STEREO METAMATERIAL WITH THREE DIMENSIONAL META-ATOMS FABRICATED BY PROGRAMMABLE STRESS INDUCED DEFORMATION FOR OPTICAL MODULATION

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ABSTRACT

We present a novel stereo metamaterial composed of three-dimensional (3D) gold split ring resonators (SRRs) in array to realize considerable optical modulation. The metamaterial is fabricated by a general 3D nanofabrication technique of focused ion beam stress induced deformation (FIB-SID). Such technique is a simple-step process, allowing programmable and accurate nanoscale origami on various metal and dielectric thin films. Theoretical and experimental results manifest that the metamaterial device with the 3D SRRs as meta-atoms has reflection minimum and abrupt phase change at 5.3 µm. In addition, to demonstrate the power of FIB-SID, other 3D meta-atoms with complex geometry such as sine shape, fold-line, and swiss-roll are also produced, proving FIB-SID an ideal tool to construct various 3D optical nanostructures and devices, including plamonic antennas, metamaterials and metasurfaces.

INTRODUCTION

Three-dimensional (3D) nanostructures often exhibit extraordinary optical properties which do not exist in nature [1-3]. Particularly, when the characteristic dimension of a structure is close to the wavelength of light, it can induce strong modulations of the incident fields and have been becoming an extensively explored field for building new generation nanophotonic devices [4,5]. Moreover, light-matter interactions such as plasmonic enhancing, nonlinear optical properties (e.g. second harmonic generation) and optical force have close relation with geometry of nano-structures, especially the symmetry, shape and period, etc. Thus, pursing an efficient and flexible fabrication strategy to construct 3D nano-structures is a never-ending target.

Presented 3D fabrication methods include direct laser writing [5], layer by layer stacking [1], nano-imprinting [6], and self-assembly [7], etc. Albeit these success, these methods suffer from some deficiencies. For example, though 3D structures with complex geometries can be fabricated by direct laser writing, the whole process is quite difficult and selected material is limited. As for layer by layer stacking, it is hard to construct structures with multilayers (under 3 layers is possible), because of the alignment error during EBL process. Nano-imprint is a quite efficient method which could produce nano-structures in large area, highly improving fabrication efficiency, but the structure's geometry is not fruitful. Last but not least, self-assembly is a smart process, but the material and geometry of target structures is limited.

Here, in this paper, we present a versatile focused ion beam (FIB) based strategy, named FIB stress induced deformation (FIB-SID), to fabricate 3D nanostructures with flexible and complex geometry. Such technique is single-process, which utilizes induced surface stress to bend cantilever upward or downward. Moreover, such technique could be applied in different materials such as metal, dielectric and semiconductor. Under this strategy, 2D thin film could be translated into 3D structures at nanometer accuracy. To prove the power of FIB-SID, we fabricate stereo metamaterials composed of "standing" 3D split ring resonators (SRR), demonstrating considerable optical absorption in IR regime. Theoretical and experimental results manifest that the metamaterial device has reflection minimum at 5.3 µm. It has also an abrupt phase change cross resonance which is in agreement with metasurface theory [8]. Last but not least, we successfully produce other 3D meta-atoms with complex geometry such as sine shape, fold-line, and swiss-roll, proving FIB-SID an ideal tool to construct various 3D optical nanostructures and devices, including plamonics and metamaterials.

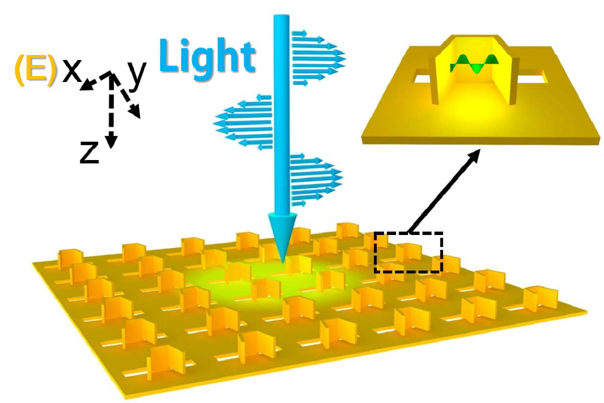

Figure 1: Schematic diagram of the stereo metamaterial. Each meta-atom in the metamaterial is a 3D SRR with two arms connected to the root, standing on the gold thin film. When incident light comes into the metamaterial, resonance will be excited.

DESIGN AND FABRICATION

Figure 1 shows the schematic diagram of the stereo metamaterial, which composes of an array of meta-atoms. Each meta-atom is a 3D SRR with root connected to two arms, standing on the gold thin film. When incident light comes into the metamaterial, resonance will be excited. Top right inset of Figure 1 shows this light-matter interaction. Due to such unique 3D design, the plasmonic resonance (green part) will be located on the gap between two arms, producing huge optical absorption.

