

# High Transmittance and Broaden Bandwidth through the Morphology of Anti-Reflective Layers on THz Polarizer with Si Substrate

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## ABSTRACT

To improve the transmittance of THz component and overcome the difficulties of fragile structure as well as ensuring precise alignment of existing methods, a new method involving the mature 3DIC through-silicon via (TSV) technology has been proposed to make anti-reflection layer with suitable effective refractive index based on the robustness of Si wafer. Cu wire-grid polarizers were also fabricated on wafer. The THz polarizers were completed after wafer bonding with Cu sealing ring and In/Sn guard ring. Not only the new method is easier for production with better performance, but also the silicon substrate has several advantages. The novel method has proven that THz optical component could be constructed with a nearly 100% transmittance, or widened the transmittance spectrum range from 0.5 to 2 THz when transmittances is sacrificed to 70% instead of a near 100%. Furthermore, a robust structure could also be expected with broadband transmission and excellent extinction ratio. It is properly optimized for mass production because the fabrication method could be easily done and does not required high cost.

**Keywords:** THz Polarizer, wire-grid, DRIE, wafer bonding

## 1. INTRODUCTION

Terahertz (THz) optical system has been widely used in spectroscopy, astronomy, medical images, security and more [1]. Finding a suitable optical component, such as polarizers, for THz system with low Fresnel loss has been a challenge. One of the fabrication methods is to fabricate wire-grids on a thin film substrate with fragile structure for long-term usage [2,3]. When THz penetrates the thin film, the transmission loss is extremely small. As for another method using the Brewster's angle concept, TM mode of electromagnetic wave can be perfectly transmitted to several substrates with high extinction ratio to TE mode and high transmission [4,5]. However, it requires precise alignment while using it. A new method is introduced in this paper, which fabricates a mono-material multilayer anti-reflection (AR) coating, by using deep reactive-ion etching (DRIE) and other etching recipes.

Through-silicon via (TSV) and wafer bonding are two important technologies of 3DIC, which extends Moore's Law, the number and performance of transistor double every 18 months. The key TSV technology utilizes the vertical electrical interconnection to make connections between the circuit elements on each chip. After that, wafer-bonding technology is carried out to connect the respective TSVs. Therefore, more chips can be stacked vertically and the density of the vias is substantially higher leading to an increase in the functionality of the device. In this research, THz polarizers by using the technologies mentioned above are demonstrated. Unlike the thin film structure, the new structure is based on the silicon wafer for its robustness. Also, the new method has shown advantages, including broadband transmission, excellent extinction ratio, low cost and easy method for mass production [6].

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## 2. DESIGN OF FABRICATING THZ COMPONENT

### 2.1 Design of AR coating

Si substrate has shown advantages of robustness, low cost, low dispersion and low absorption loss in THz. Nevertheless, the only downside of Si substrate is its high reflectance because of the high refractive index in THz region. To avoid high reflectance, AR coating is designed to have precise thickness ( $t_{AR}$ ) of a quarter of wavelength and refractive index ( $n_{AR}$ ) of square root of Si refractive index for a single frequency with high transmittance [7-9], as shown in Figure 1(a). As the incidence beam passes through the thickness ( $t_{AR}$ ) of a quarter of wavelength of AR coating, the phase difference of the first reflective and second reflective beam is half of the wavelength resulting in destructive interference. The relations among the parameters are shown in the equations below:

$$t_{AR} = \lambda_0/4n_{AR} \quad (1)$$

$$n_{AR} = \sqrt{n_{Si}} = \sqrt{3.4} = 1.84 \quad (2)$$

where  $\lambda_0$  is central wavelength in free space. Instead of finding a rare material with the exact refractive index and low absorption loss for AR layers in THz region, we etched cylindrical holes on the surface of Si to tune to a quarter of wavelength as a way to construct the AR layer with specific index and also specific thickness. According to the effective medium theory, the effective index of two mixing materials is equal to equation (3):

$$n_{AR} \cong f \times 3.4 + (1 - f) \times 1 = \sqrt{3.4} \quad (3)$$

where  $f$  is filling factor of Si and air [10]. By calculation,  $f$  is 0.35 to achieve the effective index.

