottom right) measured transmission spectra of double split ring arrays with different split sizes, the blue shift of the extra resonance peak with the increase of the split size shows that it is caused by magnetic resonance.

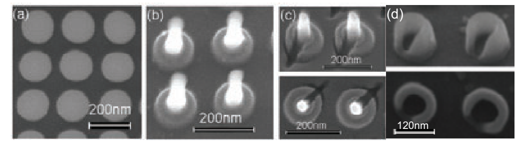

Fig. 2. SEM images of the fabrication using the steps described in Fig. 1. (a) Conformal SiNx deposition; (b) selectively etching down SiNx to expose central SiO_2 pillar; (c) single cut on the surrounding SiNx ring; and (d) final ring mold.

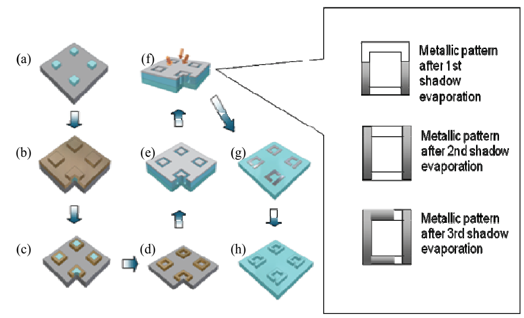

Fig. 3. The fabrication process for wafer-scale nano split-ring molds. (a) In making the second scaffold mold, a 2D square SiO2 pillar array was patterned on the mold surface (Si substrate) by nanoimprint and etching using a first scaffold Mold (a pillar mold). (b) Conformally deposit a layer of SiNx of 120 nm thick by LPCVD. (c) RIE etch the SiNx layer on the top of pillars and the mold substrate surface, leaving only SiNx square rings around SiO2 cores. (d) Etch the SiO2 cores with HF solution. (e) Use the second scaffold mold (SiNx ring array) to imprint square-ring trenches in an imprint resist on the final composite mold surface. (f) and (g) Three oblique shadow evaporations of Cr in three different angles and a lift-off create Cr square-rings with two cuts (splits). And (h) RIE etching to transfer the double split ring from the Cr mask to the patterns on the final composite mold surface, and subsequently remove the Cr by CR-7.