

High Transmittance Silicon Terahertz Polarizer Using Wafer Bonding Technology

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ABSTRACT

Due to the difficulties faced in fabricating robust Terahertz (THz) optical components with low Fresnel reflection loss, the need to increase the efficiency of THz system with reduced cost is still considered as one of the most essential tasks. In this report, a new low cost THz polarizer with robust structure is proposed and demonstrated. This new THz wire grid polarizer was based on an anti-reflection (AR) layer fabricated with low temperature metal bonding and deep reactive-ion etching (DRIE). After patterning Cu wire gratings and the corresponding In/Sn solder ring on the individual silicon wafers, the inner gratings were sealed by wafer-level Cu to In/Sn guard ring bonding, providing the protection against humidity oxidation and corrosion. With the low eutectic melting point of In/Sn solder, wafers could be bonded face to face below 150°C. Two anti-reflection layers on both outward surfaces were fabricated by DRIE. With the mixing of empty holes and silicon, the effective refractive index was designed to be the square root of the silicon refractive index. The central frequency of the anti-reflection layers was designed between 0.5THz to 2THz with an approximate bandwidth of 0.5THz. The samples were measured with a commercial free-standing wire grid polarizer by a THz time domain spectroscopy (THz-TDS) from 0.2THz to 2.2THz. The power transmittance is close to 100% at central frequency. Extinction ratio of the polarizer is between 20dB to 40dB depending on the frequency. The advantages of this new polarizer include high transmittance, robust structure and low cost with no precision optical alignment required.

Keywords: wire grid polarizer, terahertz wave, anti-reflection, wafer bonding, eutectic point, DRIE

1. INTRODUCTION

THz wave has been widely used for spectroscopy, communication, medical images and security in the past decade [1]. In order to improve the efficiency of terahertz system, the design of THz optical components becomes a major research topic. The THz optical components, such as polarizers, are difficult to fabricate with low Fresnel reflection loss due to the limitation of the suitable materials [2]. Conventionally, THz polarizers can be produced either with metal wire grids or via Brewster angle reflections. THz polarizers with substrate are usually aligned at Brewster's angle to achieve excellent extinction ratio and high transmission power [3,4]. However, the specific angle alignment set the difficulties in the optical setup and might occupy more space in the optical system and increase the difficulty for the system modularization. On the other hand, free standing wire grid polarizers or thin film wire grid polarizers do not suffer from the drawbacks of Brewster angle type polarizers. It can be aligned within wide angle range and still maintain its performance. Nevertheless, the fragile structure is a serious issue of wire grids polarizers and it keeps the cost high while generating problems during handling [5].

To overcome the problems, a new THz polarizer structure is proposed in this report. The polarizer is based on patterned Cu wires sealed between two high resistivity Si wafers using low temperature wafer bonding with anti-reflection (AR)

layers fabricated on the both sides of wafer surfaces. The new polarizer is demonstrated to be robust, low cost with high power transmittance and high extinction ratio for selected wavelength region.

2. DEVICE DESIGN AND FABRICATION

2.1 Metal wire grid polarizer with Si substrate

Wire grid polarizers are commonly used in the THz and infrared systems. High extinction ratio can be achieved by fine pitch of metal wire grids if the wire width to space ratio equals to one [4]. Such structure can be easily produced with photolithography on semiconductor wafers. A Cu wire grid polarizer was fabricated by lift-off process with a 10 μm period and a 5 μm wire width on an intrinsic double-side polished Si wafer (>10000 ohm-cm, 4 inch, 500 μm thickness, <100>) as a benchmark. The thickness of Cu wires is 3000 Å. The polarizer was then measured by THz-TDS with a commercial free-standing wire grid polarizer with the secondary reflection signal removed. Figure 1 (a) shows the SEM image of Cu wires which are well defined by the lithography process. Figure 1 (b) shows the power transmittance of the THz pulse. The results show that Si has an extremely low dispersion between 0.2 THz to 2.5 THz. Moreover, the extinction ratio of the benchmark polarizer lies within 20 dB to 35 dB. However, it has a 50% power loss caused by the high reflectance from the two air/Si interfaces because of the large refractive index of silicon ($n_{Si} = 3.4$).

