Antireflective broadband micro structure at terahertz range by a hot deformation

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***Abstract*—We fabricated an antireflective structure on a polystyrene (PS) at terahertz (THz) frequency by using a hot-emboss method. Polystyrene was spin-coated onto a silicon substrate and then deformed by using a metallic mold comprising a bunch of Chinese acupuncture needles. The transformed layer yielded gradient refractive index profiles on the substrate which can reduce the surface reflection effectively. The samples were evaluated by a terahertz time-domain spectroscope system. Compared with a bare silicon substrate, we observed an increase of ~30% in the transmittance. We also observed broader bandwidth properties compared with a single-layer antireflective structure.**

I. INTRODUCTION

As we know, the energy levels of the THz waves generated by compact THz sources, e.g., photoconductive antennae, are relatively low [1]. THz components usually suffer surface reflection loss and Fabry-Perot resonance [2]. The traditional antireflective techniques in visible range have been studied for many years, such as depositing a dielectric material with a quarter-wave thickness onto the device's surface [3]. However, the narrowband property, and the difficulty of finding proper coating materials, especially the substrate limitation make it unsuitable for broadband high-performance THz components. A polymer is a versatile material that has an excellent processability and is light, low-cost, and very transparent in the THz region [4].

In this study, in order to fabricate an antireflective sub-wavelength surface relief structure pattern, a metallic mold which comprises a bunch of Chinese acupuncture needles was used to transform a spin-coated polystyrene layer by a hot-embossing technique on a high resistant (HR) silicon substrate. By this simple process, an outside-in gradual effective refractive index profile for the antireflection was constructed successfully on a silicon wafer surface (Fig. 1).

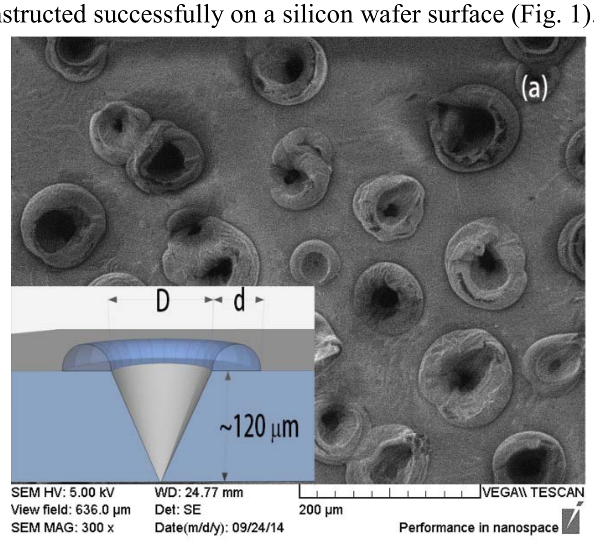

Fig. 1. SEM image of antireflection structure obtained by hot embossing where the thickness of the coating is approximately 120 μm, hole diameters (D=2R) are in the range of 30–60 μm, and annulus widths (d=2r, difference between the inner and outer diameters) are in the range of 20–40 μm.

II. RESULTS

A THz time-domain spectroscope (TDS) system (FiCO, @Zomega Corp.) was used to evaluate the transmittances of the samples, with a valid bandwidth from 0.1 to 1.5 THz. The deformed PS layer not only can bring an antireflective effect but also probably cause an extra scattering loss of the incident THz radiation. The scattered radiation is difficult to be directly detected, therefore, instead of the reflectance we measured the transmittance of the samples. To minimize the disturbance of the Fabry-Perot effect, only the primary pulse in time domain was used.

The results are shown in Fig. 2, where the y-axis represents the transmitted intensity, and the x-axis represents the frequency of the THz radiation. The black solid line is the transmitted intensity of a bare HR silicon substrate; because of the surface reflection, only 50% transmittance can be achieved. When a 120 μm PS antireflective layer was coated on the substrate, two enhanced peaks appeared (red dash-dot line in Fig. 2): at 0.37 THz (811 μm) and 1.10 THz (270 μm). These two peaks correspond to the canceling interferences between the first and second order reflection of 0.37 and 1.10 THz after phase shifts of π and 3π, respectively. The black short-dot line indicates the calculation results for the normal incident direction, not considering the absorption loss or refractive index dispersion of the PS material. We obtained the highest transmittance (blue dash line), which was approximately 20% higher than that of the single layer coated HR silicon substrate.

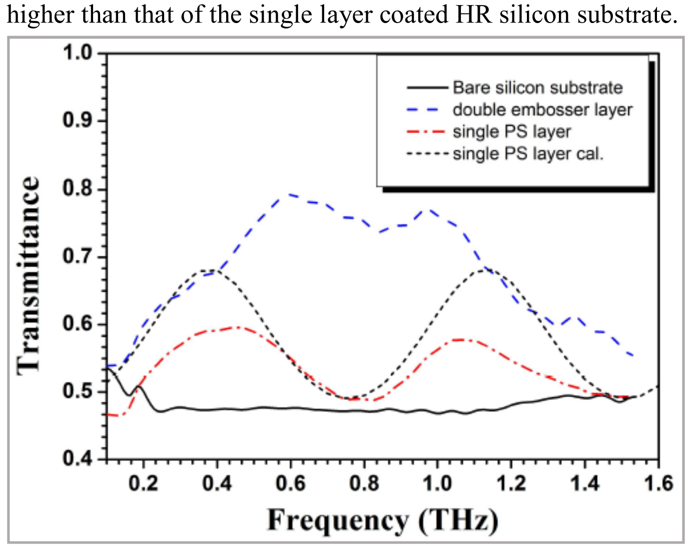

Fig. 2. (color online) Transmittance spectra of the bare HR-Si, single-layer PS, single layer PS (cal.), and double-side PS with hot-embossed samples.

