STUDY OF PARYLENE AS ANTI-REFLECTION COATING FOR SILICON OPTICS AT THz FREQUENCIES

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

***Department of Electrical and Computer Engineering**
University of Massachusetts Amherst
Amherst, Massachusetts 01003

****Submillimeter-Wave Technology Laboratory**
University of Massachusetts Lowell
Lowell, Massachusetts 01854

ABSTRACT

In this paper, we report a study of thin films of Parylene used as an anti-reflection (AR) layer for silicon optics in the THz range. Parylene is a polymer with attractive properties such as thermal stability, good adhesion and conformity, low water absorption and chemical inertness. We had two Si substrate double side coated with Parylene C and D by Specialty Coating Systems, Inc. The film thicknesses were close to 25μm. Transmission spectra were obtained between 450GHz and 2.8THz in a Fourier Transform Spectrometer. By modeling the three-layer structure, a refractive index of 1.62 was obtained for Parylene C and Parylene D, which, in combination with a modest absorption loss, makes them appropriate for AR coating materials at THz frequencies.

I. INTRODUCTION

Single layer thin films are routinely used as a means of suppressing the reflection of electromagnetic radiation from a surface. The ideal parameters of such a film for zero reflection is:

$$n_{AR} = \sqrt{n_o} \text{ and,} \qquad (1)$$

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

where n_{AR} and n_o are the refractive indices of the AR layer and the optical component, respectively, and t_{AR} is the thickness of the coating. Assume normal incidence. The thickness of the AR layer can be any odd number of quarter wavelengths and typically is minimized due to film absorption.

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_{AR} > 10 μm). Alumina-loaded epoxy has been used with good results as an AR coating for silicon lenses [1]. The epoxy material suffers from large absorption loss above 1 THz, however [2]. Common plastics such as Mylar and Kapton are potential candidates because their refractive indices are close to the required value of $\sqrt{n_{silicon}}$ • 1.85, however, these 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 – 8 THz as AR coatings on germanium lenses for the ISO satellite project [3]. 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) [4]. These sensitive detectors of terahertz radiation typically use small silicon lenses to focus radiation onto an antenna-coupled detector element. All HEB measurements so far above 1 THz have been done without the use of AR-coated focusing lenses which results in a • 30% reflection loss at the silicon lens surface. Detector noise temperatures could be improved by 20%-30% by 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 lens possible. Irwin [5] has used parylene as an AR coating on silicon at mid-infrared wavelengths in 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 [6] studied the performance of a parylene-coated metal mesh filter at mid-infrared wavelengths and reported a refractive index of 1.65. In this report, thin coatings of parylene C and parylene D were used as AR coatings for 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 1012.0 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 ($\rho > 20{,}000$ •-cm), single-crystal silicon was chosen as the substrate material because its properties were well-known at terahertz frequencies [7] 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 at normal incidence and under vacuum to minimize the influence of atmospheric water vapor at these frequencies. Figure 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 towards higher frequencies is due to loss in the silicon. From this and prior research on silicon at these frequencies [8], we were able to determine the terahertz behavior of the uncoated silicon substrates. Figures 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 Figures 2 and 3 was performed by using the Fresnel equations and a standard matrix calculation technique [9]. 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. However, by theoretical modeling of the 3-layer parylene/silicon/parylene system, we found that it was possible for all three quantities (n_{AR}, α_{AR}, and t_{AR}) of the parylene coating to be determined with reasonable accuracy from transmittance data alone, provided that the properties of the silicon substrate were known. We found that the location in frequency of the AR behavior determined the coating's thickness, the width of the transmittance envelope at the AR frequency determined the coating's refractive index, and the amount of transmittance determined the coating's loss. The refractive index n_{AR} also impacts the location of the AR behavior as may be expected, but not without impacting the width of the envelope of the spectrum. In other words, only one (n_{AR}, t_{AR}) pair was found to fit the data. 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.

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.

A refractive index of $n = 1.62$ was found for both parylene C and D and was observed to be independent of frequency between 450 GHz 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 non-ideal 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 non-ideal 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%. Due to the fact that the films were thin and parylene's absorption was relatively small at these frequencies, only upper level estimates were made for the material's loss. The absorption coefficients α for parylene C and D were modeled with an absorption coefficient linearly increasing with frequency from •

2 cm^{-1} to 16 cm^{-1} and from • 1 cm^{-1} to 10 cm^{-1}, respectively, between 450 GHz and 2.8 THz. A summary of the terahertz optical properties of parylene C and parylene D along with the silicon substrate is given in Table I.

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 • 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 of an ideal refractive index. But for frequencies below 1 THz, use of parylene for AR performance may be prohibited due to coating thickness and uniformity issues.

V. REFERENCES

1. N. G. Ugras, J. Zmuidzinas, and H. G. LeDuc, "Quasi-optical SIS mixer with a silicon lens for submillimeter astronomy," *Proceedings of the 5th Int. Symp. on Space Terahertz Tech.*, p. 125, 1994.

2. J. W. Lamb, "Miscellaneous data on materials for millimeter and submillimeter optics," *Int. J. Infrared and Millimeter Waves*, Vol. 17, No. 12, pg. 1997, Dec. 1996.