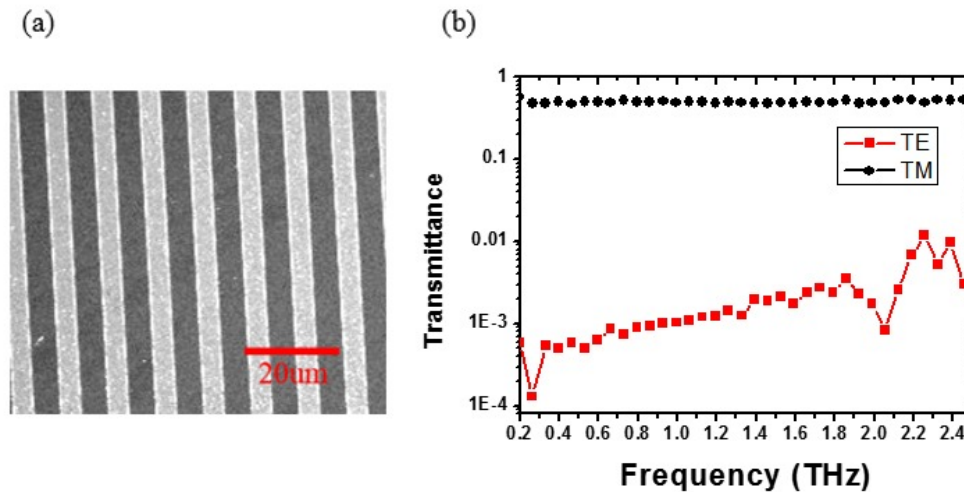


Figure 1. (a) The SEM image of the Cu wires on Si substrate, and (b) the TE and TM mode power transmittance of the wire grid polarizer without AR layer.

2.2 The design of AR layer

To reduce the high reflectance from the semiconductor air interface, AR films are frequently deposited on the substrate surface for Si optics [6]. The AR layer should have a refractive index (n_{AR}) equal to the square root of n_{Si} and the thickness of the AR layer (L_{AR}) should be

$$L_{AR} = \frac{\lambda_0}{4n_{AR}}, \quad (1)$$

where λ_0 is central wavelength in free space. Unfortunately, it is difficult to find a material with suitable index and low absorption loss for AR layers in THz region. In order to fabricate suitable AR layers for the polarizer, zero-order effective medium method is used to achieve specific refractive index [7-9]. With the combination of empty holes and Si, the index of refraction can be adjusted to

$$n_{AR} \cong f \times 3.4 + (1 - f) \times 1 = \sqrt{3.4}, \quad (2)$$

where f is the filling factor [10]. When f equals to 0.35, n_{AR} will be equal to the square root of n_{Si} to provide the good AR condition for Si substrates. Furthermore, the period of holes is selected to be significantly smaller than $\lambda_0/10$ to prevent the high order diffractions. With these parameters, AR layers were fabricated by etching cylindrical holes with hexagonal pattern on Si wafers. Samples with three different central frequencies of 0.65 THz, 1 THz and 1.66 THz were prepared and the etching depth is set to be 62.57 μm , 40.67 μm and 24.65 μm respectively. For AR layers with the effective refractive index, the period is set to 15 μm with 12.6 μm hole diameters.

