ND*nano* Summer Undergraduate Research
2017 Project Summary

1. Student name & university:
Zhaoyuan "Andy" Fang
University of Notre Dame

2. ND faculty name & department:
Prof. Anthony J. Hoffman
Department of Electrical Engineering

3. Project title:
Engineering optical modes in thin layers of epsilon-near-zero polar semiconductors

4. Briefly describe new skills you acquired during your summer research:
My summer research experience gave me insights into many aspects of professional research, especially the field related to Nano optics. In the lab, I learned how to use FTIR (Fourier transform infrared spectrometer) and other optical equipment to obtain an infrared reflection spectrum of different samples comprising thin semiconductor and metal layers. In addition, I was introduced to Raman spectroscopy, a spectroscopic technique to observe phonon modes in a crystal. Outside the lab, I used computational models such as rigorous coupled-wave analysis (RCWA) and data analysis software such as OriginPro and MATLAB to simulate and analyze the experimental results.

5. Briefly share a practical application/end use of your research:
Our research will eventually enable the development of new techniques in sensing, imaging, integrated photonics, and more. They can be further developed into applications in medicine, homeland security, industry, environmental monitoring, and basic research.

6. 50- to 75-word abstract of your project:
We demonstrate how crystal vibrations, called phonons, can be leveraged to engineer optical modes in thin layers of polar semiconductors. We characterize coupling to the Berreman mode for four different samples using polarization-, angle- and wavelength-dependent reflection spectroscopy and compare the results to numerical models developed using rigorous coupled wave analysis and finite difference frequency domain techniques; there is good agreement between experiment and simulations. These materials could eventually be used to engineer fundamentally new optoelectronic devices for the mid- and far-IR.

7. References for papers, posters, or presentations of your research:
Leland Nordin, Owen Dominguez, Christopher M. Roberts, William Streyer, **Zhaoyuan Fang**, Viktor A. Podolskiy, Anthony J. Hoffman, Daniel Wasserman, "Mid-Infrared Epsilon-Near-Zero Modes in Ultra-Thin Phononic Films," *Submitted to APL*

Project Summary

Light in the mid- and far-infrared portions of the electromagnetic spectrum (3-30 μm and 30-100 μm, respectively) is strongly absorbed by rotational and vibrational modes of molecules. This strong absorption is useful for highly sensitive and specific detection of trace amounts of gas and solids. While most of the mid-infrared is accessible using quantum cascade lasers, these sources do not operate at longer wavelengths in the far-IR (Figure 1). Indeed, the far-infrared is devoid of the optical materials, sources and detectors, and it certainly lacks compact, electrically-injected semiconductor optoelectronic devices. This technological gap results from the interaction of light with vibrations of the crystal lattice in polar crystals. In this work, we demonstrate how these crystal vibrations, called phonons, can be leveraged to engineer optical modes in thin layers of polar semiconductors that could eventually be used to engineer fundamentally new optoelectronic devices for this underserved portion of the spectrum.

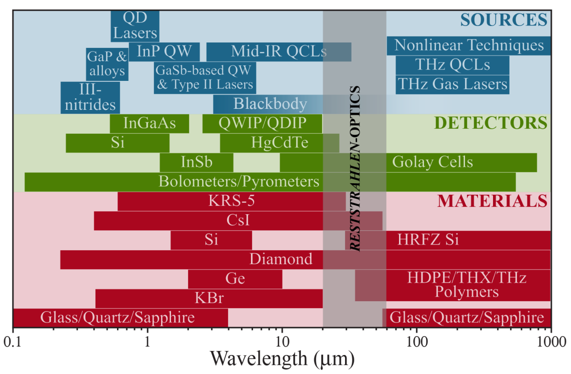

Figure 1. Summary of the materials, detectors, and sources that comprise the operational toolkit for Reststrahlen-optics.

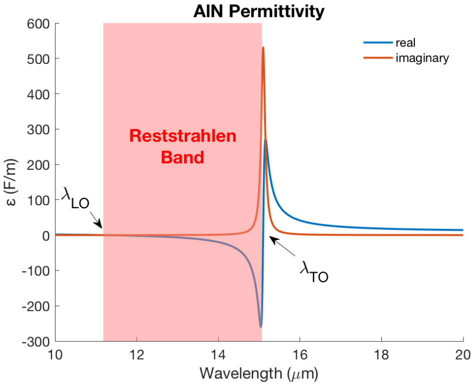

Figure 2. Real and imaginary permittivity of AlN

The region between a polar material's longitudinal optical (LO) and its transverse optical (TO) phonon energies (11.2 μm and 15.09 μm, respectively for AlN) is known as the *Reststrahlen* band. Here, the real part of the permittivity, ε, is negative and bulk materials exhibit strong reflection and high optical loss (Figure 2). In this project, we work with AlN because we this material has high energy phonons in the mid-infrared that can be readily characterized using equipment in our laboratory. Essentially we are using AlN as a testbed for long-wavelength materials that have phonon energies in the far-IR. Near the LO phonon energy, the real part of ε is close to zero, and the imaginary part is small (Figure 3). For bulk or optically thick epsilon-near-zero (ENZ) materials, Fresnel equations predict near-unity reflection, which is confirmed via experiment. However, thin layers of ENZ materials support a leaky mode which can be excited using free-space light, Figure 4. Furthermore, since optics is reciprocal, this strong, selective absorption also results in selective spectral emission at the same wavelength.

