Optical and Electrical Studies of Metal:Semiconductor Nanocomposites for Nanophotonics

Stephen D. March
Electrical Engineering, Iowa State University

NNIN REU Site: Microelectronics Research Center, The University of Texas, Austin, TX
NNIN REU Principal Investigator: Professor Seth Bank, Electrical and Computer Engineering, The University of Texas at Austin
NNIN REU Mentors: Erica Krivoy and Rodolfo Salas, Electrical and Computer Engineering, The University of Texas at Austin
Contact: sdmarch@iastate.edu, sbank@ece.utexas.edu, erica.krivoy@utexas.edu, rodolfo.salas@utexas.edu

Abstract and Introduction:

We explored the tunable optical properties of III-V compound semiconductor films grown by molecular beam epitaxy (MBE) for infrared optoelectronics and integrated plasmonics. This project has been twofold. (1) Investigate the optical tunability of MBE-grown rare-earth monopnictide (RE-V) nanoparticle superlattices by adjusting superlattice period and composition to demonstrate intermediate energy states that enable sub-bandgap tunability of gallium arsenide (GaAs). (2) Study the absorption blueshift in highly-doped indium arsenide (InAs) to demonstrate an approximately three-fold increase in the effective bandgap range and the divergence from existing non-parabolic InAs electronic band structure models. Both systems studied demonstrate two separate methods to tune III-V materials to provide greater material flexibility for optical engineering applications.

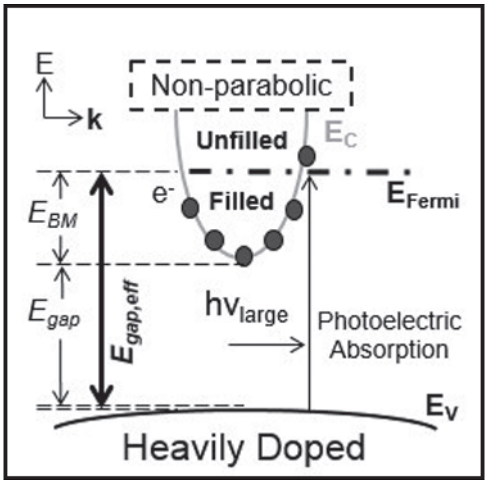

Figure 1: Burstein-Moss (E_{BM}) blueshift caused by heavy doping.

Material Systems Studied:

RE-V/III-V superlattice structures consist of periodically repeating layers with a 5 to 20 nm thick GaAs layer and a 0.25 to one monolayer (ML) deposition of RE-V, where the fractional volume of RE-V is equivalent in each structure. We investigated erbium arsenide (ErAs), lanthanum lutetium arsenide (LaLuAs), and lutetium arsenide (LuAs) RE-V nanocomposites. Work by Hanson et al. [1] on similar RE-V/III-V superlattice structures demonstrated strong sub-bandgap absorption in gallium antimonide (GaSb). We sought similar absorption changes in GaAs as our first method to optically engineer III-V materials.

InAs is a direct, narrow-bandgap semiconductor with a room temperature bandgap of 0.33 eV. We studied 500 nm thick films doped with silicon (n-type) and beryllium (p-type) with high active carrier concentrations of 6×10^{18} cm^{-3} to 9×10^{19} cm^{-3}. High n-type carrier concentrations, n, resulted in a strong absorption blueshift, which is attributable to band-filling, as described by Burstein [2] and Moss [3]. As n increases, the Fermi energy increases and more states in the conduction band, Ec, become filled with electrons. Since photoelectric absorption from the valence band, Ev, requires an unfilled state in the conduction band, the effective bandgap, $E_{gap,eff}$, increases with the Fermi energy, as shown in Figure 1. This study investigates unexplored high n values to tune $E_{gap,eff}$ in InAs as our second method to optically engineer III-V materials.

Experimental Procedure:

Near- and mid-infrared reflection and transmission spectra were collected with a 0.5 m grating spectrometer, using an InGaAs detector and a tungsten-filament source for the near-infrared, and an indium antimonide detector and carbon-rod source for the mid-infrared. Overlapping wavelength spectra were collected using LabVIEW and spliced using MATLAB, resulting in single spectra spanning wavelengths from 800 to 5000 nm (photon energies from 0.2 to 1.4 eV). The $E_{gap,eff}$ for different materials was found by using a linear extrapolation of the square of the absorption coefficient for a thin-film material, as suggested by Wu et al. [4].

