A New Kind of Microstructure Pattern Transferring onto Glass Substrate Using the Plasma Treatment

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ABSTRACT— In this work, a two-dimensional square periodic array was successfully transferred onto a rigid glass substrate during an innovative and simple-design two-step process of pattern transferring using Kapton tape and plasma technology. Flexible and stretchable, Kapton tape was selected for pattern transferring onto the glass for the first time herein; in parallel, the vacuum plasma treatment was utilized to improve surface adhesion properties and aid the pattern transferring process. The proposed 2D square plasmonic array supported the plasmon-induced transparency (PIT) phenomenon, which is caused by the excitation of surface plasmon resonances. The current study simulated the fabricated plasmonic structure using the finite-difference time-domain (FDTD) method and investigated the propagation of surface plasmon polariton (SPP) and cavity modes which enhanced transmission. This fabrication technique can offer new insights for micro/nanofabrication technology.

KEYWORDS: Micro/nanofabrication, Surface Plasmon Polariton, PIT, SPP resonance.

I. INTRODUCTION

The technology of engineered micro/nanostructures is the foundation of all aspects of nanotechnology research, which has attracted wide applications in the fields of sensing, medicine, electronics, and energy, etc. Recently, a variety of micro/nanofabrication techniques have been developed that meet many needs in the fields of nanotechnology and nanomaterials [1]-[6], thereby facilitating the integration of engineered micro/nanostructures into multi-purpose systems for their practical applications. The large-scale realization of micro/nanofabrication techniques also offers great opportunities for the development and improvement of micro/nanoelectronics systems. Overall, the advancement of micro/nanofabrication techniques will lead to advanced applications in the fields of biomedical and pharmaceutical devices [7]-[12], molecular electronics [13]-[15], energy storage [16]-[18], food safety [19]-[21], and biosensing [22]-[26].

To realize all the above-mentioned applications, the development and advancement of micro/nanofabrication approaches are essential and of interest to researchers. Micro/nanofabrication techniques are generally classified into two groups: top-down and bottom-up based on the mechanism involved in the micro/nanofabrication process. The top-down approach creates micro/nanostructures by deconstructing materials with larger dimensions through physical or chemical processes, while the bottom-up approach creates micro/nanostructures using molecular or atomic building blocks.

In the top-down approach, various lithography techniques such as electron beam [27], [28], optical [29], [30], soft [31], [32], block-copolymer [33]-[35], scanning probe [36], [37], and nanoimprint lithography [38], [39] were utilized to create micro/nanostructured patterns. On the other hand, the bottom-up micro/nanofabrication approach includes molecular self-assembly, atomic layer deposition, vapor phase deposition, and sol-gel micro/nanofabrication [40]-[43], which will be promising due to their applications in the various fields of nanotechnology such as medical diagnosis, flexible electronics, and flash memories.

In this work, a two-dimensional square periodic array was successfully transferred onto a rigid glass substrate during an innovative, simple design, and low-cost two-step process of pattern transfer using Kapton tape and plasma technology. Kapton tape was proposed and utilized for the pattern transfer process, because of its flexibility, stretchability, and good adhesion properties. The flexible Kapton tape consists of polyimide (PM) film and a silicone adhesive layer, and in addition to being flat and flexible, it has advantages such as high thermal conductivity, very thin thickness, and high mechanical and chemical stability. Further, the vacuum plasma treatment was employed to improve the surface adhesion properties and aid the pattern-transferring process. Typically, the plasma treatment process was utilized to modify the upper molecular layer of the surface, and thus improve the activation and adhesion properties of the surface. Consequently, a two-dimensional square periodic pattern was successfully created on the glass substrate during a two-step process of the pattern transferring in a novel way using Kapton tape and plasma technology, and finally, a thin gold layer was coated on the fabricated 2D glass substrate. The proposed 2D square plasmonic array supports the plasmon-induced transparency (PIT) phenomenon, which is caused by the excitation of the surface plasmon resonances. Furthermore, the fabricated plasmonic structure was simulated using the finite-difference time-domain (FDTD) method, and optical electric field distribution was calculated, which the simulation results confirm the strong plasmonic resonances.