### 2.2 Wire-Grid Fabrication

Wire-grid polarizer is the linear polarizer consists of a regular array of fine parallel metallic wires, which is placed in a plane perpendicular to the incident beam. The wire-grid structure is extremely durable which makes the design flexible. Furthermore, wire-grid polarizers are usually used in THz system for its high extinction ratio when wire width to space ratio equals to one. Lift-off process of photolithographic technique was used to place a 5 $\mu$ m wire width Cu wire-grid with a 10  $\mu$ m period on an intrinsic double-side polished Si wafer (>10000 ohm-cm, 4 inch, 500  $\mu$ m thickness, <100>) without AR layer fabrication as a benchmark, where Cu thickness is 3000 $\text{\AA}$ . Figure 1(b) shows the wire-grid structure after lithography. After fabrication, the performance of polarizers with and without AR layers would be compared by THz time-domain spectroscopy (TDS).

### 2.3 Preparation for Wafer Bonding

Low temperature metal bonding of In/Sn layer with Cu was used for wafer bonding at low temperature after AR layer fabrication [11]. According to prior art, In/Sn to Cu bonding with Ni buffer layer could make the two Si wafers bond perfectly together [12]. From the influence of bonding temperature, formation of intermetallic compound (IMC) is most likely to occur between In/Sn and Cu, which result in bonding failure [13]. Therefore, Ni buffer layer was added to delay the IMC formation. Two Si wafers were bonded together, where AR coating was outward and wire-grid were inward, to prevent Cu corrosion. The wafer bonding diagram and metal thickness are shown below in Figure 1(c). In/Sn/Ni/Ti layers were on the bottom substrate acting as sealing ring to seal Cu wire-grid polarizer on top wafer.

### 2.4 Process flow

Figure 1(d) shows the THz wire-grid polarizer with AR layers fabrication flow. Firstly, Si wafers were etched by DRIE with 12.6 $\mu$ m hole diameter and 2.4 $\mu$ m space according to the designed filling factor, and with different etching depth according to the central frequency. The arrangement of hole arrays were hexagonal. After the fabrication of Cu wires, preparation process for wafer bonding was carried out. In/Sn/Ni/Ti was deposited on bottom wafer as sealing ring. Both sealing ring and wire-grid structures would be completed after lift-off process. After fabricating the top and bottom wafers, two wafers were bonded together at a temperature of 150 $^{\circ}$ C for 30min. Therefore, AR layers were on the outer

part of the component and Cu wire-grid polarizer was sealed inward. This approach of combining two AR layers with same or different central frequency allows the polarizer to have a higher or broaden transmittance.