Results and Conclusions:

RE-V/III-V Nanoparticle Superlattices. An aggregate transmission spectrum of several representative RE-V/III-V samples is shown in Figure 2. From 0.2 to 1.4 eV, GaAs exhibited a constant reflection value, thus any change in the transmission spectrum produced an opposite change in the absorption spectrum (e.g. decreased transmission produces increased absorption). Nanocomposites with Er and LaLu, small nanoparticles (small ML), and a small number of periods showed a small dip in transmission for incident photonic energy greater than 0.75 eV. Nanocomposites with Lu, large ML, and many periods showed a more pronounced transmission spectrum dip near 0.8 eV, which is far below 1.4 eV bandgap for intrinsic GaAs. RE-V nanoparticles create sub-bandgap energy states (Figure 3) that allow for sub-bandgap photoelectric absorption [1]. By adjusting the composition and structure of superlattices we can engineer GaAs for absorption near 0.8 eV. This value is critical for fiber optic systems, because 0.8 eV (1550 nm) is used by the existing fiber optic infrastructure for optimal signal relay and acquisition; III-V-based detectors using RE-V nanocomposites may be quickly adopted to work with existing technology. Future work will explore other RE materials and adjusted MBE growth techniques to refine the tunable properties of RE-V/III-V nanocomposites.

Heavily-Doped InAs. A plot of $E_{gap,eff}$ versus n is given in Figure 4. We observed a tunable $E_{gap,eff}$ range of 0.64 to 1.16 eV, which is several times larger than the intrinsic bandgap of InAs of 0.33 eV and indicates InAs absorption may be engineered by controlling n. The data agreed well with previously published results at lower carrier concentrations and diverged noticeably from the best fit non-parabolic band model available [5, 6]. Although non-parabolic behavior is expected for large n, modeling such behavior is limited by low n values previously explored. Our larger-n trend describes non-parabolic behavior more completely and can be used to study and optically engineer narrow-bandgap materials. Future work will concentrate on quantifying a new non-parabolic model and exploring even higher n.

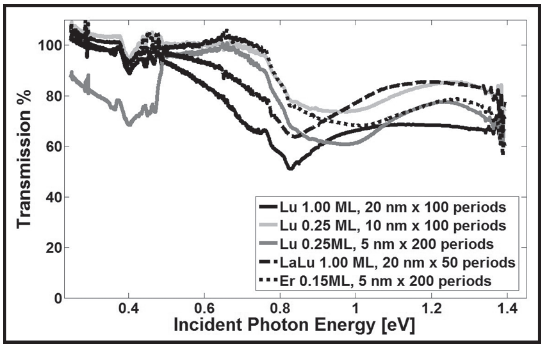

Figure 2: Transmission spectrum for RE-V/III-V nanoparticle superlattices.

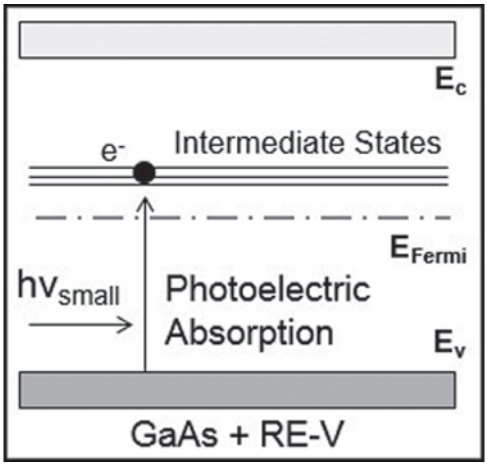

Figure 3: Sub-bandgap photoelectric absorption caused by RE-V nanoparticles.

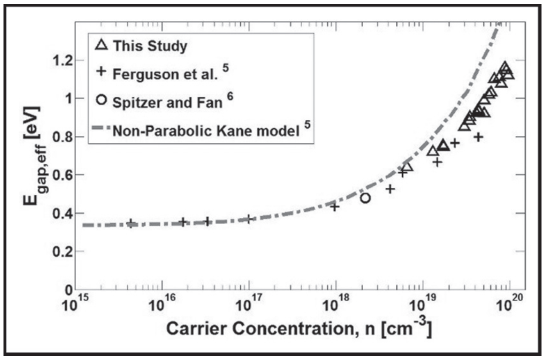

Figure 4: $E_{gap,eff}$ *versus* n *with literature values and a non-parabolic band model.*

Acknowledgments:

I want to thank Professor Seth Bank, Erica Krivoy, Rodolfo Salas, Scott Maddox, and the LASE group for their direction and creating a terrific work environment. I also want to thank the National Nanotechnology Infrastructure Network Research Experience for Undergraduates Program and the National Science Foundation for funding.

References:

[1] Hanson M., et al.; "Strong sub-bandgap absorption in GaSb/ErSb nanocomposites attribues to plasma resonances of semimetallic ErSb"; AIP Conf Proc, 772 (2004).

[2] Burstein, E.; "Anomalous Optical Absorption Limit in InSb"; Phys Rev, 93 (1954).

[3] Moss, T.; "The Interpretation of the Properties of Indium Antimonide"; Proc Phys Soc B, 67 (1954).

[4] Wu, J., et al; "Effects of the narrow band gap on the properties of InN"; Phys Rev B, 66 (2002).

[5] Ferguson, I., et al.; "Infrared reflection and transmission of undoped and Si-doped InAs grown on GaAs by molecular beam epitaxy"; Semicond Sci Technol, 8 (1993).

[6] Spitzer, G., and Fan, H.; "Determination of Optical Constants and Carrier Effective Mass of semiconductors"; Phys Rev, 106 (1957).