II. EXPERIMENTAL METHOD

In this work, a two-dimensional square periodic pattern was successfully transferred onto a rigid glass substrate using an innovative, simple design, and cost-efficient method based on the soft lithography technique. The charge-coupled device (CCD) of a camera was utilized as a stamp, which has a two-dimensional periodic pattern with a periodicity of about 2.6 μm. First, a CCD was gently extracted from a camera without scratching its surface, and then a layer of Kapton tape was stuck on the CCD by applying pressure (Fig. 1(a)). After that, the sample was placed on a heater for 1 h at 75 ℃ to allow the pattern transferring to have excellent quality. The sample was maintained under pressure at room temperature for one day to stabilize the two-dimensional pattern on the Kapton tape. After 24 h, the Kapton tape was carefully peeled off of the CCD stamp, and a 2D flat and flexible structure based on Kapton tape was achieved (Fig. 1(a)).

In the next step, the patterned Kapton and glass substrate were placed under a vacuum plasma treatment for 10 min to enhance the adhesion and activation of their surfaces. The schematic of the surface modification by plasma technology employing argon gas plasma in a vacuumed chamber is shown in Figs. 1(b)-1(c). The experimental setup consists of a high-voltage DC power supply, a vacuum chamber with high voltage and grounded sample holder electrodes, gas feeding, and measurement systems. The patterned Kapton and glass substrate were placed on the grounded electrode in the plasma treatment chamber. Afterward, the grade 5 argon gas (Farafan gas, Iran) was injected into the chamber, which increased the pressure to 13.3 Pa so that the plasma can be initiated. After the formation of plasma, the pressure was reduced to ~0.53 Pa in which the surface modification shows the best quality. The plasma treatment was continued for 10 min to enhance the adhesion and surface activation. The DC power supply output was set to a voltage of 340 V and a current of 40 mA resulting in a DC power of ~13.6 W.

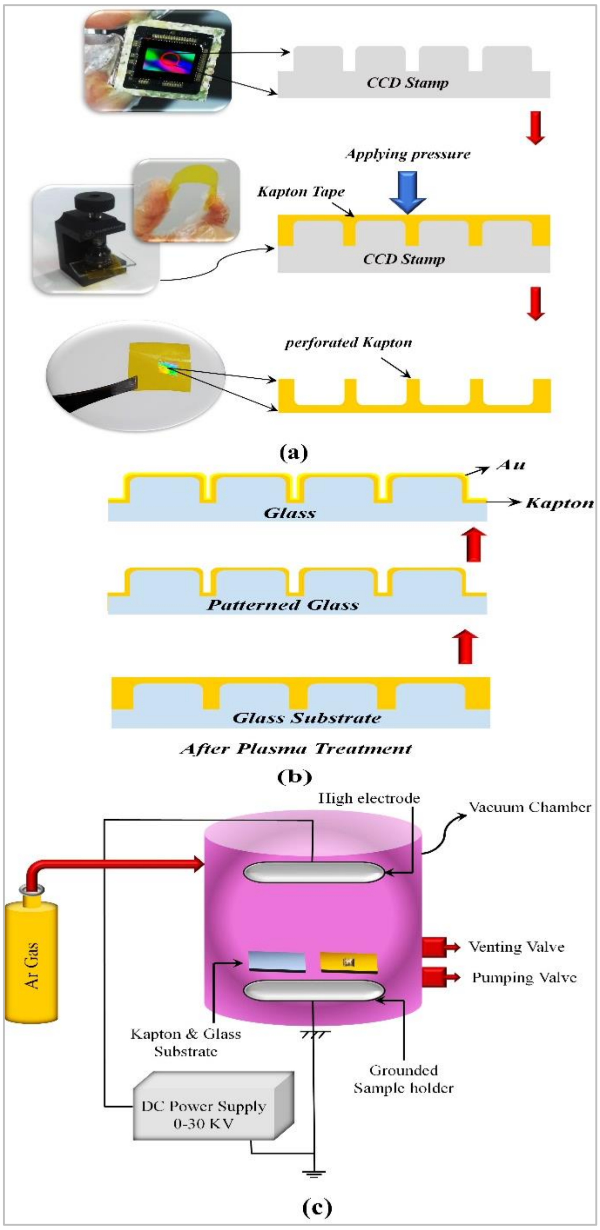

Fig. 1. A schematic array of the pattern transferring mechanism (a) before, and (b) after plasma treatment, and (c) a schematic array of the plasma treatment process.