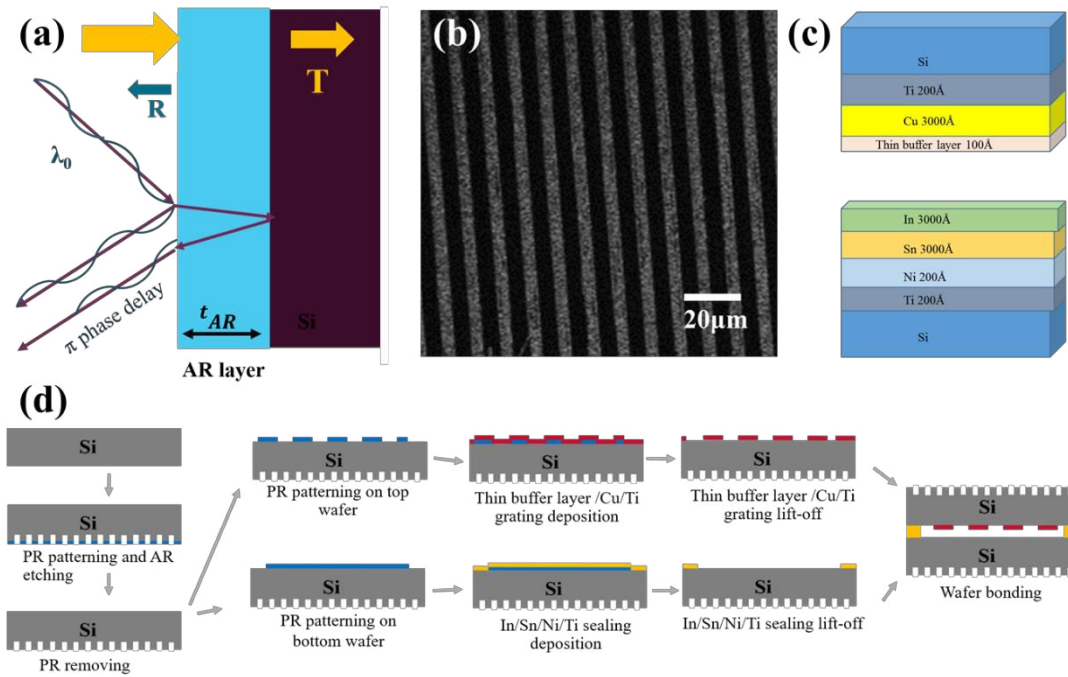


Figure 1. (a) Scheme of AR layer on Si wafer, (b) SEM image of Cu wire-grid on Si wafer, (c) scheme of wafer bonding structure and (d) process flow of fabrication of THz polarizer.

### 3. RESULTS AND DISCUSSION

#### 3.1 Etching and Bonding Results

SEM images of the etching results are shown in Figures 2(a) and (b). Hole diameter used for AR1 sample is approximately 12.2 μm while the tapered hole diameter of AR2 is an average of 13.5 μm, as shown in Table 1. The effective refractive indices of the two samples are 1.96 and gradient, which were calculated by filling factor. Both AR1 and AR2 were designed according to the parameters of Table 1. The results have shown a slight difference leading to small shift of central frequency and will be further discussed in next section. Scanning acoustic tomography (SAT) image in Figure 2(c) shows an overall good bonding result with only a few white spots indicating un-bonded area which is due to surface contamination.

Sample	AR1	AR2
The designed central frequency	1.7 THz	0.7THz
$t_{AR}$ (expectation of etching depth)	23.98μm	58.1μm
<b>Etching results</b>		
Etching depth of holes	23.8 μm	58.1μm
Hole diameter	12.2 μm	14.1μm @ top, 12.9μm @ bottom
Si filling factor	0.40	gradient
Effective refractive index	1.96	gradient

Table 1. Parameters of AR1 and AR2

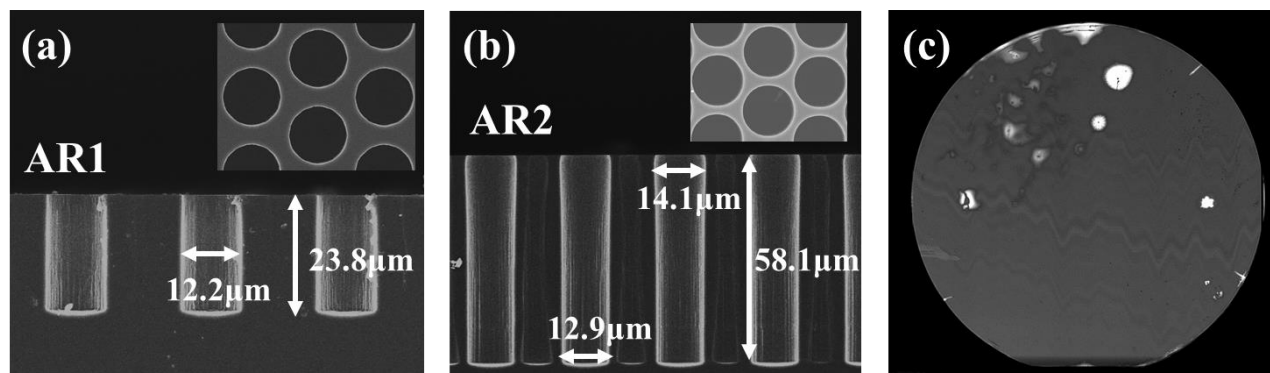


Figure 2. (a)SEM image of AR1 etching result, (b) SEM image of AR2 etching result and (c) SAT image of bonding result.

### 3.2 THz- TDS result

Figure 3(a) shows THz-TDS measurement. The results in frequency domain were transformed through Fourier transform and the second reflection pulse was ignored before normalization with free space signal. All the samples were placed after a commercial polarizer. Figure 3(b) shows the transmittance and extinction ratio of polarizer without AR layers as a benchmark. The transmittance is always about 50% because of the high index and low dispersion of Si, and the extinction ratios of TE to TM mode are between 20dB to 30dB depending on the pitch of Cu wires.

