An Anti-Reflection Coating for Silicon Optics at Terahertz Frequencies

A. J. Gatesman, J. Waldman, M. Ji, C. Musante, and S. Yngvesson

***Abstract*—A method for reducing the reflections from silicon optics at terahertz frequencies has been investigated. In this study, we used thin films of parylene as an anti-reflection (AR) layer for silicon optics and show low-loss behavior well above 1 THz. Transmittance spectra are acquired on double-sided-parylene-coated, high-resistivity, single-crystal silicon etalons between 0.45 THz and 2.8 THz. Modeling the optical behavior of the three-layer system allowed for the determination of the refractive index and absorption coefficient of parylene at these frequencies. Our data indicate a refractive index, n, of 1.62 for parylene C and parylene D, and a reasonably modest absorption coefficient make these materials a suitable AR coating for silicon at terahertz frequencies. Coatings sufficiently thick for AR performance reduced the average transmittance of the three-layer system by <10% compared to a lossless AR coating with an ideal refractive index.**

***Index Terms*—Anti-reflection, parylene, silicon, terahertz.**

I. Introduction

SINGLE layer thin films are routinely used as a means of suppressing the reflection of electromagnetic radiation from a surface. The success of such a technique depends upon how close the thin film's refractive index is to the required value, as well as the amount of electromagnetic loss encountered in the thin film. At normal incidence, the total power front surface reflection from an optical component at wavelength λ can be made zero if

$$n_{\mathrm{AR}} = \sqrt{n_o} \tag{1}$$

and

$$t_{\mathrm{AR}} = \frac{(2m+1)\lambda}{4n_{\mathrm{AR}}} \quad (m = 0, 1, 2, \cdots) \tag{2}$$

where n_{AR} and n_o are the refractive indices of the anti-reflection (AR) layer and the optical component, respectively, and t_{AR} is the thickness of the coating. The thickness of the AR layer can be any odd number of quarter wavelengths, and typically, is $\lambda/4n_{\mathrm{AR}}$ thick to minimize effects of electromagnetic loss.

AR coatings of this type are routinely achieved in the visible and infrared spectral regions (e.g., MgF_2 on glass, SiO on silicon, and ZnS on germanium) where such materials can be applied with conventional thin film deposition techniques. At terahertz frequencies, difficulties are encountered when depositing materials at the thickness required for AR behavior ($t_{\mathrm{AR}} > 10\ \mu$m). Alumina-loaded epoxy has been used with good results as an AR coating for silicon lenses [1]. However, the epoxy material suffers from large absorption loss above 1 THz [2]. Englert [3] has successfully coated both sides of a silicon window with 20 μm of LDPE ($n \approx 1.52$) to achieve AR performance at $\lambda = 118\ \mu$m. Other common plastics such as Mylar and Kapton are potential candidates because their refractive indices are close to the required value of $\sqrt{n_{\mathrm{silicon}}} \approx 1.85$; however, such materials may be difficult to apply to small, curved optics such as a silicon lens. New materials, with the necessary refractive index and low-loss behavior, must be found which can be deposited in uniform layers at least ≈10 μm thick. Vacuum-deposited parylene, a material which is primarily used as a conformal encapsulant in the electronics industry, is one such candidate. Parylene is a thermoplastic polymer which has many attractive properties such as thermal stability, good adhesion properties, chemical inertness, and low water absorption.

Parylene C films have been successfully used between 1 and 8 THz as AR coatings on germanium lenses for the ISO satellite project [4]. The parylene-coated lenses were optimized for maximum broadband sensitivity of a detector field-lens assembly. Transmission of uncoated germanium in that frequency range is ≈47%. Parylene C coatings were used to substantially increase the transmittance of the optics with transmission peaks approaching 90%. Another device which would benefit significantly from low-loss AR coatings at terahertz frequencies is the superconducting hot-electron bolometer (HEB) [5]. These sensitive detectors of terahertz radiation typically use small silicon lenses to focus radiation onto an antenna-coupled detector element. All HEB measurements above 1 THz have been implemented without the use of AR-coated focusing lenses; this results in a ≈30% reflection loss at the silicon lens surface. Detector noise temperatures could be improved by 20–30% with the use of a low-loss AR coating. The ability of parylene to be applied as a uniformly thick, conformal coating would make coating the small, curved surface of a HEB silicon focusing lens possible. It has been shown theoretically [6] that a uniform AR coating thickness on a hemispherical lens gives essentially the same efficiency as an optimized coating of variable thickness with a difference of less than 0.5%. Irwin [7] has used parylene as an AR coating on silicon at mid-infrared wavelengths in the construction of dielectric-spaced resonant mesh filters. He reports both refractive index and absorption coefficient data for parylene N. The results indicated that the refractive index was either 1.44 or 1.62, and the absorption coefficient was too large for his application at those frequencies. Chen [8] studied the performance of a parylene-coated metal mesh filter at mid-infrared wavelengths and reported a refractive index of 1.65. In

