Broadband Multilayer Antireflection Coating in THz Region

H. Y. Yao, Z. Y. Chen and T. H. Chang
Department of Physics, National Tsing Hua University, HsinChu, 30013 Taiwan

***Abstract*—A new approach to the design and the realization of a broadband multilayer anti-reflection (AR) coating is proposed in this study. The binominal multi-section transformer is employed to efficiently determine the thickness and the refractive index of each matching layer, while those layers can be further realized by doping different fraction of subwavelength-size silicon powders (for relatively-high-index layers) or air pores (for relatively-low-index layers) into the low-loss HDPE polymer. Based on this scheme, we design a ten-layer AR coating for widely used silicon wafer. The designed AR coatings are double-side integrated with a 375-μm-thick silicon wafer, which is able to enhance the overall THz transmission to higher than 95.00% from 0.250 THz to 0.919 THz (114.46% bandwidth).**

I. INTRODUCTION

An antireflection (AR) coating is used to reduce light reflection from interface of two different materials or two devices, thus possible to increase the total transmission. Recently, this technique is applied in terahertz (THz) region to enhance the transmissions (or efficiencies) of some THz devices, such as THz windows [1], filters [2], photo-conductive antennas that use Si or GaAs substrates and silicon lens [3]. Among these important THz devices, silicon has been widely used due to its electric or optical properties. Nevertheless, since refractive index of the silicon is relatively high in THz region (~ 3.42), the Fresnel reflection of the light incident from the air to silicon achieves more than 30% [4], which significantly lowers the transmission efficiencies of silicon-based THz devices and might complicate the THz beam trail in experiment. Thus, our major goal is to develop an broadband AR coating which is capable of matching the THz wave transmitted between air and silicon.

In the previous research, single-layer AR coatings were the most common and easy way to accomplish this goal [4]. However, such AR coating only worked for narrow band owing to the fact that single wavelength was matched. Recently, multilayer AR coatings [5] or the sub-wavelength relief structures [6] were developed in order to enhance transmission as well broaden the available bandwidth in THz band. Nevertheless, both of methods suffered from serious difficulty in design (without powerful guideline) as well as in fabrication (limited by nature materials).

In this paper, we design a double-side multilayer AR coating, which contains 10 layers with different indices and thicknesses for single side to match air and silicon. The required refractive index and the thickness of each layer can be calculated by the binomial multi-section transformer [7] that has been widely used in microwave region for impedance matching. To overcome the limitation of nature materials, we suggest that the flexible and high-index composite layers can be fabricated through doping sub-wavelength-size silicon powders into low-loss HDPE layers. On the other hand, it is possible to realize the low-index layers by doping the air bubbles into the HDPE layers, forming the porous structure for the reduction of index. Based on this scheme, a design of broadband multilayer AR coating for silicon is proposed, which is able to significantly enhance the overall transmission power to more than 95.00% within 0.250 THz to 0.919 THz (114.46% bandwidth).

II. DESIGNS

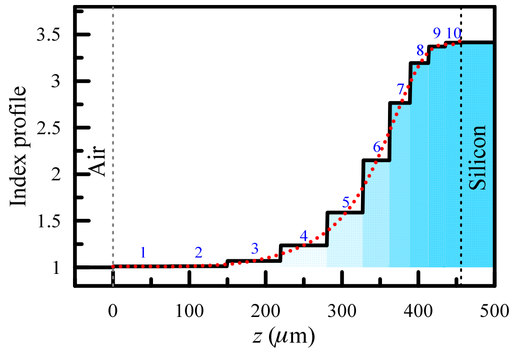

Fig. 1. The discretized index profile of the ten-layer AR coating designed for matching air (at $z < 0\ \mu$m marked by gray dashed line) and silicon (at $z > 456\ \mu$m marked by black dashed line). The location of each matching layer is indicated by the blue label. Note that the lower the index of the matching layer (closer to air), the thicker the thickness owing to the quarter-wavelength condition. The continuous red dotted curve is the 10th-degree polynomial regression; the coefficient of each term is listed in the main text.

Layer #	1	2	3	4	5
Index	1.001	1.013	1.069	1.235	1.589
d (μm)	75	74	70	61	47
ξ (%)	99.7	97.2	85.4	53	4.2
Layer #	6	7	8	9	10
Index	2.150	2.766	3.194	3.371	3.412
d (μm)	35	27	24	22	22
ξ (%)	39.4	70.4	89.7	97.4	99.1

Table 1

A ten-layer AR coating ($N = 10$) for matching air ($\text{index} = 1.000$) and silicon ($\text{index} = 3.418 + 3.817\times10^{-5} i$) at 0.550 THz is designed based on the binomial multi-section transformer [7]. Notably, the complex refractive index of silicon can be treated as a constant for current operating band (below one terahertz), whose imaginary part manifests the intrinsic dielectric absorption. The required index ($\mathrm{Re}[n_j]$) and the thickness (d_j) of each matching layer are shown in Table 1. The corresponding index profile with respect to the propagation direction ($\hat{z}$) is illustrated in Fig. 1, in which the location of each matching layer is individually specified. The continuous index profile (red dotted curve) is the 10th-degree polynomial regression fitted to the discretized index profile. Note that the fitted index profile has relatively small slope for two-side layers, *i.e.* the layers at the regions close to the input (air) and the output (silicon) zones, while varies relatively fast for the layers embedded in between. This design coincides with the suggested quantic profiles shown in [8] obtained by heavy numerical optimizations for minimizing the overall reflection.