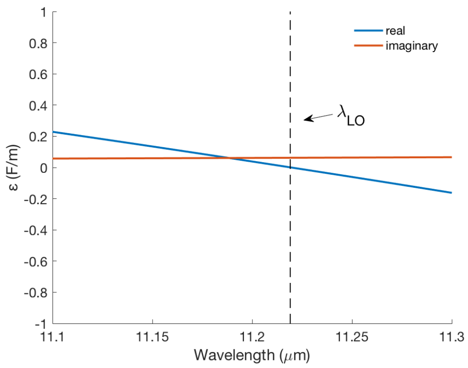

Figure 3. Real and imaginary permittivity of AlN

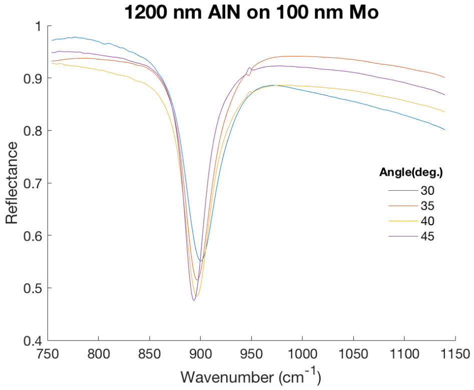

Figure 4. Optical mode of four angles

near it LO phonon energy *of AlN on Mo*

We prepare four samples with AlN thin films for optical characterization. Three samples have a 1.2 µm thick AlN film on top of different materials: (1) GaN, (2) Mo, and (3) sapphire (SiC). The forth sample, also 1.2 µm thick, comprises alternating 50 nm GaN and 50 nm AlN layers. All these thin film samples support the optical mode near the longitudinal optical phonon of AlN, called the Berreman mode. We characterize coupling to this Berreman mode using polarization-, angle- and wavelength-dependent reflection spectroscopy. We compare the measured results to numerical models developed using RCWA and finite difference frequency domain techniques. There is good agreement between experiment and simulations. Our measurements demonstrate that it is possible to control the energy and dispersion of the optical mode via the material below the AlN thin film and by interleaving thin GaN layers (Figure 5 to 8). These results could be useful for engineering the optical properties of the Berreman mode in more complex devices and materials.

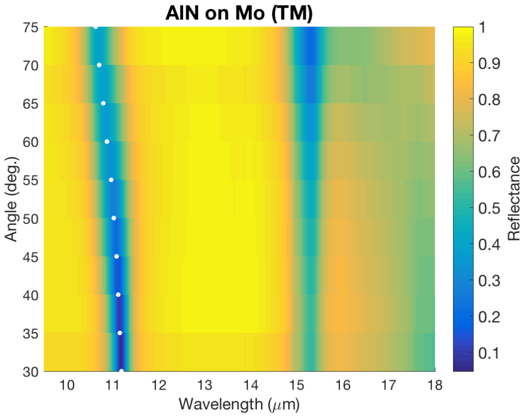

Figure 5. AlN on Mo reflection experiment color plot

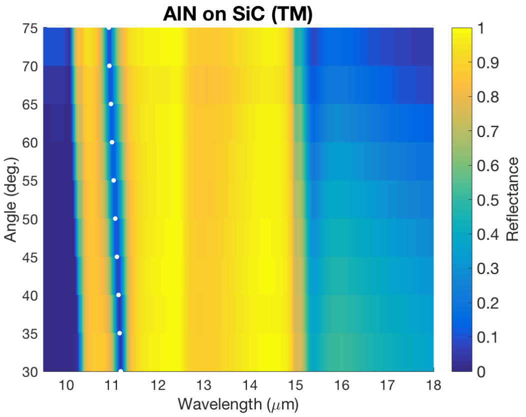

Figure 6. AlN on SiC reflection experiment color plot

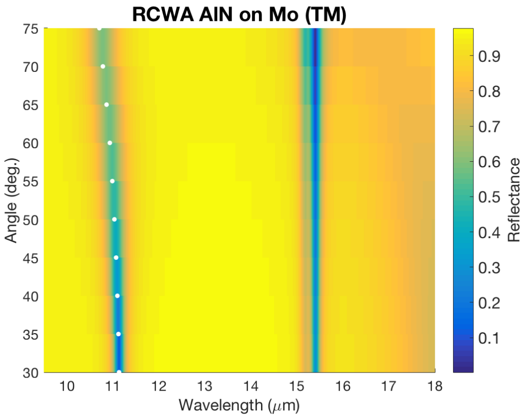

Figure 7. AlN on Mo reflection RCWA simulation color plot

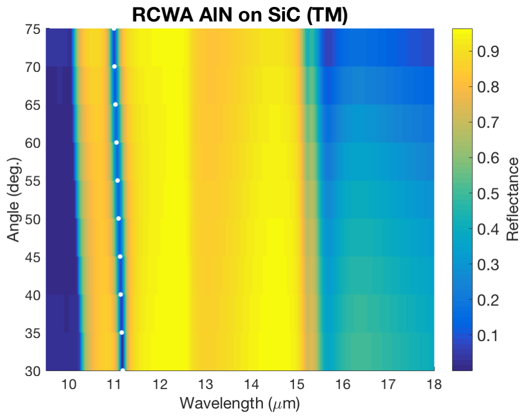

Figure 8. AlN on SiC reflection RCWA simulation color plot