Finally, the electric field between the electrodes accelerates the electrons and affects the gas molecules. These collisions produce many free electrons and ions that can interact with the substrate surfaces and break the molecular bonds of the first layers of the surface molecules, producing active sites, polar groups, and reactive factor groups on the surfaces. During this process, oxidation cycles will be started in the gas discharge plasma in the chamber, and surface modification was performed by a set of reactions between free electrons, ions, radicals, atoms, and molecules that are shaped in plasma. These reactions can be summarized as follows: the highly reactive atomic and molecular argon species and the very high energy UV photons can enhance the surface polarity for various exposed samples, usually demonstrating the increase in the surface hydrophilicity, activation, adhesion properties, and polarity after treatment. Also, there are fewer molecules in the vacuum (compared to atmospheric plasma) that prevent the uniform distribution of plasma, and the vacuum allows the plasma molecules to disperse more and more evenly into the chamber. As a result, the plasma can come in contact with the gaps and surfaces of the samples with different geometric shapes and active radicals of plasma can bind to the surface molecules, creating a surface that is highly active to bonding agents.

After the plasma treatment process, the patterned Kapton was stuck on the glass substrate, and the sample was kept at room temperature for 1 h (Fig. 1(b)). After 1 hour, the Kapton tape was gently removed from the glass substrate, and the 2D periodic square pattern was successfully transferred to the glass. Finally, a thin layer of gold (35 nm thick) was deposited on the 2D glass substrate using the sputtering device (Fig. 2(a)). It should be mentioned that direct current (DC) sputtering deposition of the gold thin film was carried out under the conditions of DC voltage of 365 V, plasma current of 0.01 mA, chamber pressure of 0.005 mbar, and substrate rotation speed of 28 rpm.

In this way, a two-dimensional square periodic array was successfully created on the glass substrate during a two-step process of the pattern transferring in a novel way using Kapton tape and plasma technology.

The scanning electron microscopy (SEM) image of the fabricated 2D plasmonic square array on a glass substrate is given in Figs. 2(b)-2(c). As can be seen, the proposed 2D plasmonic structure has a two-dimensional periodic square pattern with a good resolution.

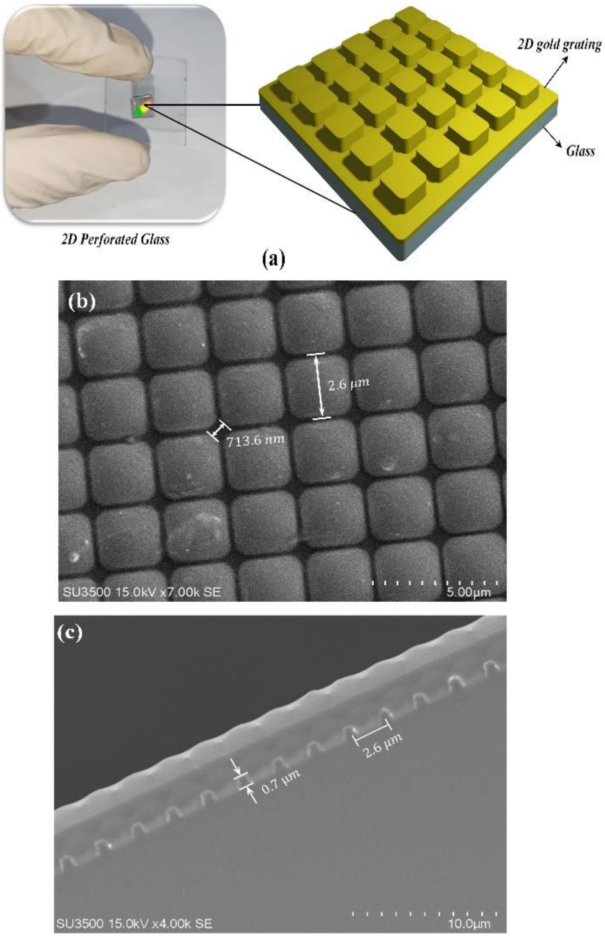

Fig. 2. (a) The real image of the fabricated 2D plasmonic square array on the glass substrate, (b) the SEM image, and (c) the cross-sectional SEM image of the proposed plasmonic structure.

