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Characterization of single layer anti-reflective coatings for bolometer-based rare event searches

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ABSTRACT: Combining analysis from phonon signals and photon signals can powerfully reduce backgrounds for bolometer-based rare event searches. Anti-reflective coatings can significantly increase the performance of the secondary light-sensing bolometer in these experiments. As a first step toward these improvements, coatings of SiO\textsubscript{2}, HfO\textsubscript{2}, and TiO\textsubscript{2} on Ge and Si wafers were fabricated and characterized at room temperature and multiple angles of incidence.

KEYWORDS: radiation detector, scintillating bolometers, double beta decay, antireflective coatings.
1. Introduction

Rare-event searches are being pursued to answer some of the greatest mysteries in physics of the present time, namely: the nature of dark matter through direct detection (DM) and the possible Majorana nature of the neutrino through searches for neutrinoless double-beta decay ($0\nu\beta\beta$). In these experiments, combining multiple signals is a powerful active background rejection technique. Scintillating bolometers use the combination of phonon and photon signals to discriminate between particle types. The CUPID (CUORE with Upgraded Particle IDentification) [1] and CRESST [2, 3] detectors are pursuing this technology for $0\nu\beta\beta$ and DM searches respectively.

A scintillating bolometer measures a phonon signal: the change in temperature in a crystal due to the interaction of charged particles with the crystal lattice. These interactions also produce a photon signal: scintillation light which is detected by a target Ge or Si bolometer. An anti-reflective coating on the target bolometer, as shown in Figure 1, increases light collection and therefore improves the energy resolution of the light measurement. In this paper, we discuss the optimization of an anti-reflective coating for two promising scintillating crystals containing $0\nu\beta\beta$ isotope: ZnSe and ZnMoO$_4$. We also discuss optimizing the anti-reflective coating to detect Cherenkov light in non-scintillating crystals like TeO$_2$, the current CUORE crystal.

The scintillation spectra of ZnSe and ZnMoO$_4$ are well characterized at temperatures down to 8 K. The spectra peak at 645 nm and 610 nm respectively [4]. The absorption cutoff for TeO$_2$ is 350 nm [5]. This is effectively the peak of the Cherenkov spectrum. Our default target bolometer is composed of hyper-pure germanium (HPGe) thin slabs run at a standard operating temperature of 15-20 mK. We also study silicon (Si) since it has equivalent performance at these operating
Figure 1. An anti-reflective coating is deposited onto the auxiliary bolometer to improve transmission of Cherenkov or scintillation photons from the bolometric crystal.

Figure 2. Reflectivity of light of various angles of incidence on bare substrates: (a) Si and (b) Ge. Vertical dashed lines indicate the cutoff wavelength of TeO$_2$ (350 nm) and the peak wavelengths of scintillation for ZnMoO$_4$ (610 nm) and ZnSe (645 nm). For these wavelengths and normal incidence, bare Si reflects over 30% of incoming light; bare Ge reflects over 40%.

temperatures and is widely available. Using refractive index data from [6], we find Ge substrates reflect ~50% of normal incident light while Si substrates reflect ~35%; see Figure 2. The results for ZnSe scintillation at 645 nm and TeO$_2$ Cherenkov light are similar. If the coating meets other design requirements for low background bolometer experiments, especially low radioactivity and robustness through thermal cycling (which will be examined in future work), then these numbers indicate that an anti-reflective coating could significantly improve the energy resolution of the target bolometer.

2. Anti-Reflective Coatings

As seen in Figure 1, the target bolometer is supplemented by depositing an anti-reflective coating to create a thin film structure where layers of contrasting refractive indices produce destructive interference in reflected beams and constructive interference in transmitted beams. This results in an overall increase of transmission. The performance of this structure depends heavily on the light’s incident angle, wavelength, and polarization. The reflection coefficient for unpolarized light
incident on a single layer anti-reflective coating (SLAR) is written \[7\] as:

$$R = \frac{1}{2} (|r_s|^2 + |r_p|^2)$$

(2.1)

where the subscripts \(s\) and \(p\) refer to waves parallel or perpendicular to the plane of incidence and the numerical subscripts refer to the medium in which the light is traveling: 0 for the outside medium (ideally vacuum), 1 for the SLAR, and 2 for the substrate. If \(\theta_{inc}\) is the angle of incidence onto the SLAR of thickness \(d\), the phase shift is given by

$$\beta = \frac{2\pi d N \cos \theta_{inc}}{\lambda}.$$  

(2.2)

