ND*nano* Summer Undergraduate Research
2019 Project Summary

1. Student name & home university:
Muireann de h-Óra, University College Cork, Ireland.

2. ND faculty name & department:
Dr. Alan Seabaugh, Pratyush Pandey, Department of Electrical Engineering.

3. Summer project title:
Spectroscopic Photoresponse System for Measurement of Semiconductor Heterostructure Band-Offsets

4. Briefly describe new skills you acquired during your summer research:
Matlab was an integral part of my summer project as it was used to not only communicate with the machines in the Spectroscopic Photoresponse Measurement System, but also to analyse the data collected. Learning more about this program contributed to my problem solving abilities and how to deal with situations where things did not always go as well as hoped. Analysing data was a focal point in the research project as I had to test the system's capabilities and limits as well as find solutions to problems in the setup. Another key skill that I acquired during my project was how to work with Cadence in designing masks for wafer fabrication. The actual fabrication of these masks and devices was also a part of my internship. Working in the clean room was a completely new experience and educational for me, one that I thoroughly enjoyed. Seeing how devices are processed from beginning to end gave me an insightful look into how the devices are structured.

5. Briefly share a practical application/end use of your research:
The spectroscopic photoresponse measurement system will not only be fundamental in the measurement of the barrier height in ionic polymers and ferroelectric metal-oxide-semiconductor (MOS) structures, but it also will be made available to other interested users at Notre Dame. Other interested users may test devices for a variety of spectroscopic photoresponses, such as their transmissivity. Furthermore, the devices that were designed and fabricated during this project will be used for analog memory and machine learning, both of which are integral components of artificial intelligence, which is being extensively researched currently.

6. 50- to 75-word abstract of your project:
Polarizable materials including ionic polymers and ferroelectrics are used as dielectrics in capacitors, and gate oxides in transistors for analog memory for machine learning. In these applications, the barrier heights presented to electrons in metal-oxide-semiconductor (MOS) structures are key design parameters. The aim is to configure a measurement system that controls the energy of incident photons on a semiconductor device and records a photoresponse as a function of applied bias and photon energy, providing a direct measurement of the electronic barrier heights in such heterostructures.

7. References for papers, posters, or presentations of your research:
[1] A. Aziz, et al., "Computing with ferroelectric FETs: Devices, models, systems, and applications," in 2018 Design, Automation Test in Europe Conference, Exhibition (DATE), pp. 1289-1298, March 2018.
[2] V. V. Afanas'ev and A. Stesmans, "Internal photoemission at interfacesof high-k insulators with semiconductors and metals," Journal of Applied Physics, vol. 102, no. 8, p. 081301, 2007.
[3] N. Nguyen, O. Kirillov, and J. Suehle, "Band alignment of metal-oxide-semiconductor structure by internal photoemission spectroscopy and spectroscopic ellipsometry," Thin Solid Films, vol. 519, no. 9, pp. 2811 - 2816, 2011.

One-page project summary that describes problem, project goal and your activities/ results:

Polarizable materials including ionic polymers and ferroelectrics are being used as dielectrics in capacitors, and gate oxides in transistors for analog memory for machine learning and in new types of circuits mimicking neural signaling[1]. In these applications, the barrier heights presented to electrons in metal-oxide-semiconductor (MOS) structures are key design parameters. Our aim this summer has been to configure a measurement system that can dynamically control the energy of incident photons impinging on a semiconductor device and record a photoresponse (e.g. photocurrent, photovoltage, photocapacitance) as a function of applied bias and photon energy. In a MOS structure there is an energetic barrier to block electron flow across the oxide. Electrons can be excited over the barrier if light with an energy exceeding the barrier is absorbed by the electron, Figure 1 (I). In the presence of an internal or external electric field the electron can flow across the barrier and current can then be detected, as seen in Figure 1 (II). By controlling the wavelength of the incident illumination, the onset of this current increase can be used to determine the barrier height. In the case of a ferroelectric or ionic polymer the barrier can be changed depending on the polarization. While this effect has been predicted, this has not been directly measured.

