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Flexible, low-loss and large area metamaterials with high *Q* value

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ABSTRACT

To get flexible, low loss and large area metamaterials with high *Q* value for biosensing, the metamaterials structures with different micro/nanogaps on parylene free-standing thin film and silicon substrates were designed, simulated, fabricated, and characterized. Especially, the parylene shadow mask technology and electronic beam lithography (EBL) were combined and used to fabricate metamaterials with nanogap (200 nm). The results show strong electromagnetic responses at terahertz (THz) frequencies ranging from 0.2 THz to 2.5 THz and indicated that parylene is an ideal low loss substrate or coating material. The bio-stable, bio-compatible properties of parylene and "hot spot" plasmonic properties of metamaterials have great potential application such as THz biosensor to detect the cancer biomarker.

1. Introduction

The artificial metamaterials on different substrates have gained tremendous researchers' attention partly due to their unique electromagnetic properties [1–4]. The blooming researches of metamaterials include the super lenses, cloaks, modulators, filters, perfect absorbers and biosensors [1]. Many of these researches were initially implemented at microwave frequencies where fabrication of multilayer metamaterials with key size (a few millimeters) have become increasingly sophisticated during the past about ten years. However, the fabrication of nano-scale metamaterials becomes increasingly challenging in moving from the microwave to visible region of the electromagnetic spectrum due to the fabrication cost, area and repeatability.

To date, through a lot of researches, it is predicted that the promising applications would thrive within the terahertz (THz) frequency range. The metamaterials operating in the THz range have had great successes in filling in the so-called "electromagnetic gap" lying between microwave and infrared frequencies. However, the fabrication methods, substrates and goals are varied for different researches fields in THz regime. There are many micro/-nano-fabrication technologies (lithography, electron beam lithography, nano-imprint, shadow mask technology, etc.) which were used to fabricate the THz metamaterials [5–7]. Compared those fabrication technologies, the nano-imprint and the shadow mask technology are cost-effective because the stamp or the shadow mask is reusable. Furthermore, the fabrication processes of the shadow mask technology are without lithography and removing the resist, which is simple and clean fabrication processes for metamaterials. Meanwhile, the flexible shadow mask could use to plane and rough surface. Especially, a combined different fabrication technologies (lithography, shadow mask) would be utilized to fabricate the flexible metamaterial structure array.

The substrates of THz metamaterials mainly were silicon, GaAs, quartz and polymers (parylene, polyimide, polyethylene terephthalate) [2–7]. The low-cost fabrication technologies and low-absorption of substrate in THz regime were two important aspects when the THz metamaterials were extensively applied in different fields, such as the THz metamaterial biosensor. The most typical research group Zhang [1,5,8,9] have fabricated a lot of polymer THz metamaterials on the flexible substrate, which offered detailed information about the fabrication, simulation and the characteristics of the different structure metamaterials. With the development of the fabrication technology and substrate materials, the researchers try to extend the application of the THz metamaterials. Recently, the THz metamaterials have been reported as an imaging tool in biomedical diagnostic field such as skin cancer detection and cancer marker immunodetection [10–12]. If the metamaterials in THz frequency are used to detect the cancer biomarker integrated with microfluidics, the substrate supporting the metamaterials plays an important role. The substrate should have high transmittance, strong resonances and low loss at THz frequency. Therefore, the parylene C film is an ideal substrate materials for the metamaterials. The use of parylene as a substrate or coating for metamaterials is further motivated by the fact that many diagnostic detectors which are implanted directly into the human body and immunode-

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tection [8,11]. There are four kinds of merits for fabricating the metamaterials structures on parylene C film: (1) The transmittance of parylene C film is bigger than that of silicon wafer in terahertz regime, which could reduce dielectric losses [5,9,12]; (2) It lowers the effective permittivity of the supporting media, an important feature for biosensing applications [10]; (3) The transmission spectra have high Q value compared with that of silicon substrate metamaterials; (4) The resonant frequency is higher than that of silicon substrate metamaterials. In addition, the parylene C film allows us to release the metamaterial covered membranes and drape them over a range of curved surfaces, therefore showing a clear path towards creating flexible, low-loss and large area metamaterials with high Q value, which is a goal that the researchers want to explore biosensing at THz frequency. Therefore, we developed a route to fabricate metamaterials with high Q value on large area parylene C film and 4 inches silicon wafers.

2. Experiment

Before fabricating the metamaterials, we simulated the electromagnetic response of the metamaterials using the commercial FDTD program Microwave Studio. Perfect electric and perfect magnetic boundary conditions were used to polarize the electric and magnetic field components. Ports were use on the remaining two boundaries to simulate a plane wave incident on the metamaterial. The transient solver was used to obtain the complex S-parameters. Based on the simulation results, the metamaterials structures, which would be utilized for biosensing and were well characterized at THz frequencies, were designed with 2 kinds of structures and different width gaps (from 0.1 μm to 20 μm).