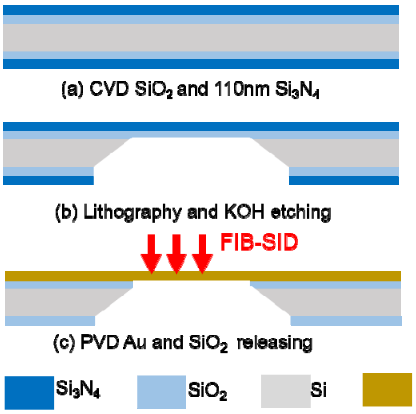

Figure 2: The fabrication process of suspended gold film. (a) 150 nm silicon oxide and 110 nm silicon nitride membrane were deposited on the both sides of a silicon wafer by LPCVD. (b) After photolithography and RIE process, KOH solution was used to remove silicon substrate and the top silicon nitride was wiped off by RIE. (c) 60 nm-thick gold was sputtered on front side of wafer and the supporting silicon dioxide layer was released by BHF solution.

Figure 2 shows the fabrication process of suspended gold film by bulk-silicon MEMS process. (a) 150 nm silicon oxide and 110 nm silicon nitride membrane were deposited on the both sides of a silicon wafer by low press chemical vapor deposition (LPCVD). (b) After photolithography and reactive ion etching (RIE), 1 mm×1 mm silicon region in the back was exposed. Then KOH resolution was used to totally remove the silicon substrate from the backside. After that, the top silicon nitride was wiped off by RIE and 150 nm-thick suspended silicon oxide membrane was obtained. (c) Finally, a 60 nm-thick gold was sputtered on front side of the wafer and the supporting silicon dioxide layer was then released by BHF solution. By these process steps, suspended gold thin film was obtained.

The stereo metamaterial was then produced on the suspended gold film by the FIB-SID technique [9-11]. The formation of the unique 3D SRRs consists of two deforming steps. Each deformation step is believed to be driven by the ion-irradiation induced stress at the areas of ion-beam bombardment. Figure 3 shows the fabrication process. After the original polygon 2D patterns was predefined by FIB milling function on the suspended 60 nm-thick gold film, two object regions (red dot) were orderly irradiated under ion beam. First of all, the two arms of each SRRs were obtained by bending the end portions of the cantilevers up to about 90 degree (region 1 in Figure 3a). Secondly, the root of cantilevers (region 2 in Figure 3b) was irradiated and the whole structure "standed up" (Figure 3c).

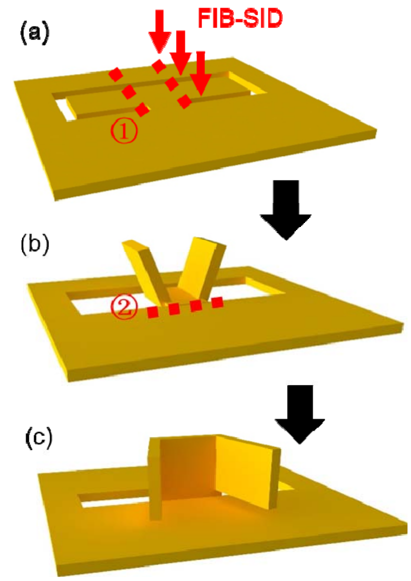

Figure 3: The fabrication process of 3D SRR using FIB-SID. (a) Region 1 at the ends of cantilevers was irradiated by ion dose. Two cantilevers will bend up to about 90 degree, forming the arms of 3D SRR. (b) The root of cantilevers (region 2) was irradiated and the whole structure "stands up".

RESULTS AND DISCUSSION

In the above fabrication process, the initial gap width of each SRR was set to be ~500 nm. Figure 4 shows SEM images of the fabricated SRRs array. The overall size of the obtained metamaterial is 60 µm by 60 µm, with the period of 2.8 µm along the x-direction and of 1.6 µm along the y-direction. The width of SRR's root is ~500 nm and the length of arm is ~800 nm. From the SEM image, we can see that the fabricated SRRs has good consistency.

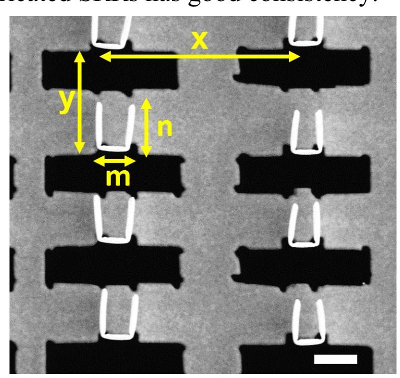

Figure 4: Detailed SEM images of the fabricated stereo metamaterial. The overall size of the obtained metamaterial is 60 µm by 60 µm, with the periods of 2.8 µm along the x-direction and of 1.6 µm along the y-direction. The width of the SRR's root is ~500 nm and the length of the arms is ~800 nm. Scale bar donates 1 µm.