2.3 Sample preparation

The fabrication steps of the proposed polarizers were shown in Figure 2 (a). The process flow included Ni/Cu/Ti wire fabrication, In/Sn/Ni/Ti ring formation, wafer bonding and AR layer etching. First, metal layers consisted of 200 Å Ti adhesion layer, 3000 Å Cu film and 100 Å Ni buffer layer were patterned into wires with 5 μm width and 10 μm period on the surface of first Si wafer (>10000 ohm-cm, 4 inch, thickness 525 μm , <100>). On the surface of second Si wafer, 200 Å Ti adhesion layer, 200 Å Ni wetting layer and 3000 Å of Sn and In layers were deposited and then patterned into In/Sn sealing ring by lithography. Two wafers were then bonded face to face at 150 °C with 15000 N force for 50 minutes in vacuum by a wafer bonder. The total thickness of metal layers is kept less than 1 μm to ensure that the THz wave can pass through the space between the two wafers without strong interference. AR layers were subsequently formed on the outward surfaces of the bonded wafer with photo resist (PR) hole-array as the etching mask for DRIE. The wafer was diced into 2 cm \times 2 cm polarizers. Figure 2 (b) shows the layout of 12 polarizers on a 4" Si wafer.

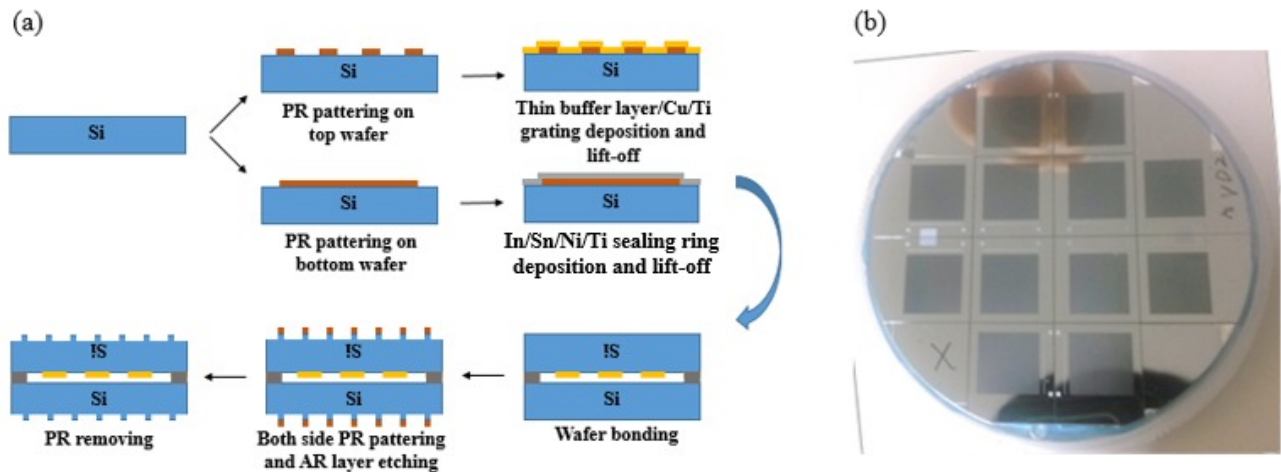


Figure 2. (a) the process flow of the polarizers, and (b) the final wafer with 2cm \times 2cm polarizers.

3. EXPERIMENTAL RESULTS

3.1 Metal bonding yield

A low temperature metal bonding of Sn/In layers with Cu has been widely studied for interconnections of Si integrated circuits in the recent years [10]. In-Sn binary system has a eutectic point at 118 °C. When the temperature rises to the eutectic point, In interacts with Sn at the interface of In/Sn layers and melts at the interface. Because of the liquid layer of In/Sn, it has large tolerance of surface roughness to improve the bonding yield. However, In/Sn solder also interacts with Cu to form intermetallic compound (IMC) with a melting point higher than 600 °C. When the thickness of In/Sn layers is too thin, the residue of In/Sn solder is not enough to form the liquid layer which would cause bonding failure. To prevent the possible bonding failure, A Ni buffer layer was deposited on Cu layer as a barrier to retard the

interdiffusion of the solder and Cu [11]. To test the bonding yield of the bonding structure in our samples, dummy wafers with the same metal bonding layers but without the metal grid was prepared as shown in figure 3 (a) and bonded with the same condition of the polarizers. Figure 3 (b) shows scanning acoustic tomography (SAT) results of the dummy sample. The bright area indicates the high reflection power of acoustic wave caused by voids. The voids were only formed by particles and the view ports of wafer bonder. We confirmed that the bonding yield of this bonding structure is high.

