Thin-Film SUEX as an Anti-Reflection Coating for mmW and THz Applications

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***Abstract*—We present a simple process for depositing SUEX dry films to realize effective anti-reflection coatings on high resistivity Silicon wafers and lenses. Heat-assisted conformal deposition of SUEX film followed by curing via ultraviolet exposure achieves robust adhesion to the Silicon lens surface. Due to its relatively-low material loss and commensurate refractive index, quarter-wavelength-thick SUEX coatings minimize reflection losses and significantly improve signal coupling into high-index Silicon lenses. As an example, a 150μm-thick SUEX layer was conformally coated on a 1cm-diameter high-resistivity Silicon lens to reduce reflection loss to less than 4% over the 220-325 GHz band.**

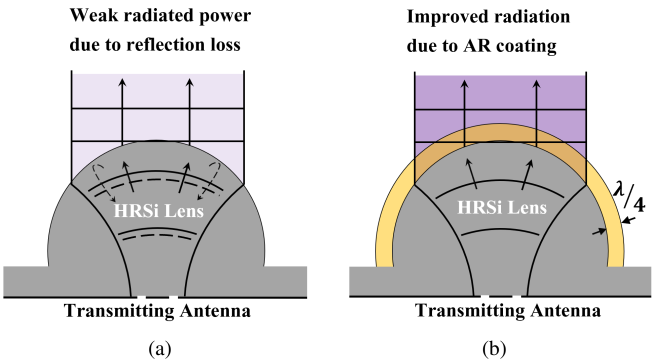
***Index Terms*—SUEX, dry-films, terahertz, millimeter-wave, anti-reflection layer**

I. INTRODUCTION

LENS-integrated antennas have been widely used for millimeter-wave (mmW) and terahertz (THz) sensors, particularly for spectroscopy applications. For imaging applications, double-slot antennas integrated with high-resistivity Silicon (HRSi) lenses are widely used as the sensor element situated on the lens focal plane [1]–[3]. For more broadband applications, such as spectroscopy, self-complementary designs are also used to realize photoconductive antennas. HRSi is the preferred lens material due to its low material losses. However, the high dielectric permittivity of HRSi (ϵ_r=11.7) results in significant impedance mismatches with air, leading to a mere 46% antenna coupling efficiency [4]. As illustrated in Fig. 1, the addition of an anti-reflection (AR) coating can mitigate reflection due to the large index difference between HRSi and air. In fact, the situation is a classical case of quarter-wave impedance transformer between the high index of HRSi and the lower index of air. To minimize reflections due to the impedance mismatch, the AR index (n_{AR}) and its thickness (d_{AR}) must be chosen as:

$$n_{AR} = \sqrt{n_{Si}}, \qquad d_{AR} = \frac{(2m+1)\lambda_0}{4n_{AR}}, \tag{1}$$

where n_{Si} is the lens index, λ_0 is the free-space wavelength and, $m = 0, 1, 2, ...$ represents integer multiples of a quarter wavelength. For the thinnest possible realization of the AR coating (with the goal of keeping the associated material losses to a minimum), the required AR thickness for THz applications can range from 400μm at 100GHz to 40μm at 1THz for Silicon optics. From (1), the permittivity of the AR coating material is $\sqrt{11.7} = 3.42$ for a HRSi lens, and a thickness of 135-um leads to best impedance match at 300 GHz.



(a) (b)

Fig. 1: Illustration of the impact of AR coatings on lens-integrated antenna performance: (a) Due to large index difference, a large portion of the planar double slot antenna radiation is reflected back into the lens, (b) A single layer quarter-wave AR coating can significantly mitigate reflections losses and improve lens-integrated antenna performance.

Such large thicknesses, particularly for lower THz frequencies, cannot be readily realized with conventional thin film deposition techniques. Previously, vacuum-deposited Parylene polymers (ϵ_r=2.6) have been used as AR coatings on HRSi lenses [5]. Also, other approaches using different types of AR coatings, such as the direct machining of mixed epoxies applied on lens surface, deep reactive ion etching (DRIE) and laser machining of anti-reflective structures onto the lens surface have been reported [6]. Although these methods are effective, they require rather specialized fabrication tools. Alternatively, the availability of various low-loss polymers that can more readily be fabricated on lenses could enable more straightforward realizations of effective AR coatings.