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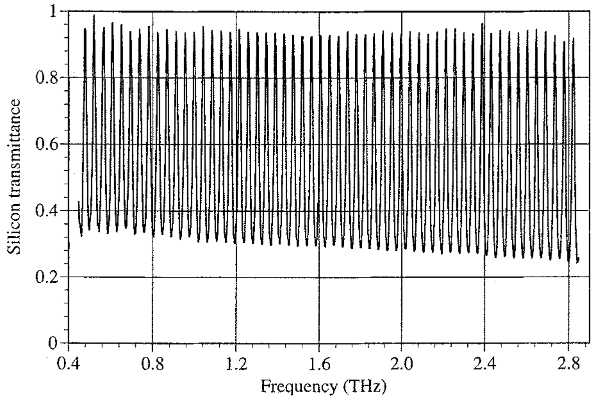

Fig. 1. Under-resolved terahertz transmittance of an uncoated high-resistivity ($\rho > 20\,000$ Ω-cm) 1011-μm thick silicon substrate.

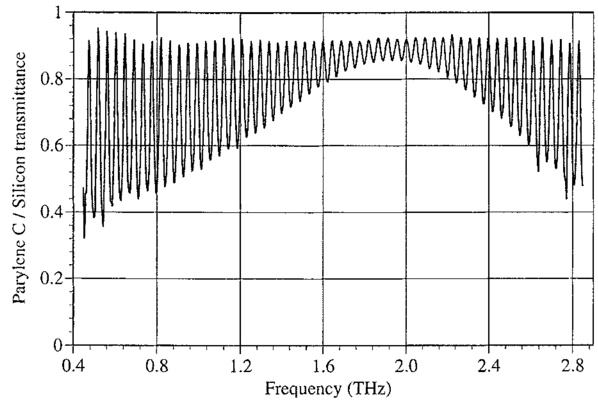

Fig. 2. Terahertz transmittance of a high-resistivity ($\rho > 20\,000$ Ω-cm) 1011-μm thick silicon substrate coated with 24.0 μm of parylene C on both sides.

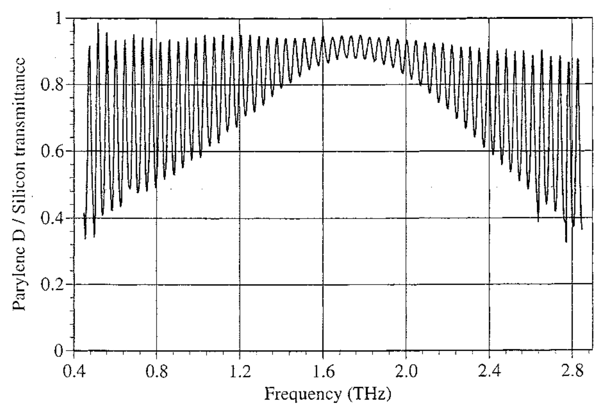

Fig. 3. Terahertz transmittance of a high-resistivity ($\rho > 20\,000$ Ω-cm) 1011-μm thick silicon substrate coated with 26.5 μm of parylene D on both sides.

this letter, thin coatings of parylene C and parylene D were used as AR coatings on high-resistivity silicon optics. Types C and D were chosen because of their higher dielectric constant compared with parylene N. The refractive index and absorption coefficient were found by studying the transmittance spectra of the parylene-coated silicon.

II. Measurements

Two 25-mm-diameter silicon etalons, polished to a thickness of 1011 μm, were coated with parylene C and parylene D by Specialty Coating Systems, Inc., Clear Lake, WI, to a thickness of 24.0 μm and 26.5 μm (both sides), respectively. High-resistivity ($\rho > 20\,000$ Ω-cm), single-crystal silicon was chosen as the substrate material because its properties were well-known at terahertz frequencies [9], and its low-loss behavior would permit the loss of the parylene to be estimated.

Submillimeter-wave spectra were acquired using a Bruker IFS 66v Interferometer configured with a Hg-lamp source, Mylar beamsplitter, and a LHe-cooled Si bolometer detector. Unpolarized, power transmittance measurements were acquired under vacuum to minimize the influence of atmospheric water vapor at these frequencies. Samples were oriented away from normal incidence by 1–2° to prevent reflected radiation from reentering the interferometer which can result in measurement errors. Fig. 1 shows an under-resolved transmittance spectrum of one of the high-resistivity silicon etalons prior to coating. The gradual downward trend of the spectrum's transmittance at higher frequencies is due to loss in the silicon. From this and prior research on silicon at these frequencies [10], we were able to determine the terahertz behavior of the uncoated silicon substrates. Figs. 2 and 3 show the transmittance of the parylene C and parylene D coated silicon, respectively. AR behavior can be observed at approximately 1.9 THz for the parylene C coated silicon and 1.7 THz for the parylene D coated silicon. The two frequencies do not coincide due to slight differences in coating thicknesses. These experimental data, along with the knowledge of the properties of silicon, allowed for the determination of the refractive index n, and absorption coefficient, α, of parylene C and parylene D.