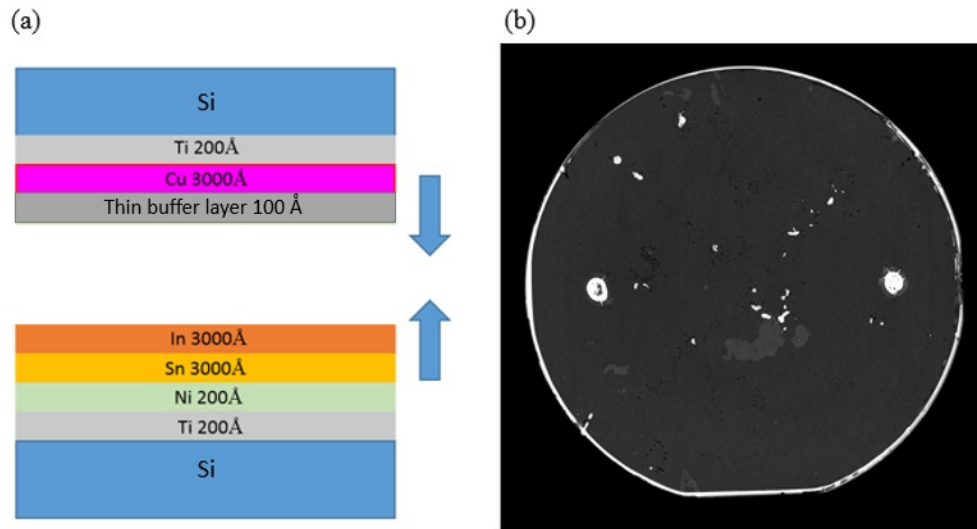


Figure 3. (a) the schematic of the bonding structure, and (b) SAT image of the dummy wafers after bonding.

3.2 AR layers

As mentioned in 2.2, the central frequency and the index of refraction of the AR layer depend on the thickness and filling factor of the patterned holes. The dimensions of the patterned holes in our samples were measured with SEM to confirm the control of fabrication process. Table 1 lists the designed parameters and measurement results of the three different AR layers. SEM pictures are shown in figure 4. Comparing the measurement numbers with the designed parameters, AR1 and AR2 samples are close to the original design. The diameter of the holes in AR3 sample is 17% larger than the designed value. Because of the large aspect ratio of the holes in AR3, the openings of PR mask were enlarged by ion bombardments during the long etching time. This generates a larger diameter for the etching holes. The large holes reduced the filling factor which makes the n_{AR} smaller than the designed value. Modification of the etching process with hard masks or smaller mask openings is planned to improve the production process in the future.

Table 1. The designed parameters of AR layers and the etching results.

Sample	AR1	AR2	AR3
The designed central frequency	1.66 THz	1 THz	0.65 THz
L_{AR} (expectation of etching depth)	24.65 μm	40.67 μm	62.57 μm
Etching depth of holes	23.8 μm	40.9 μm	58.8 μm
Hole diameter (with 12.6 μm mask opening)	12.2 μm	12.5 μm	14.0 μm
Filling factor	0.40	0.37	0.21
Effective n_{AR}	1.96	1.89	1.50