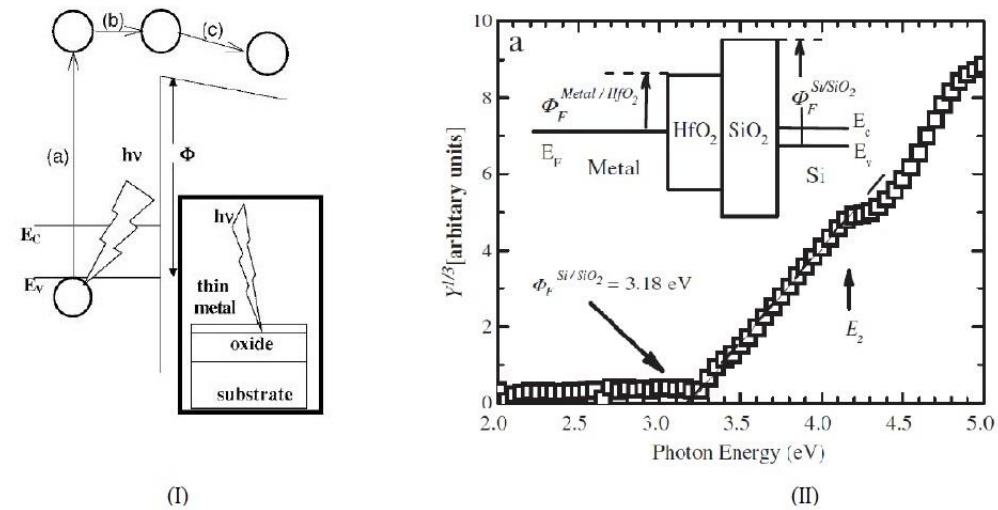

Figure 1. (I) IPE measurement involving exciting a charge carrier with an incident photon of energy, $E = h\nu$, in a MOS structure. The outcome of this is (a) excitation of an electron/hole within a material, (b) transport of said charge carrier to the potential barrier due to an applied bias, and (c) transferal over the barrier. Figure from Afanasev 2007 [2].

(II) Linearized yield (proportional to current) $Y^{1/3}$ plotted vs. the photon energy in a MOS stack structure at an average electric field of 3.6 MV/cm from the metal gate to semiconductor. Inset shows a band diagram schematic illustrating the various barrier heights in the structure. Figure from Nguyen 2011 [3].

A Spectroscopic Photoresponse Measurement System, as seen in Figure 2, has been configured consisting of an Energetiq Laser Driven Light Source, Newport Monochromator, Newport Filter Wheel, Thorlabs optical fibers, Thorlabs detectors, and Keithley sourcemeter. The laser driven light source injects light into the monochromator which is then set to a certain diffraction grating and a known wavelength of light is output. This light then travels through the filter wheel blocking all higher order harmonics of light. Coupling this light with an appropriate optical fiber allows for an average of 1×10^{-5} W of power for grating 1 and 4×10^{-4} W for grating 2 to be focused on a device. To calibrate the system, a range of wavelengths were swept and the output light was detected using an appropriate powermeter.

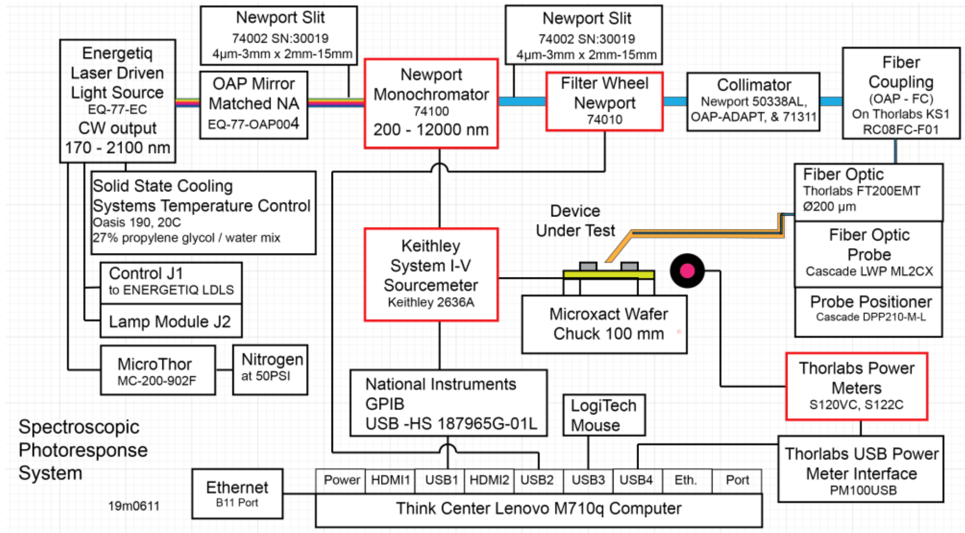

Figure 2. Spectroscopic Photoresponse system with the devices controlled using MATLAB highlighted in red.