III. Analysis

Theoretical modeling of the spectra in Figs. 2 and 3 was performed by using the Fresnel equations and a standard matrix calculation technique [11]. Typically, the refractive index and absorption coefficient of a single layer of low-loss material can be determined at terahertz frequencies from transmission spectra (such as Fig. 1) provided that the material thickness is known and not too large. In the situation here, the refractive index, absorption coefficient, and thickness of the parylene film are all unknown. Even though there are three unknowns, it is still possible to independently determine each of these film parameters from the transmittance data of Figs. 2 and 3. As shown by (1), the AR wavelength is determined by the product of n_{AR} times t_{AR}. This, however, poses no difficulty in the independent determination of n_{AR} and t_{AR} because it is n_{AR} alone that impacts the width of the transmittance envelop at the AR wavelength. The following steps were used to determine n_{AR}, α_{AR}, and t_{AR} of the parylene films from the spectral transmittance data.

1) An initial theoretical model was generated by using the known properties of silicon, the film thickness provided by the coater, a guessed value for the film's refractive index, and a film absorption coefficient of zero.

TABLE I
TERAHERTZ OPTICAL PROPERTIES OF A SILICON SUBSTRATE AND PARYLENE FILMS

	Terahertz Refractive index n	Absorption Coefficient (1/cm) at 2 THz	Thickness
uncoated silicon	3.4160 ± 0.0005	< 0.2	1011 μm ± 1 μm
parylene C	1.62 ± 2%	11 ± 20%	24.0 μm ± 5%
parylene D	1.62 ± 2%	7 ± 20%	26.5 μm ± 5%

2) The refractive index was varied until the width of the transmittance envelop at the AR wavelength was modeled correctly.
3) The film thickness was then adjusted until the experimental and modeled AR wavelengths matched.
4) Finally, loss was added to the parylene coating until a good match between the absolute transmission was obtained.

It was in this fashion that the optical properties and thickness were obtained for the parylene C and parylene D films from transmittance data alone. A summary of the terahertz optical properties of parylene C and parylene D along with the silicon substrate is given in Table I.

A refractive index of $n = 1.62$ was found for both parylene C and D, and it was observed to be independent of frequency between 0.45 and 2.8 THz. A value of $n = 1.62$ is lower than the ideal value of 1.85; however, excellent AR performance was still observed. For the parylene C sample, the average transmittance (averaged over a few fringes) at 1.9 THz reached 89%. Of the 11% difference from unity, loss in the silicon accounted for 1-2%, loss in the parylene accounted for 6%, and the remaining 3-4% was due to parylene C's nonideal refractive index. For the parylene D sample, the average transmittance at 1.7 THz was 91%. Of the 9% difference from unity, the loss in the silicon accounted for 1-2%, loss in the parylene accounted for 4%, and the remaining 3-4% was due to parylene D's nonideal refractive index. In the case where only a single AR layer is required, such as a silicon hemispherical lens for a HEB, total absorption losses due to the parylene would be only ≈2–3%.

The absorption for parylene C and D were modeled with an absorption coefficient, $\alpha_{\rm AR}$, linearly increasing with frequency from ≈3 cm^{-1} to 18 cm^{-1} and from ≈2 cm^{-1} to 11 cm^{-1}, respectively, between 0.45 and .8 THz. The thicknesses of the films provided by the coater were larger than the thicknesses found by modeling the data. The coater reported thicknesses of 27.2 μm and 32.3 μm for the parylene C and D films, respectively, by using a step profilometer. Optical modeling indicated slightly lower thicknesses of 24.0 μm for parylene C and 26.5 μm for parylene D which agreed well with micrometer measurements of 22.5 μm and 28.0 μm for the two films, respectively.

Uncertainties in the parylene's thickness and refractive index were determined by independently varying each parameter and finding the range of values over which a reasonable fit to the experimental transmittance could be established. Uncertainty in the parylene's absorption was estimated from the experimental accuracy of the transmittance data. Accuracy of the data of Figs. 2 and 3 are estimated to be ±1% which is typical of far-infrared FT–IR spectra with a stable source and detector. The ±1% accuracy of the transmittance data resulted in a ±20% uncertainty in the parylene's absorption. Estimates for the error in $n_{\rm AR}$, $\alpha_{\rm AR}$, and $t_{\rm AR}$ are given in Table I. Uncertainties in the silicon's refractive index, absorption, and thickness did not have a significant impact on the determination of the parylene's properties.

IV. CONCLUSIONS

We have successfully used thin films of parylene as an AR coating for silicon optics at terahertz frequencies. The measured refractive index of $n = 1.62$ is not optimal for silicon, which prefers an AR coating to have a refractive index of $n \approx 1.85$; however, excellent AR performance was still observed. Our data indicate that parylene C and parylene D with their reasonably modest absorption coefficients would each make a suitable choice for an AR coating for silicon at terahertz frequencies. Coatings sufficiently thick for AR performance at ≈2 THz reduced the average transmittance by <10% compared to a lossless AR coating with an ideal refractive index. Coating thickness requirements and uniformity issues, however, may prohibit the use of parylene for AR coatings below ≈1 THz.

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