# Anti-Reflective Coatings for Room Temperature Terahertz Quantum Cascade Laser Sources


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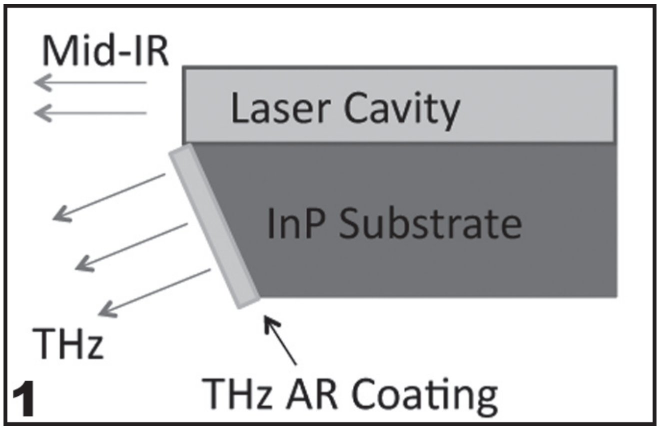

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### Abstract and Introduction:

There are currently no electrically-pumped semiconductor lasers that can operate in the 1-5 terahertz (THz) spectral range at room temperature. An alternative method of producing room temperature THz light is based on intra-cavity difference frequency generation (DFG) in dual wavelength mid-infrared quantum cascade lasers. Our THz DFG sources can provide tunable output of over 20 microwatts in the 1-5 THz range at room temperature. However, for these devices an estimated 30% of the THz radiation is reflected back into the laser from the emission surface. A schematic is shown in Figure 1. Single-layer anti-reflective (AR) coatings were investigated as a method for improving the power output by reducing these reflection losses.


### Experimental Procedure:

Mathematica was used to simulate the transmission of several different AR coatings using Equation 1 [1]. For a single coating, the appropriate layer thickness is given as $d = \lambda_{THz}/4n_{AR}$, where $n_{AR}$ is the refractive index of the AR coating materials and is also the geometric mean of the substrate and air refractive indices.

$$T = 4 * \left[\frac{n^2}{ns} + \frac{ns}{n^2} + 2 + \left(\frac{1}{ns} + ns - \frac{n^2}{ns} - \frac{ns}{n^2}\right)\cos^2\left(2 * \pi * n * \frac{d}{\lambda}\right)\right]^{-1}$$

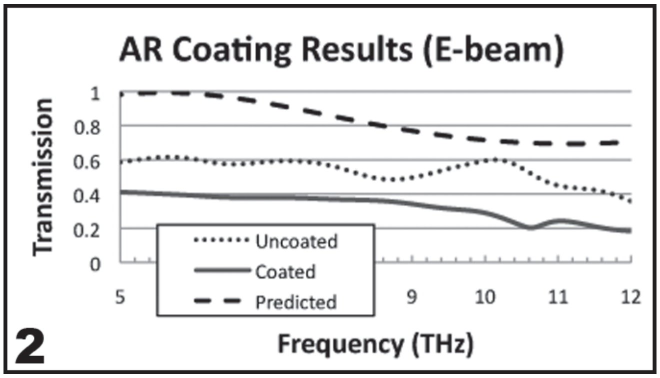
*Equation 1:*
n = refractive index of AR coating
ns = refractive index of substrate
d = coating thickness
T = transmitted intensity

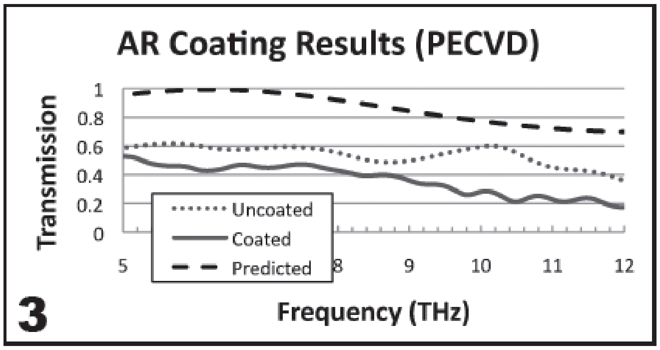
For our devices, the THz emission was traveling from an indium phosphide (InP) substrate (n ≈ 3.6) into air (n ≈ 1), yielding an ideal refractive index of 1.91 for an AR coating in the 1-5 THz range. Silicon dioxide ($SiO_2$) was used for AR coatings because of its near-ideal refractive index ($n_{SiO_2}$ = 2.00) and low absorption losses in the THz [2]. Parylene and Pyrex® were also considered, but discarded due to equipment constraints.