Particularly, SUEX is a new line of thick, dry photoresist, manufactured by DJ MicroLaminates, which can be easily molded onto the curved lens surfaces, leading to effective AR coatings, thanks to its favorable material properties and ease of application. In a previous work [7], we studied the material properties of SUEX and reported its permittivity and loss

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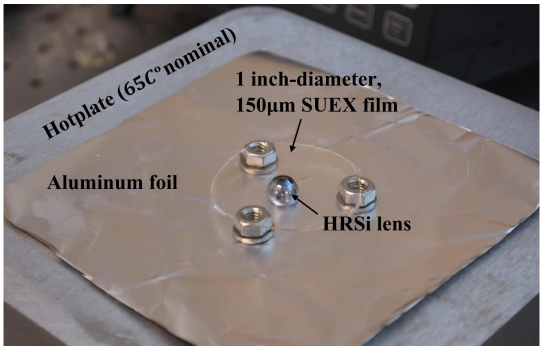


Fig. 2: Illustration of the conformal SUEX coating process via dry film reflow on a hot plate.

tangent at 200 GHz as 2.86 and 0.020, respectively. According to (1), an SUEX AR coating layer optimized for 270 GHz should be around 160 μm, a thickness that is available upon request from the manufacturer.

In the following, we present the AR performance of SUEX films on HRSi wafers and lenses. We first consider transmission measurements on a 1-mm-thick HRSi wafer with and without the SUEX AR coating. Subsequently, the deposition and characterization of SUEX on a 1cm-diameter HRSi hyper-hemispherical lens is presented. Reflections from the spherical and planar back surfaces are both measured to show the effect of SUEX coatings on flat and curved material boundaries. The paper is organized as follows: Section 2 presents the process flow for SUEX deposition on a lens surface. In Section 3, the transmission and reflection measurements are summarized and the results are compared with the analytical models, illustrating the efficacy of the SUEX AR coatings. In Section 4, we highlight our conclusions based on the measured results.

II. CONFORMAL SUEX COATING PROCESS VIA THERMAL REFLOW AND UV CURE

A simple and repeatable process for conformally coating thin SUEX dry films on convex lens surfaces can be easily realized using a conventional hot plate and an ultraviolet (UV) curing station. First, the HRSi lens is placed on the hotplate and the green (uncrosslinked) SUEX film is carefully balanced on the lens surface, as shown in Fig. 2. Next, the hotplate is heated to 65 °C to slowly facilitate thermal reflow of the dry film [8]. As the SUEX reflow temperature is achieved, the dry film starts to slowly and conformally adhere to the lens surface. Here, care must be exercised such that the reflow of the thin SUEX layer occurs slowly, over several minutes. Increasing the hotplate temperature further softens the dry film, impacting its reflow rate, and a faster reflow may result in reduced SUEX thickness or more detrimental non-uniformities within the AR layer across the lens surface. Moreover, care must be exercised while depositing the SUEX on the HRSi surface to avoid air bubbles forming between the lens and the SUEX. However, thanks to the convex shape of the lens surface, the conformal molding of the flat SUEX film starts from the apex of the lens and thus helps avoid air bubbles naturally. Following the conformal coating, the hot plate is turned off and the coated lens is allowed to cool down. Excess SUEX can be removed at this stage using acetone. Subsequently, a simple UV curing tool must be used to crosslink and harden the coated SUEX film. Likewise, application of SUEX on flat surfaces starts with the lamination of the dry film onto the substrate using a hot-roll laminator, followed by a UV exposure and post exposure bake steps, as described in [8].

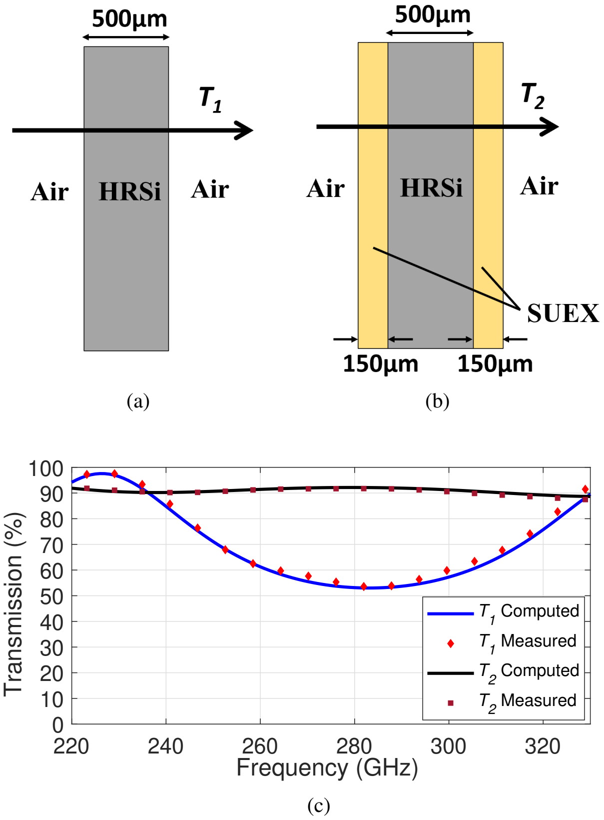
III. MEASUREMENT SETUP FOR AR PERFORMANCE