We see that after the hot embossing, the sample exhibited an increased transmittance throughout the frequency range of 0.1–1.5 THz. Meanwhile, the canceling interference between the first and second reflections became weaker than the non-processed one. Compared with the single-layer antireflection coating, the extra embossing process can significantly broaden the antireflective bandwidth.

To verify the experimental data, we simulated the transmittances of the samples by the CST MICROWAVE STUDIO. For the embossed samples the structure shown in Fig. 1 was used (D=60, d=30), the simulation model and results are shown in Fig. 3(a) and (b). In the simulation, the THz radiation was irradiated normally to the samples, absorption loss as well as refractive index dispersion of the PS material were not considered.

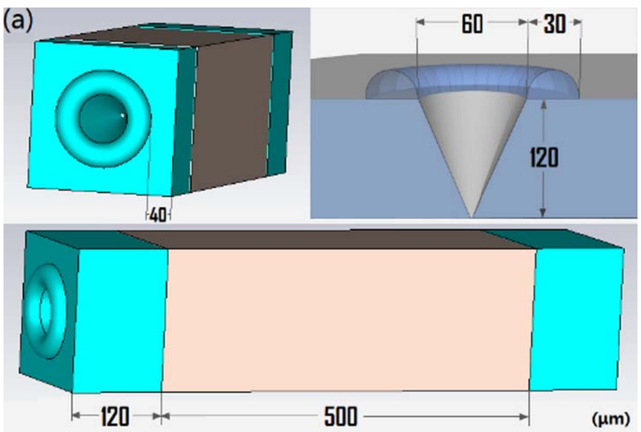

Fig. 3. (a) Simulation model, the diameter of the cone (D=60 µm), the diameter of the annular bulge (d=30 µm), the space between each unit (~40 µm), the thickness of the PS layer (Hps=120 µm), and the thickness of the silicon substrate (His=500 µm) were marked.

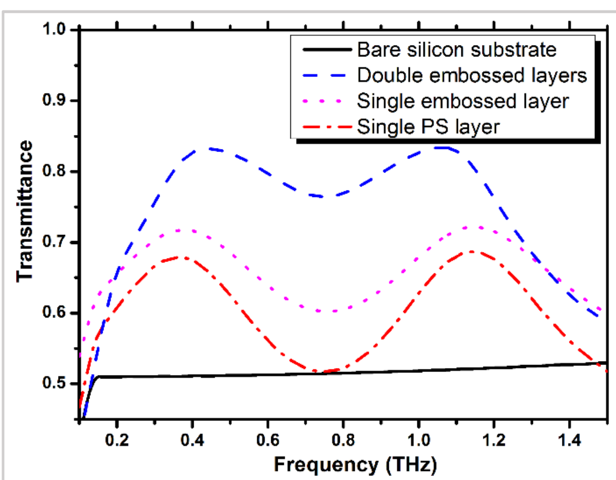

Fig. 3. (b) Simulation result of the transmittance spectra of the bare HR-Si, single-layer PS, single hot-embossed PS layer, and double-side PS with hot-embossed samples.

The pink dot line in Fig. 3 (b) indicates the transmittance of the single-side embossed PS/silicon sample. From the simulation we can see that with the relief structure, the sample exhibited an increased transmittance throughout the frequency range of 0.1–1.5 THz. Meanwhile, the interference between the first and second reflections of the coated layer became weaker than the non-processed one (red dash-dot line in Fig. 3(b)). The simulation agrees well with the experiment results. For the double-side embossed sample, the transmittance can be further enhanced and the highest transmittance was achieved (blue dash line in Fig. 3(b)). In the experiment, we obtained an approximately 20% enhancement than that of the single layer coated HR silicon substrate. The experimental peaks slightly deviate from the theoretical simulation peaks, this may be because the incident THz waves were not perfectly normal to the sample's surface and the thickness of the PS layer were not precisely controlled. In addition, the simulated data exhibit values 4%-7% higher than those of the experimental data; this could be due to the absorption of the silicon and PS layer.

Because of the refractive index gap ($\triangle n = 1.83$) between the PS and silicon substrate, the reflectance at the PS/silicon interface suppresses the total antireflective effect of the embossed microstructure. Thus, achieving a high refractive index and highly transparent THz materials is the foremost challenge.

III. Summary

In conclusion, Chinese acupuncture needles were utilized for a metallic mold, and hot embossing was applied to form a gradient refractive index profile for antireflection in the THz region. Using this very-low-cost equipment and simple process, we increased the transmittance from 50%, for a bare silicon substrate, to approximately 75%, which is ~20% higher than that of single antireflective layer. The proposed structure provides a far broader bandwidth (0.1–1.5 THz) than the single-layer antireflective structure and can decrease the Fabry-Perot resonance effectively. In contrast with other surface relief structure fabrication methods, hot embossing imposes lesser substrate limiting and can therefore be applied onto various THz substrates and devices. By optimizing the mold structure, coating material, and other design parameters, the antireflective effect can be further enhanced.

References

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