To test the coating, $SiO_2$ was applied to bare high-resistivity InP (HR-InP) and high-resistivity silicon (HR-Si) wafers. High-resistivity wafers were chosen to reduce the THz transmission loss due to free carrier absorption. Silicon wafers were used because of their availability and ideal dielectric properties (low absorption loss and a refractive index close to that of InP, $n_{Si}$ = 3.50.)

Two methods were used to deposit $SiO_2$. The primary deposition method used was electron beam (e-beam) evaporation. The e-beam system allowed for precise layer thickness control. A 6.9 $\mu$m layer of $SiO_2$ was deposited at 70°C and a maximum rate of 6 Å/s onto both HR-Si and HR-InP wafers. The layer thickness was monitored during deposition with a crystal quartz oscillator and confirmed using a Veeco Dektak 150 profilometer. $SiO_2$ began flaking off of the InP sample immediately after deposition, making accurate measurement impossible. A Bruker Vertex 70 Fourier transform infrared spectrometer (FTIR) was used to measure the transmission spectrum of the samples before and after the application of AR coatings. The results for HR-Si samples are shown in Figure 2.

Plasma-enhanced chemical vapor deposition (PECVD) was another technique used to deposit $SiO_2$. PECVD can achieve very high growth rates (~ 1 $\mu$m/hr) at the expense of lower thickness uniformity. A 5.9 $\mu$m layer of $SiO_2$ was deposited at 200°C onto both HR-InP and HR-Si wafers. Post-deposition profilometry was used to measure the film thickness.




As in the case with e-beam deposition, the $SiO_2$ film did not adhere well to the InP sample and flaked off easily. A substantial amount (~ 500 nm) of bowing was also observed in the coated HR-Si wafers. FTIR spectrometry was used to compare the transmission spectra of the Si wafer before and after deposition. The results are compared to the simulated transmission in Figure 3.

## Results and Conclusions:

For both PECVD and e-beam evaporation, the actual transmission of THz light was significantly less than theory predicted. In each case, the addition of an $SiO_2$ AR coating did not increase the transmission of THz light for any of the measured frequencies. The absorption losses of the e-beam deposition were consistently 5% higher than those of the PECVD samples. We suspect that the high absorption of the AR coating overcompensated for any improvement in the transmission. The trend in the post-coating transmission spectrum for both cases suggests that the AR coating improved transmission for some frequencies relative to others. However, without knowing exactly the absorption characteristics of $SiO_2$ in these frequencies, we cannot conclude that the AR coating truly decreased the amount of light reflected.

For both deposition methods, the poor adhesion of $SiO_2$ to the InP samples and the observed bowing on the Si samples could be due to the difference in the thermal expansion between the $SiO_2$ and InP. A large difference would cause a buildup of stress in the $SiO_2$ film and cracks could form if the stress goes beyond a critical threshold. To account for the discrepancy between the two methods, we suspect several factors.

First, the higher temperature deposition via PECVD likely produced a more uniform layer than the lower temperature e-beam deposition. Second, the e-beam deposition took place over several sessions, which might have created several distinct layers, leading to losses between each layer. It is also possible that contaminants from the deposition chamber or other samples might have been in the $SiO_2$ target used for E-beam deposition.

We also suspect that the literature values of the real and imaginary parts of the refractive index for $SiO_2$ were significantly different from those in our materials. The dielectric properties of $SiO_2$ depend heavily on the deposition methods used; it is likely that the literature values for amorphous material were not accurate for E-beam and PECVD deposited material. This error would likely have shifted the predicted peak in transmission, possibly even beyond the measurement range of our FTIR spectrometer.

## Future Work:

For future progress, Parylene-C will be investigated as an alternative to SiO2. Parylene has a well-developed deposition process and would eliminate much of the variability present in working with SiO2. An ion source assisted e-beam deposition might also give a lower-absorption AR coating.

## Acknowledgements:

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## References:


[1] Jihua Xu, Applied Physics Letters 91, 121104 (2007); doi: 10.1063/1.2786587.

[2] Palik, E; "Handbook of Optical Constants of Solids", Volume II, 1997.