The performance of the SUEX film as AR coating is verified with transmission as well as reflection measurements. Details about each measurement setup are given in the following:

A. Transmission Measurements using a THz Time Domain Spectroscopy Instrument

To demonstrate the efficacy of the SUEX AR coatings, we first considered a 2-inch-diameter HRSi wafer to highlight the improvement of signal transmission. As a first test, we simply attached the readily available cross-linked SUEX film on both sides of the HRSi wafer using adhesive tape. Alternatively, green SUEX film can be laminated onto the wafer as detailed in [8].

For transmission measurements, we have utilized a commercial Time Domain Spectroscopy (TDS) system (TPS Spectra 3000 from TeraView, Inc.). The TDS set-up measures transmission coefficient of thin samples and has a frequency



(a) (b)

(c)

Fig. 3: Measured and computed transmission through a 500μm-thick HRSi wafer: (a) Bare HRSi wafer model (transmission coefficient is denoted as T_1), (b) AR-coated HRSi wafer model (T_2), (c) Measured and computed data showing the impact of SUEX AR coating.

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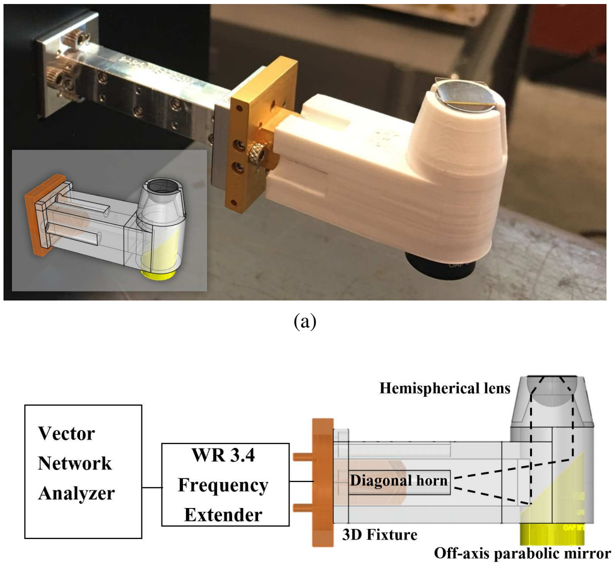
resolution of 3.59 GHz, where each frequency is averaged over 300 times to eliminate the random errors from the amplitude fluctuations of femtosecond model-locked laser. For this test case, a 1mm-thick HRSi wafer with 20,000 Ω-cm resistivity was used. In order to observe the effect of SUEX coating, two transmission measurements are performed. We first measured the transmission through the bare HRSi wafer (denoted as T_1), as illustrated in Fig. 3a. Next, both sides of the HRSi wafer are covered with cross-linked SUEX films and the transmission coefficient, (denoted as T_2), through the AR-coated HRSi wafer is captured, as shown in Fig. 3b. We also note that although it is possible to obtain dry SUEX films with custom thickness, the manufacturing variations result in film thicknesses that can vary as much as $\pm 5\mu$m. Such variations could slightly impact the best AR match frequency, however, the overall AR performance is not impacted significantly. We also compared our measurements with an analytical multilayered media transmission coefficient model for further verification. As seen in Fig. 3c, the use of SUEX AR coatings achieve over 90% transmission across the entire 220-325GHz band, and are consistent with the analytical formulas based on plane wave propagation in layered media [9]. Also, as given in Fig. 3c, the maximum computed transmission for bare HRSi wafer does not reach to 100%, which is mainly due to material losses in HRSi sample. For accurate comparison, we first measured the loss tangent of HRSi in the WR3.4 band as $\tan\delta = 0.0042$ and incorporated it into our analytical calculations.