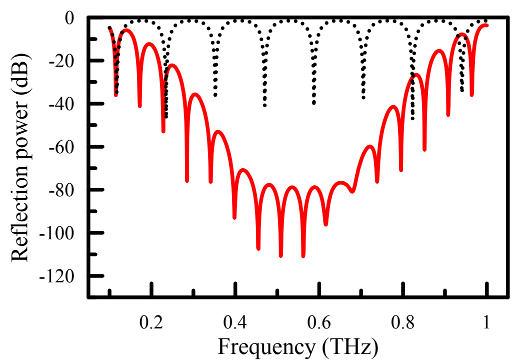

Fig. 2. Reflection powers of 375-μm-thick silicon in the absence (black dashed curve) and the presence (red solid curve) of the designed multilayer AR coating.

To overcome the limitation of nature material, we suggest that low-loss high-density polypropylene (HDPE, Index=$1.530+4.660\times10^{-4}i$) doped with subwavelength-size high-resistivity silicon powders should be suitable to realize the high-index layers (for all layers with their $\mathrm{Re}[n_j]\geq1.530$). On the other hand, it is possible to fabricate the low-index layers (for all layer with their $\mathrm{Re}[n_j]<1.530$) by doping air pores into HDPE layer. The effective medium theory [9] is employed to calculate the effective refractive index of composite as a function of the volumetric doping ratio. The suggested recipes (doping rates) of the designed matching layers are listed in Table 1.

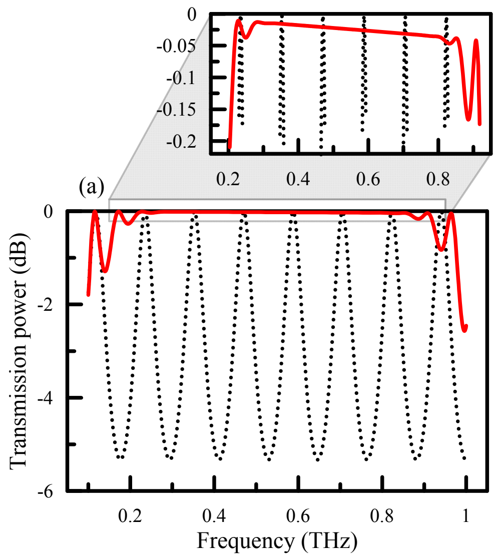

Fig. 3. Transmission powers of 375-μm-thick silicon in the absence (black dashed curve) and the presence (red solid curve) of the designed multilayer AR coating.

Figure 2 displays the overall reflection power for a 375-μm-thick silicon integrated with the designed AR coating by the red solid curve (defined as the well-matched system). While reflection performance of the case in the absence of AR coating (defined as the unmatched system) is also illustrated by the black dotted curve for comparison. While the AR layers are coated on the double sides of the wafer, the overall reflection is significantly suppressed below the Fresnel reflection (-5.24 dB) from 0.102 THz to 1.031 THz, yielding a 163.99% bandwidth of improvement. Despite the several resonant depths in the reflection spectrum, it is clear that the well-matched system exhibits much lower reflection and broader bandwidth, in which the minimum reflection (-110.92 dB) appears at 0.562 THz, quite matching the design central frequency (0.550 THz).

Figure 3 demonstrates the overall transmission powers for the wave transmitting through the unmatched silicon (black dotted curve) and the well-matched system (red solid curve). The transmission power of the well-matched system could get higher than -0.223 dB (95.00%) from 0.203 THz to 0.919 THz, implying an ultra-broad bandwidth of 127.63%. Within this range, the maximum transmission achieves -0.008 dB (99.82%) at 0.115 THz.

III. Conclusions

We design a ten-layer anti-reflection coating for widely used silicon wafer in THz region. The thickness of each matching layer and the refractive index profile are determined based on the guideline of binomial multi-section transformer, while those layers are realized by doping the high-index (silicon) or low-index (air pore) subwavelength-size particles into the host polymer layers (HDPE). The THz transmission power from a 375-μm-thick silicon double-side integrated with the designed AR coating is as high as 95.00% for 0.250 THz to 0.919 THz (114.46% bandwidth). This implies that the present design might have multiple further applications in THz windows, THz filters, THz lenses, and semiconductor source devices.

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