The reflection spectra were measured using a Fourier transform infrared spectrometer (Nicolet iN10), under normal incident light with the electric field polarized along the x-direction (Figure 1c). Figure 5a shows the measurement results. The device has resonant reflection minima in the midwave infrared at ~5.4 μm, with reflection coefficient R ~30%. Theoretical simulations (Figure 5b) are performed using finite different time domain (FDTD) method, which is quite in agreement with the measurement results, except the resonance strength. This is because: (1) Not all the SRRs could perform the same big reconfiguration due to fabrication deviation. (2) The golden material of the SRRs was damaged to certain degree due to FIB irradiation process, leading to the loss of optical properties.

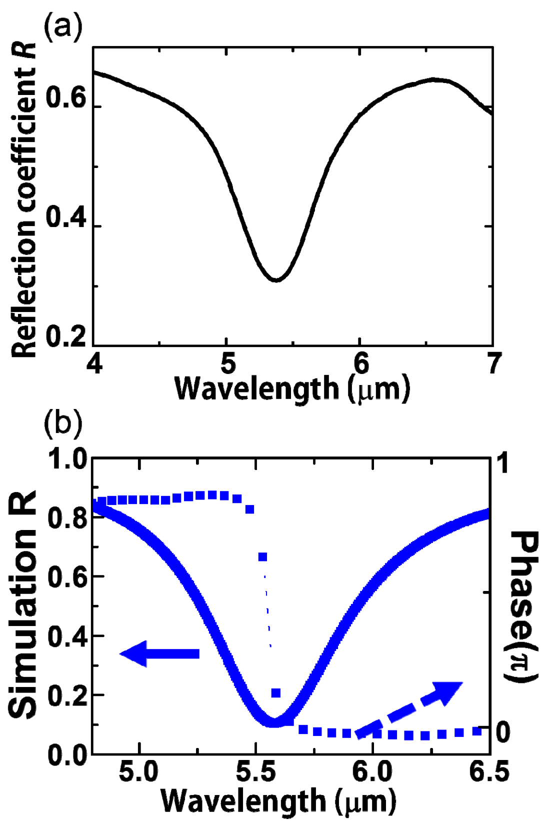

Figure 5: Simulated and measured reflection spectra of the metamaterial device. (a) The device has resonant reflection minima in the midwave infrared at ~5.4 μm with reflection coefficient R ~30%. (b) Simulations of both amplitude and phase of electric resonance, which is in agreement with measurement results. It is observed that there is an abrupt phase change cross the resonance dip.

As a resonant structure, there are strong phase modulations associated with amplitude modulations at the resonance wavelengths. Figure 5b shows the simulated results. Results show that the phase change reaches ~150 degree across the resonance peak (blue dotted), which is in agreement with current metasurface theory [8]. We attribute this large phase change to the coupling of the electric dipole mode and magnetic dipole mode.

The nature of the drastic absorption in optical properties could be understood in this way. When the wavelenght of incident light gets close to the period of meta-atoms, both the electric and magnetic resonance will happen simutaneously. These resonances mainly concentrates in the gaps between the arms or between the lower edges of arms and the substrate. This hybrid resonance mode will cause a build-up of charge with a storage of energy across the gap as a capacitance, leading to considerable optical absorptions.

To demonstrate the power of FIB-SID technique, we also fabricated diversiform nano-structures with more degree of freedom. For example, we have fabricated sine shaped ribbon, a folding structure and a swiss roll, which are shown in Figure 6.