B. Reflection Measurements using a Vector Network Analyzer

Next, we evaluated the SUEX AR performance for minimizing internal lens reflections. The setup and the diagram for this measurement setup is shown in Fig. 4. A conventional vector network analyzer (VNA) was used in conjunction with a WR 3.4 frequency extender from Virginia Diodes, Inc. (covering 220-325 GHz). The waveguide output of the frequency extender is coupled to a 1cm-diameter HRSi lens through a diagonal horn antenna (21 dB-gain standard horn from Virginia Diodes, Inc.) and a parabolic off-axis reflector, as illustrated in Fig. 4b. A 3D printed fixture was used to achieve accurate positioning of the diagonal horn antenna, off-axis parabolic mirror and the HRSi extended-hemispherical lens. A close-up photo of the setup with dry SUEX film at the focal plane of the lens is shown in Fig. 4a.

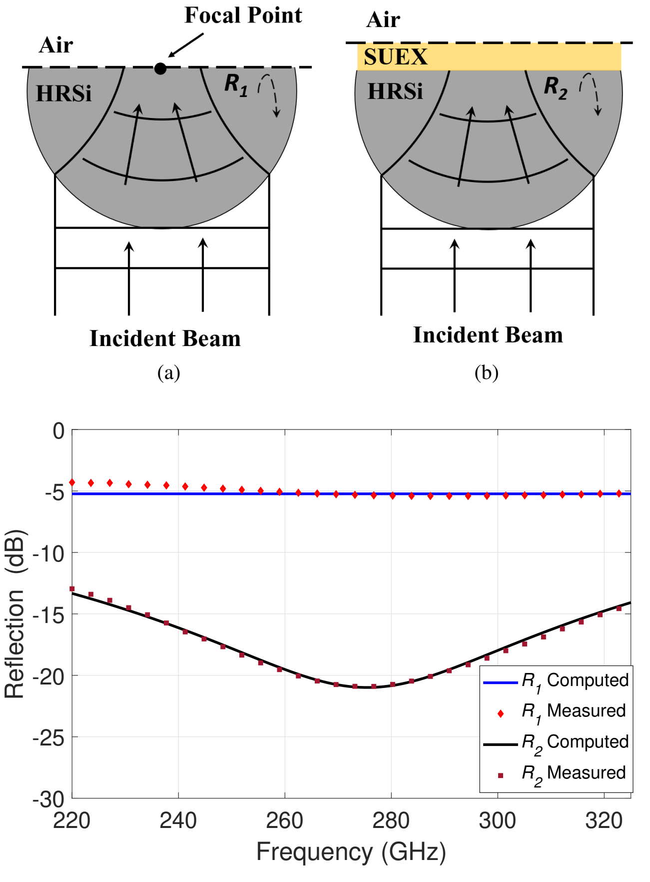
For this measurement, the internal reflection from the planar surface at the focal plane of the lens is considered, as illustrated in Fig 5a. The reflection from the flat focal plane of the HRSi lens is considered for both without (denoted as R_1) and with a cross-linked SUEX film (denoted as R_2). We started with a standard VNA calibration up to the frequency extender's waveguide flange. Next, we assembled the 3D printed fixture, off-axis parabolic mirror and the HRSi lens and a planar conductive layer was placed at the lens focal plane for calibration of reflected signal. Figure 5c illustrates



(a)

(b)

Fig. 4: (a) Photograph of the WR3.4 frequency extender with 3D printed fixture, lens, off-axis parabolic reflector, and the SUEX layer. The inset depicts the CAD model of the fixture, (b) Schematic diagram of the VNA measurement set-up.