The smallest increment step size that the system can sweep is 1nm which enables the user to accurately measure the input energy. The system has been demonstrated to show detector response in the range from 6.2 to 0.7eV (200 to 1800 nm). As seen in the calibration measurements in Figure 3, sweeping this range requires two gratings, grating 1 ranges from 200-1100nm and grating 2 from 875-1800nm. Also in this figure is the laser driven light source output to compare intensity peaks with those from the Monochromator sweeps. The Monochromator was swept for two different step sizes (25nm and 5nm), for increasing and decreasing wavelengths, and each sweep was then repeated three times for consistency. There is little variation, 0.1%, shown in the setup in repeated measurements for both forward and backward sweeps.

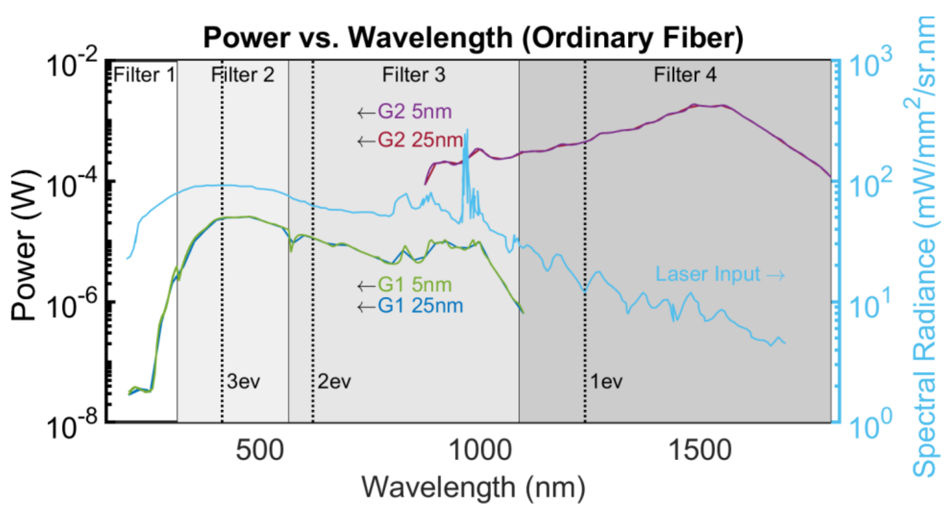

Figure 3. Measured power of the spectroscopic response measurement system with 25nm and 5nm increment sweeps from grating 1 (G1) and grating 2 (G2), the region for which the filters operate, 1, 2, and 3ev, and the laser output.

Further, a process for fabrication of MOS structures has been designed and a three-level photomask set for fabrication of devices has been designed. Both FET and IPE structures with Corbino disc geometry were added to the mask. The Corbino disc geometry allows measurement of photocurrent in lateral structures without the need for device isolation. Transmission Electron Microscopy (TEM) and Scanning

Electron Microscopy/ Atomic Force Microscopy (SEM/AFM) test structures were also added to the mask along with alignment marks to align the three mask layers. Future work will include testing the devices that have been fabricated and determining their barrier height.

To conclude, a measurement system has been configured to spectroscopically control incident illumination on a device, the onset of this current increase is used to determine barrier height. The spectroscopic photoresponse system will not only be fundamental in measurement of the barrier height in ionic polymers and ferroelectric MOS structures, but it also will be made available to other interested users at Notre Dame.

Acknowledgements:
I would like to thank Dr. Seabaugh and Pratyush Pandey for their support on this project. It has truly been a pleasure working with you and the team. I would also like to thank The Naughton Foundation and NDnano for providing me with this amazing opportunity.

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