The individual reflection coefficients are given by

$$r_{jm,s} = \frac{N_m \cos \theta_j - N_j \cos \theta_m}{N_m \cos \theta_j + N_j \cos \theta_m} \quad r_{jm,p} = \frac{N_j \cos \theta_j - N_m \cos \theta_m}{N_m \cos \theta_j + N_j \cos \theta_m}$$

(2.3)

and

$$N_j = (n_j + ik_j) \quad \theta_j = \arcsin \left( \frac{N_0}{N_j} \sin \theta_{inc} \right)$$

(2.4)

where \(n\) and \(k\) are the real and imaginary parts, respectively, of the complex refractive index of the material which are also dependent on wavelength. The ideal coating will minimize \(R\) with respect to \(n\) and \(k\).

### 2.1 Comparison to Previous Experiment (Mancuso, Beeman, et.al.)

This work builds upon the study done by Mancuso et al. \[11\]. They tested SiO\(_2\) films, 70 nm thick and deposited on a Ge substrate using a sputtering technique. The films were evaluated at \(~10\) mK. SiO\(_2\) decreased reflectivity by 18-20\% \[11\].

In Mancuso et.al., the scintillation light is assumed to reach the target bolometer at normal incidence. As they indicate, this is a crude assumption. In the primary bolometers of interest, namely ZnSe, ZnMoO\(_4\), and TeO\(_2\), the refractive index is high enough to allow total internal reflection at a relatively low angle; see Table 1. This implies that even a slight deviation from normal (in the plane of incidence) as the ray leaves the primary bolometer can cause the refracted ray to deviate significantly from normal as it strikes the target bolometer. The distance between primary and target bolometers is small enough (on the order of 1 cm) that the angle of incidence on the target bolometer will range from 0\(^\circ\) to roughly 88\(^\circ\) in the plane of incidence (assuming a CUORE-sized 5cm\(\times\)5cm crystal). From Equations 2.1-2.4, it is clear that a phase difference between reflected

<table>
<thead>
<tr>
<th>Material</th>
<th>(n(\lambda))</th>
<th>(\theta_{exit})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnSe</td>
<td>2.58 (645 nm)</td>
<td>22.8(^\circ)</td>
</tr>
<tr>
<td>ZnMO(_4)</td>
<td>(~1.90 (655 nm)^*)</td>
<td>31.7(^\circ)</td>
</tr>
<tr>
<td>TeO(_2)</td>
<td>2.25 (645 nm)</td>
<td>26.4(^\circ)</td>
</tr>
</tbody>
</table>
Table 2. refractive index at 645nm for coatings considered in this work.

<table>
<thead>
<tr>
<th>Material</th>
<th>n (645nm)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>1.76</td>
<td>Malitson (1972) [17]</td>
</tr>
<tr>
<td>HfO₂</td>
<td>2.10</td>
<td>Wood (1990) [18]</td>
</tr>
<tr>
<td>Si₃N₄</td>
<td>2.00</td>
<td>Philipp (1973) [19]</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1.48</td>
<td>Gao (2013) [20]</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.58</td>
<td>Devore (1951) [21]</td>
</tr>
</tbody>
</table>

waves from the film layer and reflected waves from the substrate layer is introduced whenever the incident angle is non-normal, leading to a substantial change in reflectivity for non-normal incidence.

In this paper, we manufacture similar coatings as Mancuso et.al. but characterize them at room temperature so that we can study the angular effects.

2.2 Choice of Substrates

Ge is the logical choice for the target bolometer because it absorbs photons better than Si in the visible range; the absorption coefficient of Ge is roughly two orders of magnitude greater [12]. However, Si is more readily available and the manufacturing processes are extremely well understood. These include techniques that could improve anti-reflective coatings, such as micromachining and deposition masking [13]. Finally, Ge has a specific heat ∼4.5 times greater than that of Si [14]. Because signal amplitude is inversely proportional to the heat capacity of the device, Si detectors can be made into much larger systems without sacrificing signal quality [15]. Considering these factors, we chose to study both Ge and Si as target bolometer candidates for this work.