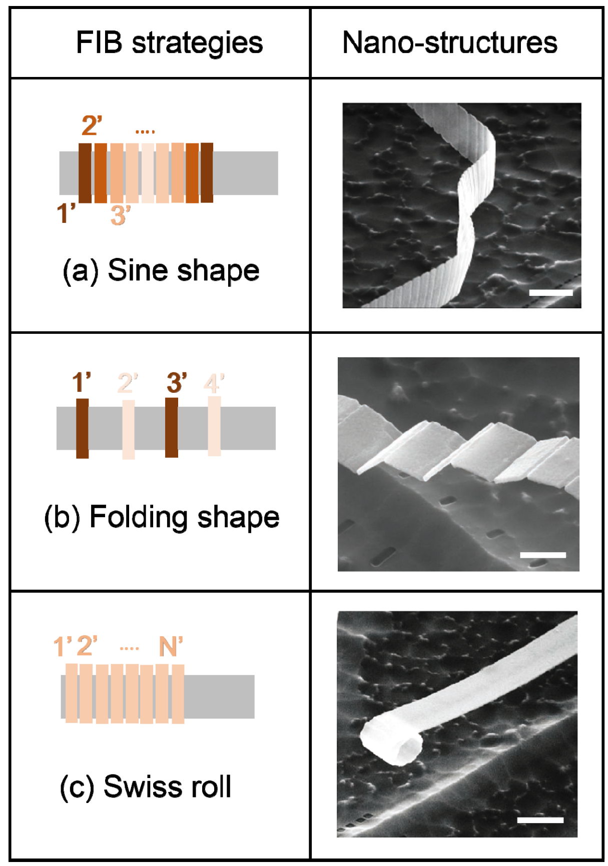

Figure 6: Other 3D structures obtained by FIB-SID with complex geometries including (a) sine shape, (b) fold-line shape, and (c) swiss-roll shape. Such flexible deformation is realized by selecting different parameters, such as 2D patterns (gray region), incident ion doses (dark brown represents high ion irradiation, and light brown represents low ion irradiation) and irradiation sequence. Scale bar donates 1 μm.

Noted that this ion beam induced process of geometric transformation from 2D to 3D is governed by (i) the 2D layout of the predefined thin film, (ii) the value of incident ion dose on each step and (iii) the irradiation sequence. For example, the fabrication difference between the sine-shape ribbon (Figure 5a) and the folding structure (Figure 5b) is the value of ion dose and the irradiation period. The ion dose difference (∆d) of sine-shape structure is ~5.0×10^{15} cm^{-2}, with scanning period ~200 nm. However, in the process of the folding structure, ∆d = ~2.0×10^{16} cm^{-2} with period ~500 nm.

CONCLUSIONS

In conclusion, we have demonstrated an improved FIB-SID strategy to realize plasmonic structures by nanoscale origami on suspended thin metal film, and have successfully fabricated stereo metamaterials composed of arrayed 3D "standing" SRRs. Importantly, structures could be manipulated at nanometer accuracy due to the fact that direction and degree of each folding process depend on the value of incident ion dose, which could be controlled precisely. Based on this technique, diversified structures can be fabricated/realized, which is significant to optics because more unique interactions between light and 3D structures, such as hybridization mode of plamonics, remains to be uncovered. Such less-damage, great-compatibility and flexible fabrication strategy opens lots of opportunities for optical application such as metamaterials, chiral optics, to name a few.

ACKNOWLEDGEMENT

This work is supported by the Research Project of Advanced Fabrication Technology of China, the Research Fund for the Doctoral Program of Higher Education (Grant No. 20130001110007), the National Natural Science Foundation of China (Grant No. 50775001), and the National Basic Research Program of China (973 Program, Grant No.2015CB352100).

REFERENCES

[1] N. Liu, et al., "Three-dimensional photonic metamaterials at optical frequencies", *Nature Materials*, vol. 7, pp.31-37, 2008.

[2] C. Soukoulis, et al., "Past achievements and future challenges in the development of three-dimensional photonic metamaterial", *Nature Photonics*, vol. 5, pp. 523-530, 2011.

[3] A. Schaedler, et al., "Ultralight metallic microlattices", *Science,* vol. 334, pp. 962-965, 2011.

[4] P. Alonso-González, et al., "Controlling graphene plasmons with resonant metal antennas and spatial conductivity patterns", *Science, vol.* 334, pp. 1369-1373, 2014.

[5] J. K. Gansel, et al., "Gold helix photonic metamaterial as broadband circular polarizer", *Science, vol.* 325, pp. 1513-1515, 2009.

[6] D. Chanda, et al., "Large-area flexible 3D optical negative index metamaterial formed by nanotransfer printing", *Nature Nanotechnology, vol.* 5, pp. 402-407, 2011.

[7] T. Leong, et al., "Three-dimensional fabrication at small size scales", *Small, vol.* 6, no. 7, pp. 792-806, 2010.

[8] N. Yu, et al., "Flat optics with designer metasurfaces", *Nature Materials, vol.* 23, no. 7, pp. 139-150, 2014.

[9] Y. Mao, et al., "Multi-Direction-Tunable Three-Dimensional Meta-Atoms for Reversible Switching between Midwave and Long-Wave Infrared Regimes", *Nano Letters,* 2016. DOI: 10.1021/acs.nanolett.6b03210.

[10] Y. Mao, et al., "Electromechanically Tunable 3D Nano-Split-Ring Array for Dynamic Control of Light", Conference on Lasers and Electro-Optics *(CLEO 2016)*, San jose, California United States, (June 5-10, 2016).

[11] Y. Mao, et al., "Randomly Controlled Metamaterial Modulator for Dynamic Tuning of Optical Property", The 29th IEEE International Conference on Micro Electro Mechanical Systems *(IEEE MEMS 2016)*, Shanghai, China (January 24-28, 2016).

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