3. M. J. M. van der Vorst, "Integrated lens antennas for submillimeter-wave applications," Ph.D. thesis, Techn. University Eindhoven, 1999.

4. E. Gerecht, C. F. Musante, Y. Zhuang, K. S. Yngvesson, T. Goyette, J. Dickinson, J. Waldman, P. A. Yagoubov, G. N. Gol'tsman, B. M. Voronov, and E. M. Gershenzon, "NbN hot electron bolometric mixers–a new technology for low-noise THz receivers," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 47, No. 12, pg. 2519, Dec. 1999.

5. P. G. J. Irwin, P. A. R. Ade, S. B. Calcutt, F. W. Taylor, J. S. Seeley, R. Hunneman, and L. Walton, "Investigation of the dielectric spaced resonant

mesh filter designs for PMIRR," *Infrared Physics*, Vol. 34, No. 6, pgs. 549-563, 1993.

6. P. A. Chen, "The performance of dielectric coated mesh filter," *Journal of Infrared and Millimeter Waves*, Vol. 8, No. 1, Jan. 1987.

7. A. J. Gatesman, R. H. Giles, and J. Waldman, "High-precision reflectometer for submillimeter wavelengths," *J. Opt. Soc. Am. B*, Vol. 12, No. 2, February 1995.

8. A. J. Gatesman, "A high precision reflectometer for the study of optical properties of materials in the submillimeter," Ph.D. dissertation, University of Massachusetts Lowell, Lowell, MA, 1993.

9. R. M. A. Azzam and N. M. Bashara, *Ellipsometry and Polarized Light*, North-Holland Publishing Co., 1977.

Table I. Terahertz optical properties of silicon substrate and parylene films

	THz Refractive Index n	Absorption Coefficient α (1/cm) from ν = 450 GHz - 2800 GHz
uncoated silicon	3.416*	0.17*
parylene C	1.62	$0.006\,\nu - 0.7$
parylene D	1.62	$0.004\,\nu - 0.8$

* at 2 THz

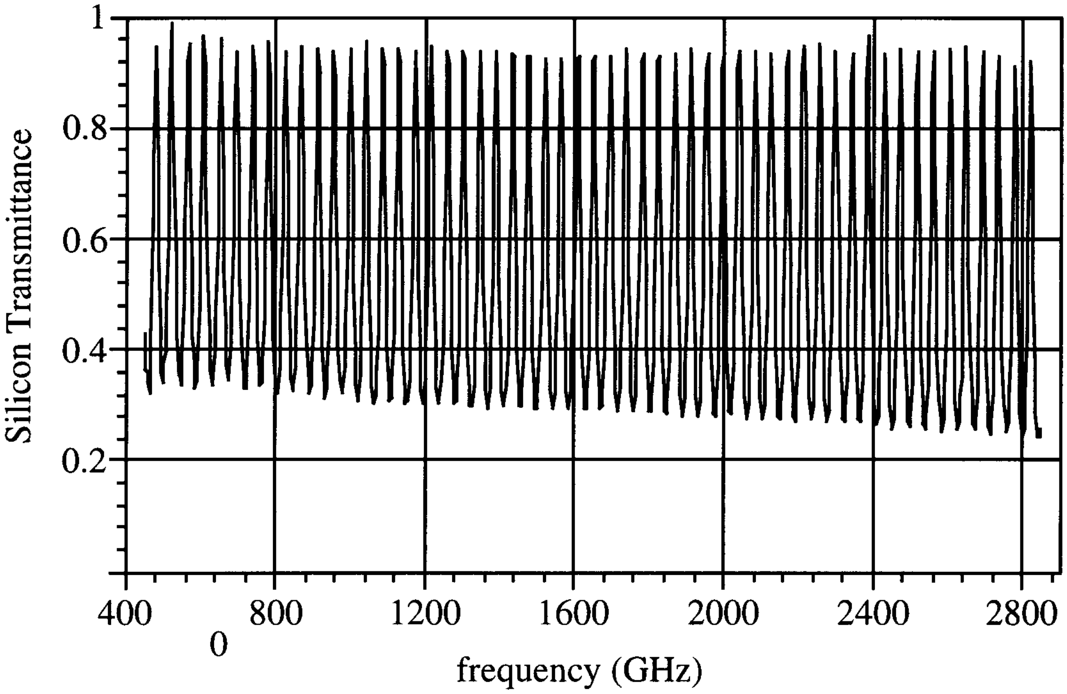

Figure 1. Under-resolved THz transmittance of an uncoated high-resistivity (ρ>20,000 •–cm) 1012-μm-thick silicon substrate.