2.3 Choice of Coatings

For a particular substrate, the minimum possible reflectivity using a SLAR can be calculated using the curves from Equation 2.1. For a Ge substrate and incident 645 nm light from the ZnSe scintillation peak, the complex refractive index of Ge has components $n = 5.36$ and $k = 0.705$. Assuming no losses to the thin film and normal incidence, the reflection coefficient can be decreased maximally with a coating medium with refractive index $n = 2.32$. The closest match considering available materials is TiO₂; see Table 2. HfO₂ is also a possibility. Performing the same calculation for a Si substrate, the minimum reflectivity is achieved for a coating with $n = 1.96$. Si₃N₄, HfO₂, and Al₂O₃ (sapphire) are good matches.

A second anti-reflective layer can be used to further reduce reflectivity. The optimization proceeds similarly to above, except that, in this case, the refractive index is tuned to the first coating instead of the substrate. For example, a Ge-TiO₂ target system could be improved by adding second coating with a refractive index of $n = 1.52$. GeO₂ ($n = 1.60$ [16]) is not readily available, but the more common SiO₂ is a good candidate. Traditionally, SiO₂ has been used as a single layer coating for Si substrates because it is readily available, easily manufactured, and has better mechanical strength and adhesion under thermal cycling. In this work, we focus on single layer coatings, but future work will include two layer systems.
Figure 3. Dependence of reflection on angle of incidence for Si (a) and Ge (b). Values for bare substrate (solid) and 70 nm SiO$_2$ [2] single layer antireflective coating (dashed) are presented. Plots on left emphasize the wavelengths of interest (350 nm cutoff wavelength for TeO$_2$ and 610 nm and 645 nm scintillation peaks of ZnMoO$_4$ and ZnSe, respectively). Calculations are taken directly from equations 2.1-2.4 and contain no experimental data.

The performance of the anti-reflective coating is dependent on the angle of the incoming light. Using equation 2.1 for non-normal incidence, reflection curves were plotted for use in selecting SLAR candidates; these curves for SiO$_2$ on Si and Ge substrates can be seen in Figure 3. The coating always improves the performance of the target bolometer. However, the improvement may not be sufficient to overcome the increased complexity and cost of adding the coating.

The above calculations assume all reflections are specular, the refractive index is constant throughout the thickness of the SLAR, and there are no losses in the SLAR ($k_{SLAR} = 0$). The incident light is also assumed to be unpolarized. This final assumption is not valid for TeO$_2$ due to birefringence. In this case, the refractive index varies between 1 and the true refractive index depending on the axis of propagation.
Table 3. Characteristics of wafers used in this work

<table>
<thead>
<tr>
<th></th>
<th>Ge (1)</th>
<th>Ge (2)</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>crystalline, &lt;100&gt;</td>
<td>crystalline &lt;100&gt;</td>
<td>crystalline, &lt;100&gt;</td>
</tr>
<tr>
<td>Thickness</td>
<td>500 µm</td>
<td>350 µm</td>
<td>280 µm</td>
</tr>
<tr>
<td>Diameter</td>
<td>2 in</td>
<td>1 in</td>
<td>2 in</td>
</tr>
<tr>
<td>Doping</td>
<td>undoped</td>
<td>undoped</td>
<td>N Type, P Doped</td>
</tr>
<tr>
<td>Polish</td>
<td>2SP</td>
<td>1SP</td>
<td>1SP</td>
</tr>
<tr>
<td>Resistivity</td>
<td>&gt;50 Ω·cm</td>
<td>30 Ω·cm</td>
<td>1-100 Ω·cm (test)</td>
</tr>
</tbody>
</table>

Based on their refractive index and availability, the following coatings were selected. For Ge, we study SiO$_2$, TiO$_2$, and HfO$_2$. For Si, we study SiO$_2$ and HfO$_2$. Figure 4 shows the wafers produced for this study. We would have liked to test Al$_2$O$_3$ on Si, but it was unavailable. This is why Al$_2$O$_3$ was only used for Ge.