III. Results and Discussion

The transmission spectrum of the fabricated 2D plasmonic square array was measured and is shown in Fig. 3(a). As can be seen, a broad peak with a center of 512.35 nm and a width of 450-600 nm was observed, which corresponds to the excitation of surface plasmon polaritons (SPPs) that can be propagated in the vertical and horizontal directions of the square lattice. In addition, two weaker resonant modes were observed at λ_1=282.23 nm and λ_2=365.52 nm, which correspond to the light scattering inside the unit cells and were related to the cavity modes.

The proposed plasmonic structure was simulated using the FDTD method, and the electric field distribution was calculated. The fabricated structure consists of a 2D periodic square array arranged on a glass substrate (Fig. 2(a)). The periodicity of the simulated structure was considered according to the SEM image (Fig. 2(b)) and periodic boundary conditions were applied. The refractive index of the glass and Au materials was taken from the Palik [44] and Johnson and Christy [45] databases, respectively. Also, the refractive index of the Kapton silicon adhesive layer was assumed to be a constant value of 1.43. The refractive index profile of a one-unit cell of the simulated 2D plasmonic structure and the electric field distribution at the transmission peaks of 282.23 nm, 365.52 nm, and 512.35 nm are given in Figs. 3(b)-3(e). The electric field localization occurred around the gold grating boundary at the main resonance wavelength (λ=512.35 nm), which is related to the excitation of the propagating SPP modes (Fig. 3(c)). Electric field enhancement occurred inside the unit cell for the other two weaker peaks (λ_1 and λ_2), which confirms the role of cavity modes and light scattering inside the unit cell (Figs. 3(d) and 3(e)). The combination of the propagating SPP and cavity modes enhances transmission and plays an important role in the PIT phenomenon.

Since the polarization caused the different propagating modes within the structure and the mechanism of the PIT phenomenon, the electric field distribution of the proposed structure was simulated at the resonance wavelength of 512.35 nm for TM (x-polarized) and TE (y-polarized) polarization and shown in Figs. 3(f)-3(g), respectively. As can be seen, field distribution was localized at the gold grating boundary for TM polarization, which is related to SPP resonances (Fig. 3(f)). Whereas for TE polarization, the electric field distribution was focused on the edges of the vertical walls and a weaker intensity distribution occurs compared to TM polarization (Fig. 3(g)). Consequently, TM polarization has a dominant contribution in the SPP excitation and the mechanism of the PIT phenomenon for the proposed structure, and TM- and TE- polarization excite the SPP modes at the gold grating boundary and the edges of the vertical walls, respectively.

It is worth mentioning that the periodicity of the proposed structure is the order of micrometers, and no direct matching occurred between the wavelength of incident light in the visible region and the lattice constant (or periodicity) due to the large unit cell of the mentioned gratings. Additionally, the distance between adjacent unit cells is about 660 nm (Fig. 2(b)), and each side of the lattice squares acts as a wire and is coupled to the corresponding wire of the neighboring unit cell. In this way, each unit cell is coupled to the adjacent unit cell and satisfies the coupled resonance condition in the visible region for the proposed plasmonic structure.