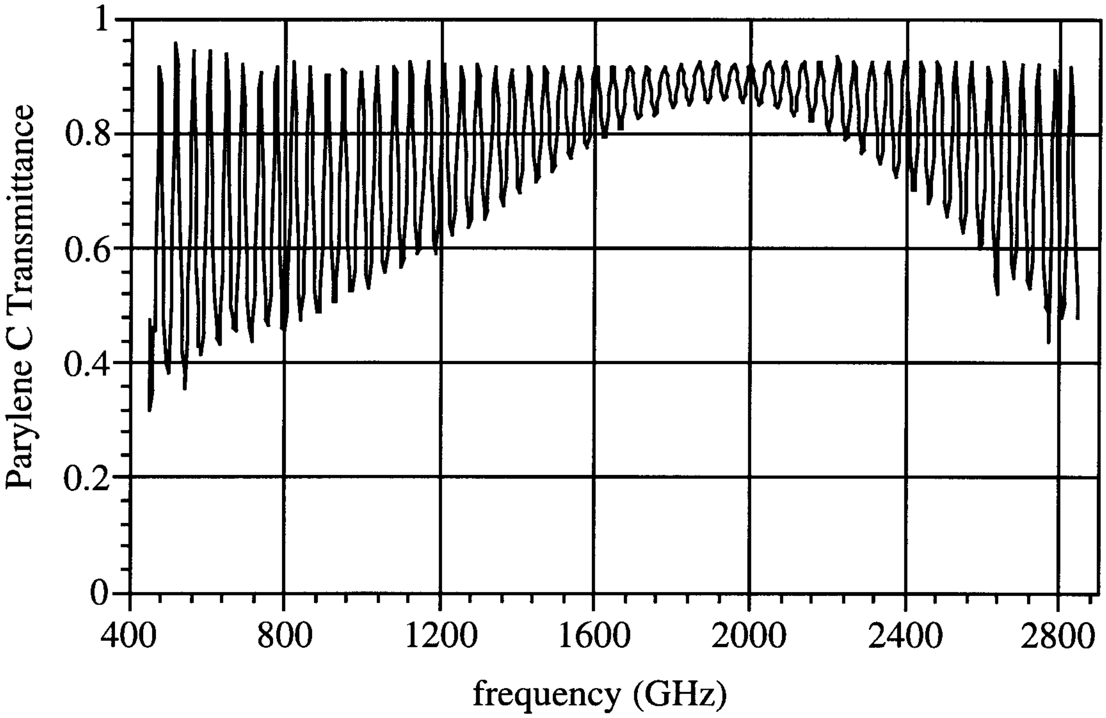

Figure 2. Terahertz transmittance of a high-resistivity (ρ > 20,000 •-cm) 1012–µm–thick silicon substrate coated with 24.0 µm of parylene C on both sides.

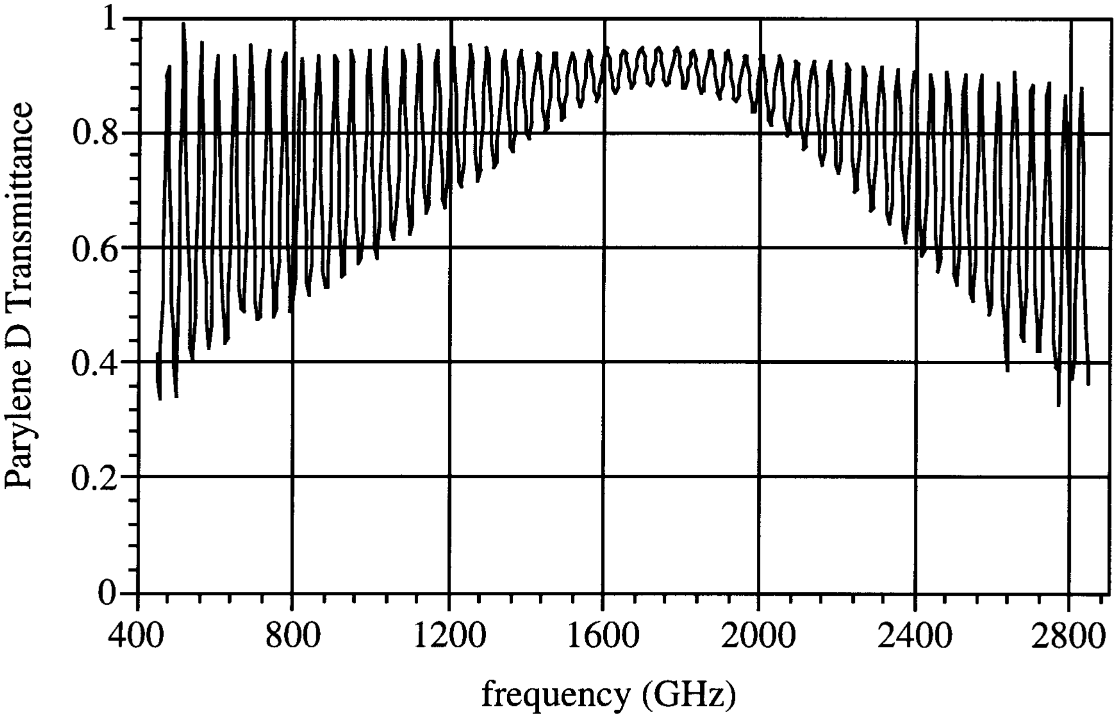

Fig. 3. Terahertz transmittance of a high-resistivity ($\rho > 20{,}000$ •-cm) 1012-μm-thick silicon substrate coated with 26.5 μm of parylene D on both sides.