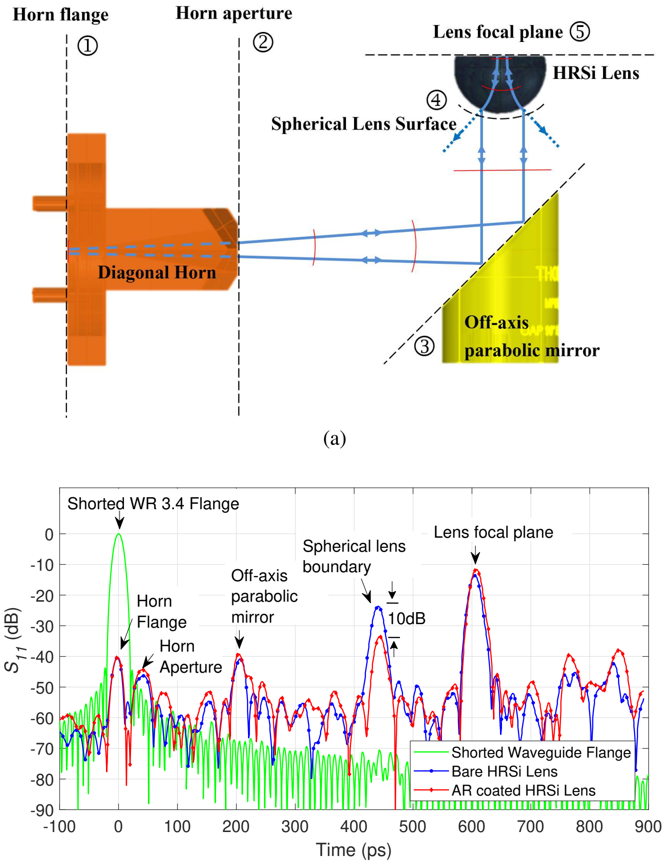


(a)

(b)

(c)

Fig. 5: Measured reflection from a HRSi-air interface: (a) Focal plane of the bare HRSi lens model illustrating the reflected fields denoted as R_1, (b) AR-coated focal plane of the HRSi lens model illustrating the reflected fields denoted as R_2, (c) Comparison of reflection measurements from bare and AR coated focal plane of the HRSi lens surface.



(a)

(b)

Fig. 6: Measurements setup and the time domain S_{11} response of SUEX-coated HRSi lens: (a) Schematic of the setup, (b) Measured time-domain response.

the reflection measurements from the planar lens surface as well as the analytical model, with and without an AR layer. Reflection from the HRSi-air interface without any AR coating is expected to be around -5 dB (54% reflection), whereas the AR coating reduces the reflection to less than 1% for 260-290 GHz. On average, the reflected signal level is reduced by 12 dB due to the SUEX coating as seen in Fig. 5c, consistent with the analytical model based on reflection from a planar material boundary [9].

To further demonstrate the AR performance, the same setup was used for measuring the reflection from the convex surface of the lens with and without SUEX coating. To do so, we have coated the convex surface of a 1-cm diameter spherical silicon lens with 150-um-thick SUEX film, using the process details given in Section-2. Unfortunately, a proper calibration is not readily achievable for the spherical surface. Thus, instead of using calibrated frequency-domain data, we demonstrate here the time-domain reflected signals for the AR performance characterization, as given in Fig. 6. Here, the solid curve depicts the measured time-domain response of S_{11} from a shorted waveguide flange, verifying the waveguide flange calibration with a 0 dB peak at zero time. Measured S_{11} for the bare HRSi lens and the AR-coated HRSi lens are also shown in Fig. 6b. Also noted in the figure are the time domain reflections from the horn antenna, the off-axis parabolic mirror, the spherical lens surface and the lens focal plane. We note that the reflected signal from the spherical lens surface arriving at 440 ps is reduced by 10 dB after the HRSi lens coated with SUEX. In addition to the planar reflection and transmission measurements which prove the effectiveness of SUEX AR layer, this demonstration also validates that SUEX AR coating works well on the spherical lens surface. Compared to a multilayered, dry-etched structures studied in [6], our approach is simpler and uses a single-layer structure with straightforward application, which can easily achieve less than 4% reflection for the entire 220-325 GHz band.

IV. CONCLUSION

We demonstrated a new material and a simple fabrication method for realizing effective AR coatings for HRSi lenses. Based on SUEX dry films, the efficacy of the proposed approach was illustrated via: i) Transmission measurements on a HRSi wafer using a commercial THz TDS system, ii) Reflection measurements on a HRSi hemispherical lens using a frequency-domain VNA, and, iii) Reflection measurements using a time-domain VNA setup. Measured data are also demonstrated to be consistent with the analytical models in all cases. Using a 150μm-thick SUEX AR coating, the transmission through a HRSi wafer can be improved as high as 90% for the entire WR3.4 frequency band. Similarly, the reflection loss from the lens focal plane was below 4% for the entire band, further reaching down to 1% over 260-290 GHz. We compared the time domain reflection responses of bare and AR coated HRSi lenses and showed that 10 dB reduction in the reflection coefficient for the curved lens surface can be readily achieved using SUEX as an AR coating. SUEX is a simple yet effective choice as an AR coating material for Silicon optics, particularly for mmW and THz applications.

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