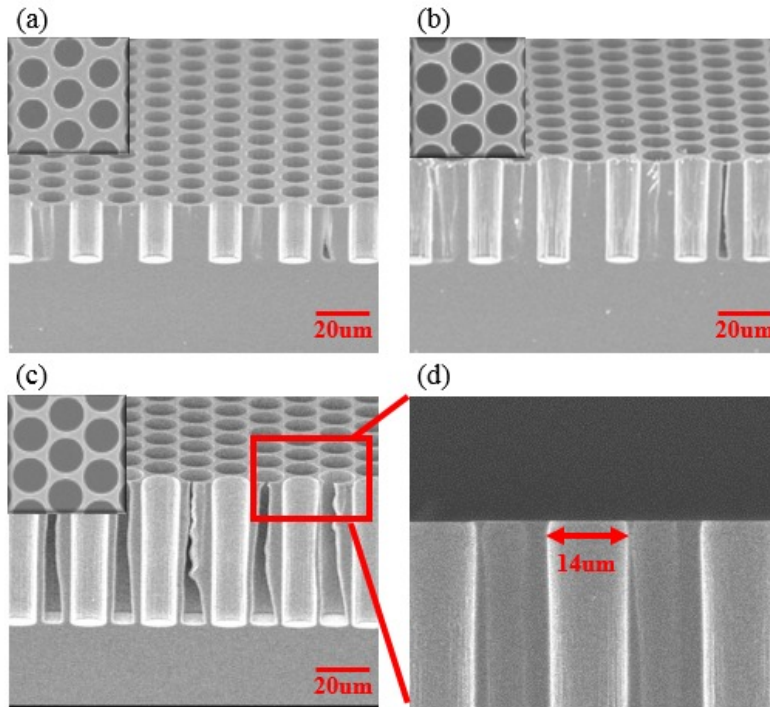


Figure 4. The SEM images of the etching profiles of (a) AR1, (b) AR2, (c) AR3 and the enlarged view of AR3(d) .

3.3 THz time domain spectroscopy

All the THz polarizer samples were measured by THz-TDS. The THz-TDS system is sealed by an acrylic box and dehumidified with relative humidity less than 5 % to minimize the absorption from water vapor. The central frequency of the THz pulse was 0.66 THz with 0.6 THz bandwidth. The samples were placed behind a commercial free standing wire grid polarizer with fixed polarization direction during the measurement. The TE and TM mode transmission signals were measured by rotating the samples. Figure 5 (a) shows the set up diagram of the THz-TDS measurement. The raw data of THz-TDS shows electric field variation in time domain. The same time interval was chosen for each measurement with and without the sample. The secondary reflection signal from the sample was removed from the data. To obtain the frequency information, the fast Fourier transform (FFT) is applied to the TDS signal. FFT algorithm converted the time signal to frequency domain with complex amplitude and phase information. Figure 5 (b) shows the power spectra without and with the sample at different orientations. It clearly shows the effect of the polarizer. The transmittance of the polarizer with different polarization direction was calculated from the power spectrum and shown in Figure 5 (c) and (d) for linear and log scales respectively. Each polarizer sample has maximum transmittance over 90 % of TM mode and minimum transmittance about 0.01 % of TE mode. Especially, the AR2 sample has almost 100 % TM transmittance at the designed central frequency. However, the central frequency of AR3 sample is shifted to higher frequency as a result of enlarged holes. According to equation (1) and (2), n_{AR} decreases with the smaller filling factor. With the fixed etching depth L_{AR} , the central frequency of the AR layer increases. Nevertheless, all three samples show high extinction ratio between 20 dB to 40 dB from 0.2 to 2.2 THz. Figure 5 (e) shows the extinction ratio for the samples.