3. Fabrication

The 1 in Ge wafers and 2 in Si wafers were procured from University Wafer [22]. The 2 in Ge wafers were purchased from MTI Corporation [23]. Table 3 summarizes the properties of these wafers. The wafers were coated at the UCLA Nanoelectronics Research Facility (NRF) in a class-1000 multiuse cleanroom.

Al$_2$O$_3$, HfO$_2$, TiO$_2$ coatings  Non-silicate coatings were deposited using a Fiji thermal atomic layer deposition (ALD) system. In such a system, precursors were pulsed into an Argon atmosphere such that for each pulse a single atomic layer adhered to the surface of the wafer. Each wafer was loaded into the machine at room temperature and atmosphere, and processed at 200°C and 0.02 mTorr.

Al$_2$O$_3$ was used as a test wafer. It is a common coating that starts from TMA (trimethylaluminum) or Al(CH$_3$)$_3$. For HfO$_2$ coatings, precursors of Hf(NMe$_2$)$_4$ and H$_2$O were pulsed at 0.06 sec each until the desired thickness was reached. For TiO$_2$, coatings were processed similarly from a precursor of Tetrakis(Dimethylamido)Titanium (Ti(NMe$_2$)$_4$).

The ALD process was lengthy and required up to six hours to produce a single wafer. This technique has the advantage that more complex coating geometries can be achieved through nanopatterning. These geometries will be explored in future work.

SiO$_2$ coatings  Silicate coatings were deposited using a High Deposition BMR plasma-enhanced chemical vapor deposition (PECVD). The system uses time-varying magnetic fields to generate highly dissociated plasmas of the precursor material which allows for a higher rate of deposition. Precursors of SiH$_4$ and O$_2$ gasses were used to create SiO$_2$ films at rates of up to 3000 Å/min. In the case of the BMR PECVD at the UCLA NRF, a user would input a desired time of deposition (as opposed to a desired thickness). This led to less precision in the final thickness of the coating; however, this process was very efficient and several wafers of different thicknesses could be produced over the course of a few hours.
Figure 4. Wafers post-fabrication: (a) Si wafers clockwise from top left: SiO$_2$ 180 nm, SiO$_2$ 90 nm, SiO$_2$ 60 nm, HfO$_2$ 60 nm. (b) Ge wafers clockwise from top left: blank, Al$_2$O$_3$ 7 nm, TiO$_2$ 20 nm, SiO$_2$ 70 nm, TiO$_2$ 30 nm.

Table 4. Samples characterized for this study. Other samples were manufactured but their models did not reach acceptable goodness of fit values and therefore are not presented here. Discrepancies between ULVAC and Woolam measurements can be attributed to separate calibrations.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Substrate</th>
<th>Coating</th>
<th>Thickness (nm)</th>
<th>Thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(ULVAC)</td>
<td>(Woolam)</td>
</tr>
<tr>
<td>1</td>
<td>Si</td>
<td>SiO$_2$</td>
<td>66.116 ± 1.899</td>
<td>75.655 ± 0.021</td>
</tr>
<tr>
<td>2</td>
<td>Si</td>
<td>SiO$_2$</td>
<td>79.627 ± 1.245</td>
<td>90.09 ± 0.49</td>
</tr>
<tr>
<td>3</td>
<td>Si</td>
<td>SiO$_2$</td>
<td>181.902 ± 0.782</td>
<td>180.029 ± 0.037</td>
</tr>
<tr>
<td>4</td>
<td>Ge</td>
<td>SiO$_2$</td>
<td>–</td>
<td>75.26 ± 2.294</td>
</tr>
<tr>
<td>5</td>
<td>Ge</td>
<td>SiO$_2$</td>
<td>–</td>
<td>140.84 ± 3.13</td>
</tr>
</tbody>
</table>

4. Characterization

Samples were characterized using fixed and variable angle ellipsometry. The coated substrates were subjected to unpolarized light at an angle which reflected into a detector to measure the relative amplitude and phase of s- and p-polarizations. Relative amplitudes and phases of polarizations are described as a function of wavelength and angle by two variables [7]:

$$\tan \psi = \left| \frac{r_p}{r_s} \right| \quad \text{and} \quad \Delta = \delta_p - \delta_s$$  \hspace{1cm} (4.1)

which can be combined to measure the total ratio of polarized reflections.

$$\tan \psi \exp(-i\Delta) = \frac{r_p (N_1, N_2, \theta_{inc}, d)}{r_s (N_1, N_2, \theta_{inc}, d)}$$  \hspace{1cm} (4.2)

Figure 5 shows an example of representative $\Psi'/\Delta$ data.

