Introduction: The last few years have seen an explosion of research into third-generation solar cells, which seek to exploit nanostructures and quantum phenomena to surpass the classical Shockley-Quiesser efficiency limit of 31% for a single homojunction.[1] In contrast to solar cells of the first generation (expensive silicon) and second generation (cheap but inefficient thin films), third generation technologies are extremely efficient and potentially transformative. If successfully developed, they could propel the world one step closer toward generating cheap, clean, and renewable energy.

With Professor Ed Yu in 2008 and 2009, I researched third generation solar cell concepts, becoming familiar with the theory and cleanroom fabrication of nanowire solar cells, quantum well (QW) solar cells, quantum dot solar cells, plasmonic structures, and nanoparticle scattering. While modeling core-shell nanowire solar cells, I realized that a fundamental aspect of nanowire solar cells, the decoupling of optical and electronic path lengths into orthogonal directions, could be applied to QW solar cells, by growing the QWs vertically in nanowire form. Fabricating QW solar cells with nanowires offers to circumvent a key hurdle in typical QW solar cells, while also presenting new challenges. Exploring these new challenges is the focus of my research proposal.

Background: QW solar cells are one of the most promising third-generation solar technologies, with theoretical maximum efficiencies of ~45%-63% at single sun illumination, well exceeding the Shockley-Queisser limit.[2,3] They harness QWs in the photo-active region of a solar cell to extend its absorption edge and increase its photocurrent. This results in enhanced power output as long as the charge-carrier populations in the QWs can avoid reaching equilibrium with the bulk material (i.e., have different quasi Fermi levels).

One critical design tradeoff in QW solar cells is choosing the thickness of the active QW region. Many QWs will absorb more light, but also trap more carriers. This is a hurdle to attaining the theoretical maximum efficiencies of QW solar cells, as it makes it challenging to achieve high optical absorption efficiency and high carrier collection efficiency simultaneously.

A clever way to circumvent this tradeoff is to orthogonalize the paths of photons and carriers by redirecting the photons. Notably, in 2008, my lab was able to use gold and silica nanoparticles on the surface of a QW solar cell to couple normally incident light into lateral propagation paths, using the QWs as waveguides.[4] Because the light travels laterally along the wells, instead of vertically through them, the QW region can be made thinner without severely diminishing the optical absorption.

One can also orthogonalize the paths by leaving the light path alone and instead rotating the solar cell's p-n junction, by building it into 3D nanostructures. Coaxially doped QW nanowires are ideal for decoupling the optical and electronic paths: light would be absorbed along the entire length of the nanowire, while carriers would only have to travel across the relatively thin radius. An effective QW nanowire solar cell might only need ~1-10 QWs, significantly fewer than its thin film counterparts (~10-100), allowing for simultaneously high optical absorption and high carrier-collection efficiency. This promising characteristic of QW nanowire solar cells makes them strong candidates for focused study.

Hypothesis: I hypothesize that QW nanowire solar cells will exhibit the same non-equilibrium QW phenomena as thin film QW solar cells, necessary to surpass the Shockley-Queisser efficiency limit. Measurement of this effect in nanowires would be a major step toward demonstrating the feasibility of QW nanowire solar cells and characterizing their behavior.

Research Plan: The proposed materials for the QW nanowires are AlGaAs and GaAs, due to their tiny lattice mismatch (~0.12%), near optimal bandgaps for QW solar cells,[2] and relatively well understood growth processes.[5] The first step toward fabricating an AlGaAs nanowire device will be to replicate results achieved by LaPierre et al. in 2008, in which AlGaAs nanowires with QWs were fabricated using gold-catalyzed VLS growth in a gas source molecular beam epitaxy growth chamber (GS-MBE).[5]

After high quality nanowires can be grown consistently with MBE (available in MIT's state-of-the-art cleanroom), the same structures will be fabricated with p-n junctions, by doping the core with Be and the outermost shell with Te during MBE growth. Note that Te is used as an n-type dopant because commonly used Group IV dopants such as Si are amphoteric in AlGaAs nanowires, which grow preferentially along the (111)B direction.[6] During this phase, the effects of varying doping and growth conditions will be investigated with a scanning electron microscope (SEM) and high-angle annular dark-field scanning transmission microscope (HAADF STEM), both available at MIT.

Once the morphological effects of doping are suitably characterized and understood, contacts will be deposited on the devices. The back contact will be e-beam evaporated onto the device, and after covering all but the tips of the nanowires with SiO_2 (using plasma-enhanced CVD and then a plasma reactive ion etch chamber), the top contact, made of transparent indium tin oxide, will be sputtered on.

The resultant solar cells will be extensively characterized. SEM measurements will be used to show the growth steps and nanowire morphology, HAADF STEM measurements will test the presence of QWs inside the nanowires, and dark current measurements will test whether the GaAs QWs are in equilibrium with the AlGaAs barrier material during operation. Finally, using a solar simulator (available at MIT), the illuminated IV characteristics will be measured to further understand the device and also provide an overall efficiency figure.

Broader Impacts: Someday, transformative third-generation solar cell designs like this one may replace fossil fuels in our electricity generation portfolio and provide cheap, clean, and renewable power. I know personally from my work on the Kenya TIES project (see personal statement) that cheap solar cells are of especially great importance in developing countries where, due to unreliable national grids, distributed microgrids are frequently built to power villages and communities.

I hope my research will help educate students, particularly underrepresented students, who face especially great challenges in engineering. I know firsthand how enlightening and inspiring it is to research as an undergraduate, so as a graduate student, I plan to bring in undergraduate research assistants so that they too can experience the forefront of engineering.

I attest that I invented, researched, developed, and wrote this original research proposal.

Citations:

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