GCEP

Global Climate & Energy Project

STANFORD UNIVERSITY

Nanostructured Silicon-Based Tandem Solar Cells

Investigators

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Objective

This project will develop an innovative photovoltaic device based on integrating low-cost polycrystalline silicon thin films with higher bandgap semiconducting materials synthesized using silicon quantum dots embedded in a matrix of silicon oxide, nitride, or carbide to produce two- or three-cell tandem stacks. By capturing different energies within the solar spectrum in each cell in the stack, a significant increase in the efficiency of silicon-based thin films is anticipated without adding appreciably to large-volume manufacturing costs per unit, thus decreasing installed system costs.

Background

The cost of thin-film solar cells using low-cost inorganic semiconductor materials, called "second generation" photovoltaics, is fundamentally limited by encapsulation and balance-of-system costs. To achieve the cost and performance levels needed to compete in the wholesale energy market, "third generation" photovoltaic technology requires not only a significant improvement in efficiency without adding appreciably to large-scale manufacturing costs, but also that it uses abundant, non-toxic, stable, and durable materials. Among the possible strategies that could meet these criteria, tandem or stack-cells of different bandgaps have been identified as having high potential for efficiency improvement, with efficiency limits of 45% and 50.5% for two- and three-cell stacks respectively. This project addresses the challenge of fabricating tandem devices from silicon-based materials. Essential to this is the development of techniques for controlling the bandgap of silicon. Carrier confinement in nanoscale structures provides such a technique. The integration of silicon nanoparticles in matrices formed from compounds of silicon allows tuning of the bandgap by exploiting the quantum effects related to their size and their distribution across the cell. Figure 1 is a schematic of the energy levels of such a silicon-based three-cell stack, with a conventional silicon cell as the lowermost cell shown on the right. Critical parameters to be controlled for tuning the absorption spectrum of the single cells include dot spacing and size, as

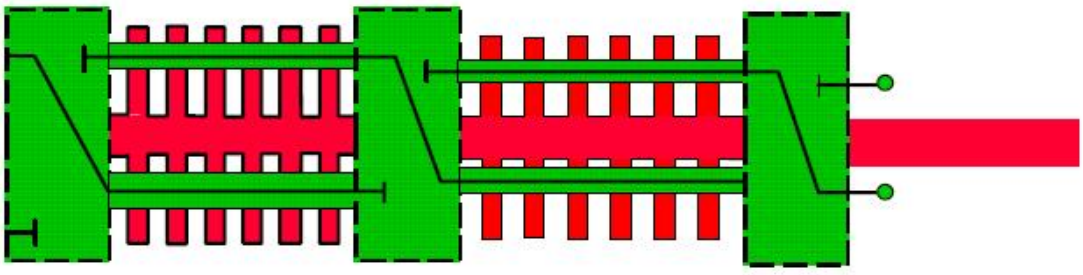

Figure 1: Energy levels of a silicon-based three-cell stack using quantum dot superlattices for the uppermost cells. Quantum dots are embedded in a higher bandgap matrix. The two green horizontal bars represent confined minibands formed by the nanoparticle network. The energy gap between them is determined by the dot size, and their energy range depends upon the spacing between the dots, degeneracy within the silicon band structure, and fluctuations in dot size. The rectangular regions between cells represent tunnel or defect junction connections.

well as fluctuations in the sizes of the dots. The geometry of the nanoparticle networks also needs to be optimized to enhance carrier transport through resonant hopping between layers in a cell.

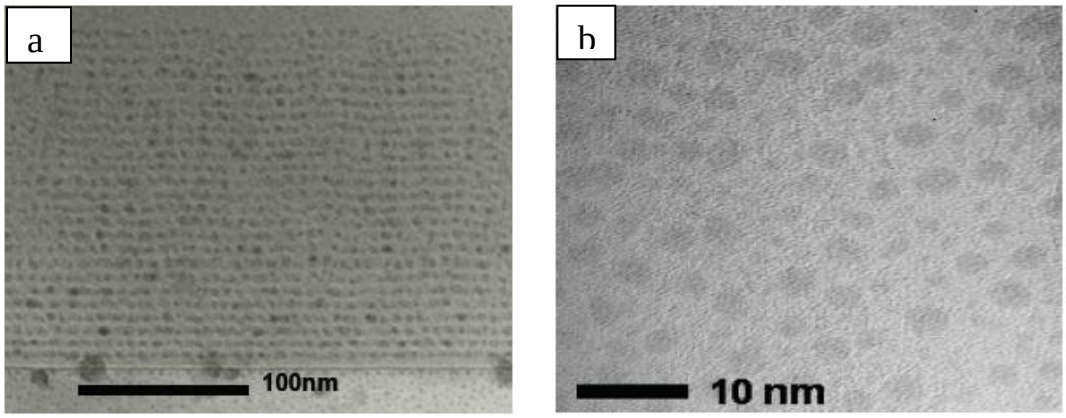

Figure 2: (a) Cross-sectional view TEM image of silicon quantum dot layers prepared in an oxide matrix; **(b)** Plan view TEM image of a single layer of silicon quantum dots showing lateral spacing.

Approach

Four main areas of activity are being followed in this effort:

- *Materials Preparation:* Networks of Si nanoparticles embedded in silicon-based matrices are prepared by depositing thin layers (a few nm thick) of alternating stoichiometric SiO_2 and Si-rich SiO_2. On annealing, Si precipitates from the super-saturated solid solution within the silicon-rich layer as nearly spherical quantum dots enclosed by the SiO_2 matrix. Figure 2 shows high-resolution TEM images of the quantum dots and layers. The preparation technique (deposition technology, layer thickness, annealing temperature, and times) will be optimized to control the size and uniformity of the silicon nanoparticles. Replacing some or all of the Si with Group IV elemental semiconductors such as Ge or Sn, as well as doping of the quantum dots, will also be explored. Silicon nitride and carbide are also being investigated as matrices.

- *Physical, Optical, and Electronic Characterization:* TEM and synchrotron XRD analysis will be used to characterize the physical dot properties. Optical and electronic properties of the device will be studied using photoluminescence, conductivity, Hall effect, and atomic force microscopy measurements among others.

- *Simulation and Modeling*: Numerical modeling will be used to understand electronic transport properties of partly organized quantum-dot structures, and the effect of doping upon free carrier concentration and electron affinity. Additionally, it will be a critical tool for designing the overall stack geometry and properties, and for interpretation of the high-resolution TEM images for the physical characterization of the cell.

- *Device Fabrication:* In developing experimental devices, activities will include investigation of low sheet resistivity contacting layers, fabrication of both defect p-n junctions (required for the cell interconnection) and p-i-n junctions.