At this point, refractive index and thickness information for the coating was modeled and fit to experimental curves using equations 2.2 - 2.4. It was not possible to directly calculate total reflection...
Figure 5. Example of ‘raw’ ellipsometric data $\Psi$ and $\Delta$ (defined in Section 4). These values are then modeled using Cauchy film theory to find indexes of refraction shown in the next figure.

from these measurements, but a satisfactory result was found by reusing the calculated refractive index and thickness in equations 2.1-2.4. It should be noted that the measurement error of $\Psi$ and $\Delta$ are systematic; calculations of film thickness and optical characteristics are model dependent.

The UCLA Nanoelectronics Research Facility ULVAC UNECS-2000 fixed angle ellipsometer was used for immediate characterization after fabrication and provided only a model dependent thickness for Si wafers, no Ge model was available. The UCSB Nanofabrication Facility’s Woollam M2000DI VASE Spectroscopic Ellipsometer was used to fully characterize all samples at variable angles.

Film thickness and single-point were analyzed in two groups. The ULVAC companion software was used for normal incidence, and the Woollam ellipsometer’s companion software CompleteEase was used for variable angle incidence. The results are shown in Table 4. SiO$_2$ coatings were assumed to follow Cauchy’s equation:

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} + \ldots$$ \hspace{1cm} (4.3)

The resultant fits for SiO$_2$ on Si and Ge are shown in Figure 6. The goodness of fit of these curves is demonstrated by the root mean squared error, defined as:

$$\text{MSE} = \left[ \frac{1}{3n - m} \sum_{i=1}^{n} \left\{ (N_{Ei} - N_{Gi})^2 + (C_{Ei} - C_{Gi})^2 + (S_{Ei} - S_{Gi})^2 \right\} \right]^{1/2} \cdot 1000$$ \hspace{1cm} (4.4)
where subscripts $E$ and $G$ refer to measured and modeled parameters, respectively, and

\[
\begin{align*}
    n &= \text{number of wavelengths} \\
    m &= \text{number of fit parameters} = 3 \text{ (as follows)} \\
    N &= \cos(2\Psi) \\
    C &= \sin(2\Psi)\cos(\Delta) \\
    S &= \sin(2\Psi)\sin(\Delta)
\end{align*}
\]

The precision and accuracy in measurement in terms of $N$, $C$, and $S$ is typically 0.001, leading to the extra multiplicative factor of "1000". From equation 4.4, this implied that a fit with an MSE on the order of unity was considered in "perfect agreement" with the data. Values less than 100 were accepted for our purposes (as suggested by [24]). Fits for HfO$_2$ and TiO$_2$ samples had MSE values greater than 100, and were rejected. This method of testing goodness of fit is done automatically through the CompleteEase software. These are non-standard coatings and the software is proprietary which made debugging difficult. In the future, the ellipsometers should be specifically calibrated to measure total reflectivity and transmissivity to better characterize the performance of the SLAR.

![Figure 6](image)

**Figure 6.** Refractive index fit for SiO$_2$ on (a) Si and (b) Ge. MSE values correspond to goodness of fit (see Eq 4.4; MSE < 10 are excellent, MSE < 100 are acceptable). Black solid line indicates literature values.

5. Predicted Reflectance

From the indexes characterized in Figure 6, it is possible to reproduce the reflectivity curves for each system. The indices are used as input to equations 2.1-2.4 and plotted for various thicknesses and angles of incidence\(^1\); the results for Si are shown in Figure 7; the results for Ge are shown

\(^1\)Incident angles are plotted up to the ellipsometer maximum of 85°, although calculations suggest the true maximum could be larger.
Figure 7. Predicted reflectivity values for SiO$_2$ coating on Si substrate for varied angles of incidence. Black solid curve indicates reflectivity of bare Si [6]. Angles of incidence are as follows: (a) 0$^\circ$, (b) 15$^\circ$, (c) 45$^\circ$, (d) 85$^\circ$. Colored reflectivity curves are calculated based on ellipsometric measurements for $n$(λ) (see Figure 6). Thicknesses of 70, 90, and 180 nm (with MSE values 5.13, 6.47 and 6.18 respectively) are displayed. For plots (b)-(d), the reflectivity curve for normal incidence is provided as a reference (black dotted). For all angles of incidence and thicknesses, coating with SiO$_2$ should improve reflectivity. Recommendations for wavelengths of interest can be found in Section 5.