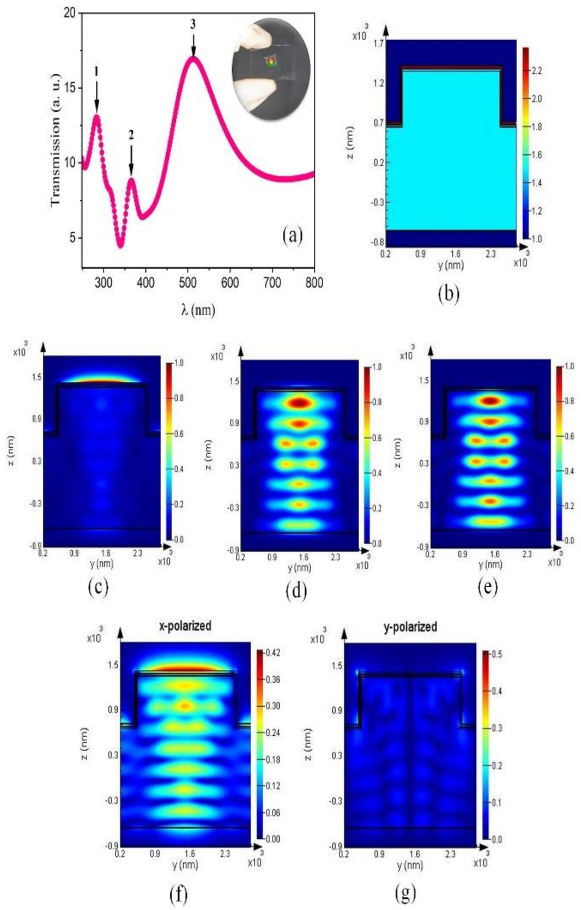

Fig. 3. (a) The experimental transmission spectra of the fabricated 2D plasmonic square array on the glass substrate, (b) The refractive index profile of each unit cell of the simulated structure, and (c)-(e) The total electric field distribution of the proposed structure at wavelengths of (c) 512.35 nm, (d) λ_2=365.52 nm, (e) λ_1=282.23 nm, (f), and (g) The electric field distribution of the proposed structure at the resonance wavelength of 512.35 nm for x- and y-polarization, respectively.

For a closer look, the proposed plasmonic structure consisting of a 2×2 array of unit cells (Fig. 4(a)) was simulated to better investigate the interaction between adjacent unit cells, and the optical electric field distribution of the plasmonic structure was calculated at the resonance wavelength of 512.35 nm (Fig. 4(b)). As seen, localization of the field amplitude occurs at the boundary between two adjacent unit cells, and each unit cell is coupled to the adjacent unit cell. In this way, each unit cell affects the adjacent unit cell and thus the coupled resonance condition is satisfied. In other words, the electromagnetic fields related to surface plasmon polaritons (SPP) resonances of one wire were coupled to the neighboring wires response when microstructures are arranged in a periodic array.

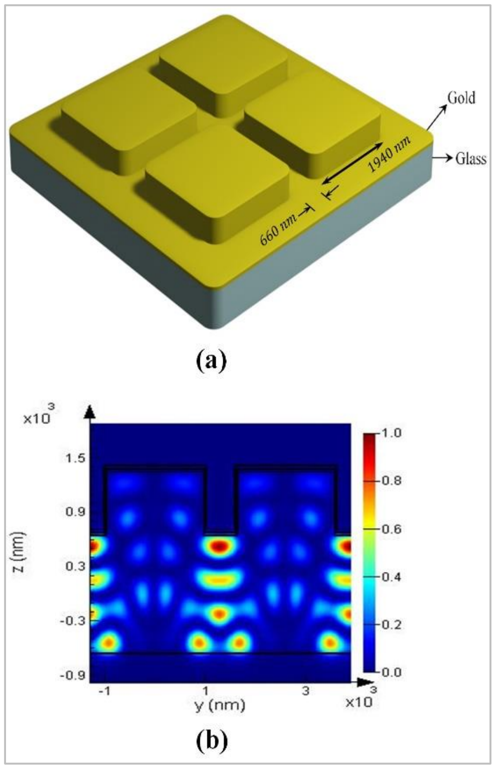

Fig. 4. (a) A schematic array of the simulated 2D plasmonic square array on the glass substrate, and (b) The electric field distribution of the plasmonic structure at the resonance wavelength of 512.35 nm.

IV. Conclusion

The current research has proposed and produced a two-dimensional microstructure pattern on a rigid glass substrate using a novel, simple design, and cost-efficient method based on the soft lithography technique. Kapton tape was utilized for the pattern transferring process, as it is a good candidate due to its flexibility, stretchability, and good adhesion properties. Further, vacuum plasma technology was applied to improve the pattern-transferring process through surface modification, and finally, a thin gold layer was deposited on the fabricated two-dimensional (2D) glass substrate. The fabricated 2D plasmonic array supports the plasmon induced transparency (PIT) phenomenon, which is related to the excitation of the surface plasmon resonances. The experimental and simulation results confirm the PIT phenomenon due to the strong plasmonic resonances. The proposed microfabrication technique allows high-resolution microstructures to be achieved using an innovative, simple design, and cost-efficient method.

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