The metamaterials, which have a resonant response in the terahertz regime, were made of 50 nm Cr followed by 200 nm Au on the Parylene C film which was coated on a 4 inches wafer or on 4-inch high resistivity silicon wafer. There are three methods to fabricate the metamaterials (shown in Fig. 1). The first one includes the sections (1) and (2), which is to fabricate metamaterials using Parylene C film shadow-mask. The second one includes the sections (1), (2) and (3), which is used to fabricate the nanogap on the metamaterials. The third fabrication process include the sections (1) and (4), which is an important method to fabricate large area metamaterials with high Q value. The detailed information of the fabrication processes were described as following. The first fabrication processes (Fig. 1A) were to transfer the designed metamaterials structures to the parylene C thin film which was coating on 4-inch silicon wafer. The processes include evaporating Al, lithography, oxygen plasma etching, lift-off. And then, the metal film (Cr 50 nm/Au 200 nm) was deposited on high resistivity silicon wafer (thickness: 1 mm and resistivity 5000 Ω cm) with parylene C shadow mask. Finally, the whole wafer was diced into 15 mm × 15 mm unit for testing. A reusable high aspect ratio parylene C shadow mask technology was the cheapest method compared with traditional fabrication methods. The second fabrication processes (Fig. 1B) were almost similar to the first one except the different substrates. In the second one, the parylene was used as the substrate to support the metamaterials. The electronic beam lithography was also used to form nanogap in metamaterials structures, which followed metamaterials transferring on high resistivity silicon wafer by using the parylene C shadow mask. If the parylene C acts as substrate supporting metamaterial structures or shadow mask, the parylene C thin film was peeled off the silicon wafer.

To get metamaterials with high Q value, EBL (Raith 150 system) was used to fabricate the nanogap on the metamaterial structure. The positive resist, PMMA, which consists of very long polymer chains with masses of 496 and 950 kDa, was used in the experiments. A mix of solvents (such as 1:3 methyl isobutyl ketone with isopropyl alcohol for PMMA) is used to develop. However, if the resist was overdeveloped, the mechanical failure of the resist structure result in pattern collapse. Adjacent linear features or nanogaps are particularly vulnerable to this problem, especially for thick resists.

Based on the problem mentioned above, we try to optimize the EBL fabrication processes to fabricate the nanogap in the THz metamaterials on the substrate such as high resistivity silicon wafer or parylene thin film. The detailed fabrication information of EBL fabrication processes was described as below.

First, a layer of PMMA EL4 resist was coated on the sample, with a rotate speed of 4000 r/min. The thickness of PMMA EL4 resist is about 260 nm. Subsequently, the sample was prebaked with the temperature of 180 °C for 10 min on hot plate. Second, the pattern was fabricated on the sample by electron beam lithography. The accelerate voltage was 10 kV and the area dose is 140 μC/cm^2. After EBL, a mix of solvents (such as 1:3 methyl isobutyl ketone with isopropyl alcohol for PMMA) was used to develop and form the nano-structures which we designed and wanted. Subsequently. The nitrogen gun was used to dry the surface of the sample. Third, a layer of 30 nm gold was deposited on the sample and a lift-off process was implemented.

In the fabrication processes, there is a key process for form parylene C thin film (∼10 μm) and shadow mask. Therefore, the detail information about parylene C deposition was described as following.

The parylene C coating formed by CVD could provide permanent anti-adhesive property on silicon wafer surface. The parylene deposition process consists of three steps: vaporization, pyrolysis

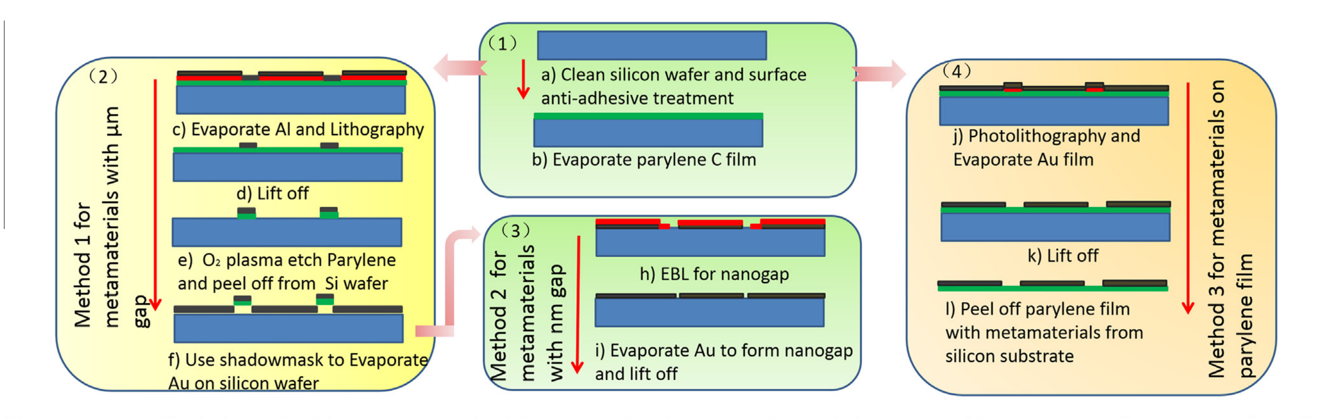

Fig. 1. The fabrication processes of the flexible, large-area metamaterials with micro/nanogap and high Q value.