For the peak scintillation wavelengths, 645 nm and 610 nm for ZeSe and ZnMoO$_4$, it is clear that Si substrate reflectivity can be improved with any of the tested SLAC thicknesses: at normal incidence, a 90 nm coating of SiO$_2$ improves reflectivity of an Si substrate by $\sim$25%. The performance of the system depends heavily on the film thickness: 180 nm films do not show nearly the same decrease in reflectivity except at higher angles; see Figure 7. In contrast, the Ge substrate performance does not depend as heavily on the SLAC thickness. Improvements of up to 22% were
Figure 8. Predicted reflectivity values for SiO$_2$ coating on Ge substrate for varied angles of incidence. Black solid curve indicates reflectivity of bare Si. Angles of incidence are as follows: (a) $0^\circ$, (b) $15^\circ$, (c) $45^\circ$, (d) $85^\circ$. Colored reflectivity curves are calculated based on ellipsometric measurements for $n(\lambda)$ (see Figure 6). Thicknesses of 75 and 140 nm (with MSE values 61.05 and 65.02 respectively) are displayed. For plots (b)-(d), the reflectivity curve for normal incidence is provided as a reference (black dotted). For all angles of incidence and thicknesses, coating with SiO$_2$ should improve reflectivity. Recommendations for wavelengths of interest can be found in Section 5.

seen for normal incidence for both 75 nm and 140 nm SiO$_2$ coatings on Ge. For the scintillation wavelength of ZnSe (645 nm), the predicted improvement is $\sim20\%$, which agrees with the findings of previous work [25].

For a signal from Cherenkov light, the solution is quite different. TeO$_2$ has a cutoff wavelength at 350 nm. At this wavelength, it is difficult for a Si substrate to get below 20% reflectivity, so a Ge substrate is a better choice. These results indicate a Ge substrate with a 70 nm SiO$_2$ coating is better than larger thicknesses.

As seen in Figures 7 and 8, results also demonstrate that the performance of these light-collecting, target bolometers is greatly affected by the angle of incident light. Significant amounts
of light will be lost simply due to reflectivity: scintillation light incident on Ge from a ZnMoO$_4$ primary bolometer at 45° (in the plane of incidence) will be reflected at a 65% loss (see Figure 8(c)). An antireflective coating of 140nm SiO$_2$ can decrease this loss to only about 35%. Further analysis is underway to calculate the angular distribution of light leaving the primary bolometer; this analysis will lend itself to calculating the light gain by the eventual target-bolometer system, a great improvement on the assumptions made by [25].

6. Conclusion

Anti-reflective coatings can significantly increase the efficiency of light collection bolometers in rare event searches with the purpose of reducing background rates. Several coatings were manufactured successfully on Ge and Si substrates. Characterizing the more rare HfO$_2$ and TiO$_2$ coatings was unsuccessful; however, five SiO$_2$ coating-substrate combinations were successfully characterized at room temperature using variable angle ellipsometry. Preliminary calculations for both Si and Ge substrates confirm a decrease in reflectivity from SiO$_2$ coatings of various thicknesses at various angles of incidence, an improvement on the calculations performed by [25]. For the ZnSe and ZnMoO$_4$ scintillation wavelengths of 645 nm and 610 nm, coatings of 90 nm SiO$_2$ on Si or 140 nm SiO$_2$ on Ge are recommended. For Cherenkov light from TeO$_2$ at 350 nm, a Ge substrate with a 70 nm SiO$_2$ coating is recommended. Work is ongoing to improve upon these ellipsometer measurements, analyze the impact of the coatings on the system radiopurity, test the coatings at characteristic bolometric operating temperatures, and explore novel coating techniques.

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