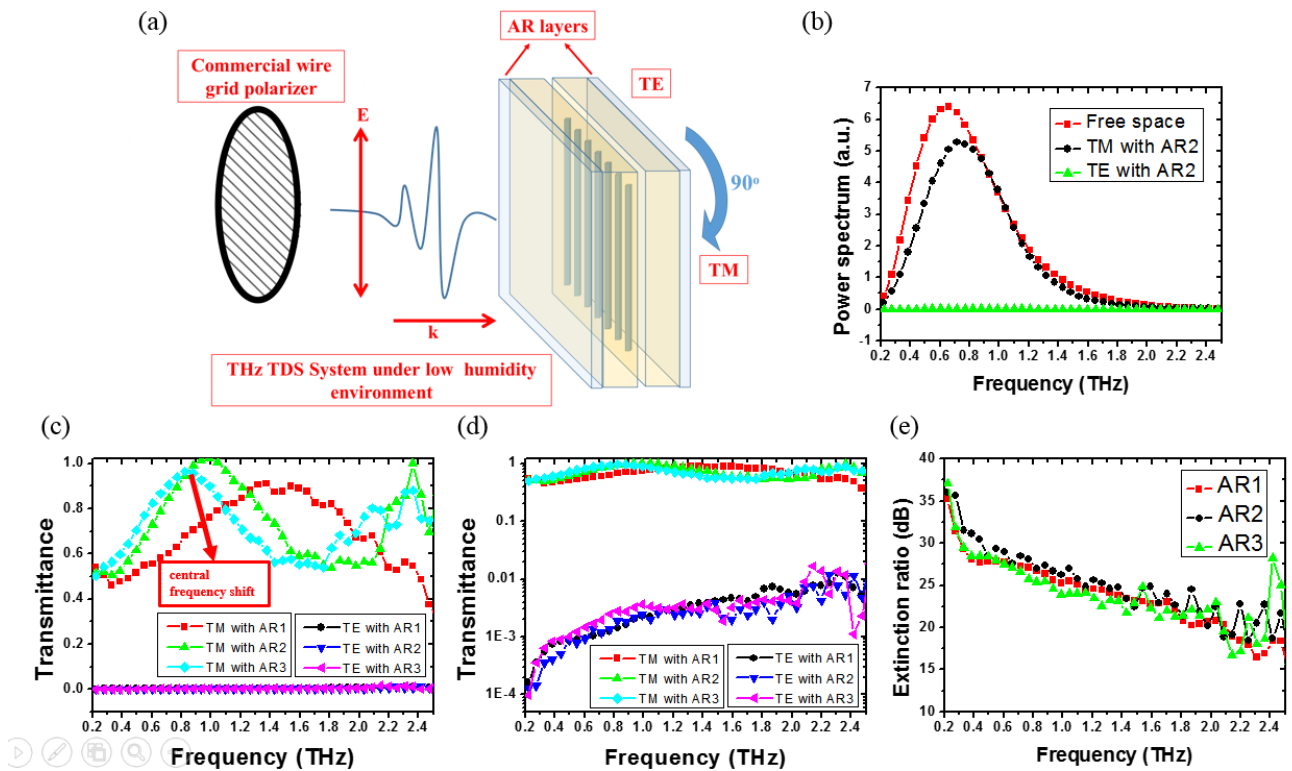


Figure 5. (a) the setup for the THz TDS measurement of the polarizers with a commercial free standing wire grid polarizer. (b) transmission power spectrum of the AR2 sample. (c) and (d) the transmittance spectrum for all samples in linear and log scales. (e) the extinction ratio of all the polarizers.

4. CONCLUSIONS

A new THz polarizer was demonstrated with robust structure, high transmittance, low cost and excellent extinction ratio. Cu wire grids are sealed and protected by two bonded wafers. Power transmittance is higher than 90% near the central frequency of the AR layer which can be adjusted with the depth and the filling factor of the etching holes. Extinction ratio of the polarizer is within 20 dB to 40 dB from 0.2 to 2.2 THz depending on the frequency and the Cu wire pitch. The polarizers provide high performance without any accurate alignment requirement, and have possibility to fabricate for infrared region (up to 10 THz). This fabrication process is compatible with the conventional semiconductor process method and is of great potential for the mass production of THz polarizers.

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