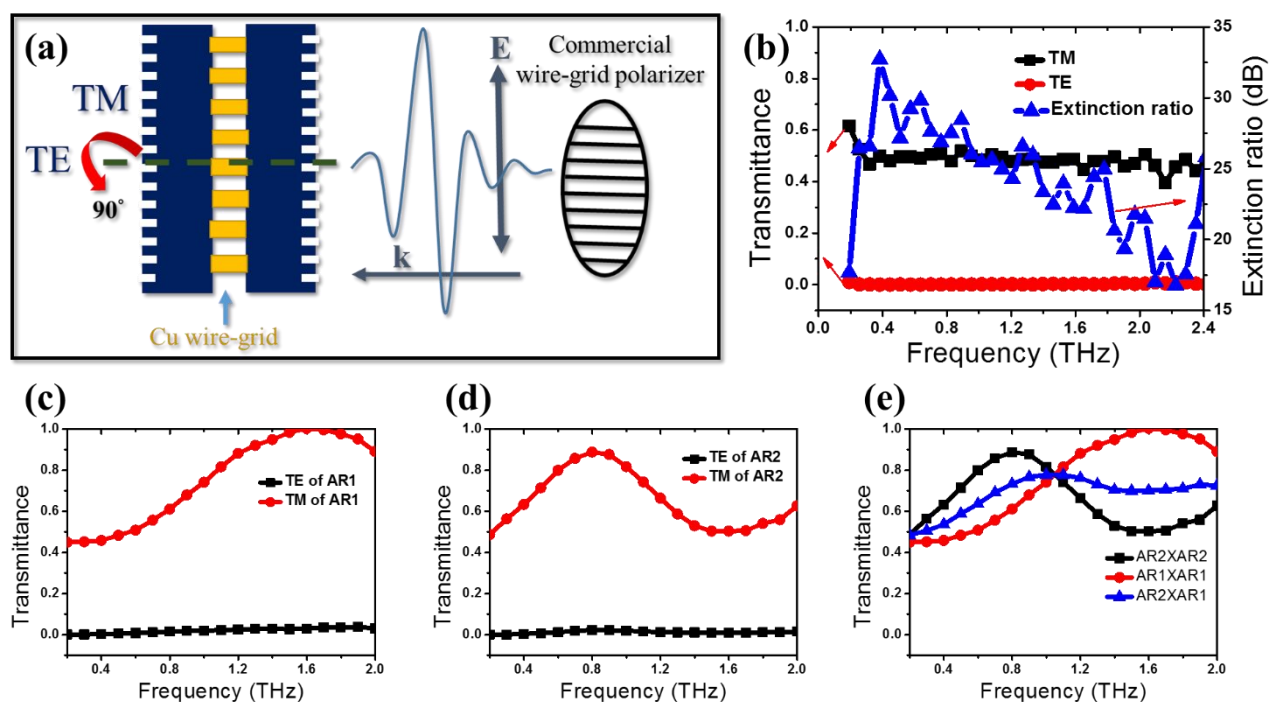


Figure 3. (a) Scheme of measurement of THz-TDS system, (b) transmittance spectrum and extinction ratio of THz polarizer without AR layer as a benchmark, (c) transmittance spectrum of TM and TE mode of AR1XAR1 polarizer, (d) transmittance spectrum of TM and TE mode of AR2XAR2 polarizer and (e) transmittance spectrum of TM mode of three types of THz polarizer and the uniform transmittance around the peak of AR1XAR2 polarizer

AR layers on both outer surfaces of bonded polarizer could solve the drawback of low transmittance. In Figures 3(c) and (d), the central frequency of AR1XAR1 polarizer is designed at 1.7THz. The designed central frequency of AR2XAR2 polarizer is at 0.7THz. AR1XAR1 and AR2XAR2 polarizers have their transmittance peaks corresponded to

the designed one with over 90% transmittance. Without precise alignment, power transmittance at the peak of AR1XAR1 and AR2XAR2 polarizers are about 100% and 90%, and peak widths are about 1.2 THz and 0.69 THz respectively. Transmittance has improved significantly with an almost 100% transmission at the peak. For the third polarizer, Cu wire-grid was sealed by using two wafers with AR1 and AR2 layers. Comparing the results with polarizer with same AR layers on both sides, the transmittance spectrum is widened and has a nearly uniform transmittance in bandwidth by bonding two different central frequency AR layers, as shown in Figure 3(e). The transmittance spectrum is broadened and the transmittance spectrum of AR1XAR2 is basically the product of the transmittance of AR1 and AR2. The peak value of AR1XAR2 polarizer has a uniform transmittance of about 70%, and the bandwidth is extended to 1.6THz. Therefore, the THz wave that passes through the AR1XAR2 polarizer would be with low distortion and high power transmission. For the AR1XAR2 polarizer, the transmittance is 70%, which is tolerable. Furthermore, the broaden bandwidth would have more usage rather than narrower bandwidth in the central frequency of AR1XAR1 and AR2XAR2 polarizers.

