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

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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

\[ d = \frac{\lambda_{\text{THz}}}{4 n_{\text{AR}}} \]

where \( n_{\text{AR}} \) is the refractive index of the AR coating materials and \( n_{\text{AR}} \) is also the geometric mean of the substrate and air refractive indices.

For our devices, the THz emission was traveling from an indium phosphide (InP) substrate \((n \approx 3.6)\) into air \((n \approx 1)\), yielding an ideal refractive index of 1.91 for an AR coating in the 1-5 THz range. Silicon dioxide (SiO₂) was used for AR coatings because of its near-ideal refractive index \((n_{\text{SiO}_2} = 2.00)\) and low absorption losses in the THz [2]. Parylene and Pyrex® were also considered, but discarded due to equipment constraints.

To test the coating, SiO₂ 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, \(n_{\text{Si}} = 3.50)\).

Plasma-enhanced chemical vapor deposition (PECVD) was another technique used to deposit SiO₂. The primary deposition method used was electron beam (e-beam) evaporation. The e-beam system allowed for precise layer thickness control. A 6.9 µm layer of SiO₂ was deposited at 70°C and a maximum rate of 6 Å/s onto both HR-Si and HR-InP wafers. Post-deposition profilometry was used to measure the film thickness.

Plasma-enhanced chemical vapor deposition (PECVD) was another technique used to deposit SiO₂. PECVD can achieve very high growth rates (\(\sim 1 \mu m/hr\)) at the expense of lower thickness uniformity. A 5.9 µm layer of SiO₂ 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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} to the InP sample and the observed bowing on the Si samples could be due to the difference in the thermal expansion between the SiO\textsubscript{2} and InP. A large difference would cause a buildup of stress in the SiO\textsubscript{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\textsubscript{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\textsubscript{2} were significantly different from those in our materials. The dielectric properties of SiO\textsubscript{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 SiO\textsubscript{2}. Parylene has a well-developed deposition process and would eliminate much of the variability present in working with SiO\textsubscript{2}. An ion source assisted e-beam deposition might also give a lower-absorption AR coating.

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**References:**