However, the central frequency of AR2XAR2 is different from the original design because of the tapered hole. The etching holes by DRIE with high aspect ratio would face the problem of RIE-Lag, which is caused by the decrease of gas exchanging rate in the deep etching hole [14]. Therefore, rigorous coupled-wave analysis (RCWA) was used to simulate the transmittance spectrum of polarizer with straight and tapered holes. Figure 4(a) shows the models of AR layers with straight and tapered holes using in simulation, and (b) shows the simulation results of TM mode. The central frequency and peak width of polarizer with tapered-hole AR layers of simulation are changed from 0.7 to 0.88 THz and from 0.56 to 0.9THz because of the gradient index caused by non-columnar etching profile. Nevertheless, TDS results of AR2XAR2 do not match perfectly with the simulation results. According to Figure 2(b), the side-walls of holes are not oblique but curve. Therefore, the gradient of the AR layer index is not linear and different to simulation model. However, the peak width of TDS results in Figure 4(c) still has a broaden width of 0.68THz.

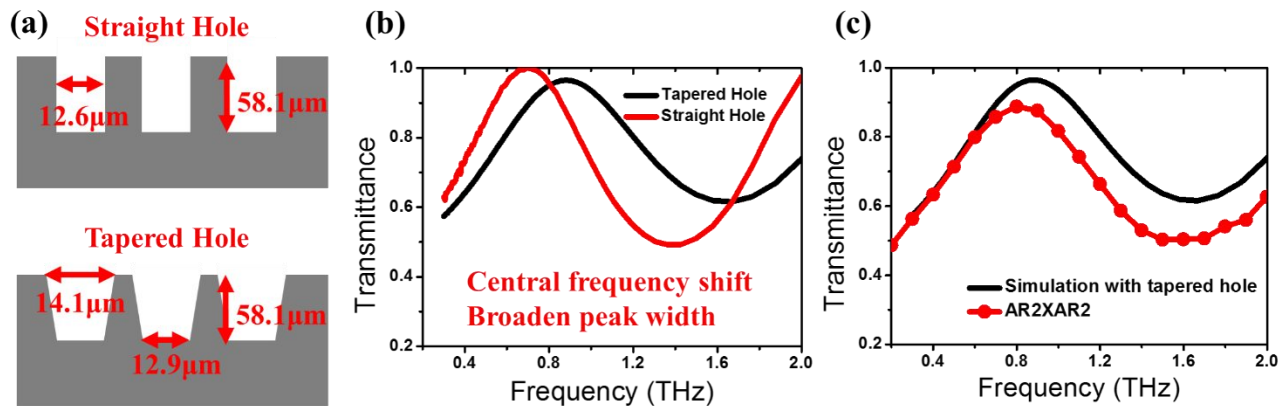


Figure 4. (a) Simulation models of straight hole and tapered hole, (b) simulation results of TM mode of straight and tapered holes, and (c) transmittance spectrum comparison between simulation and AR2XAR2 polarizer.

#### 4. CONCLUSION

A new fabrication method of THz polarizer has overcome the drawbacks of traditional method, such as fragile and its high level of difficulty in alignment. Si is used as a good substrate with its low dispersion, robustness, low cost and easy method for mass production. Furthermore, the fabrication parameters of AR layers are based on the calculated filling factor, the effective refractive index and thickness. Hence, the results have shown a high transmittance of an almost 100% at a specific central frequency of AR layer. Broaden bandwidth of transmittance spectrum can also be realized by stacking different central frequency AR layers or using different etching profile with non-columnar structure. Broad bandwidth could reach up to 1.6 THz with a near uniform 70% transmittance. The results prove that not only does the new method works excellently but it also has the potential of being mass-produced for more applications.

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