Solar Cells and Quantum Dots – A White Paper

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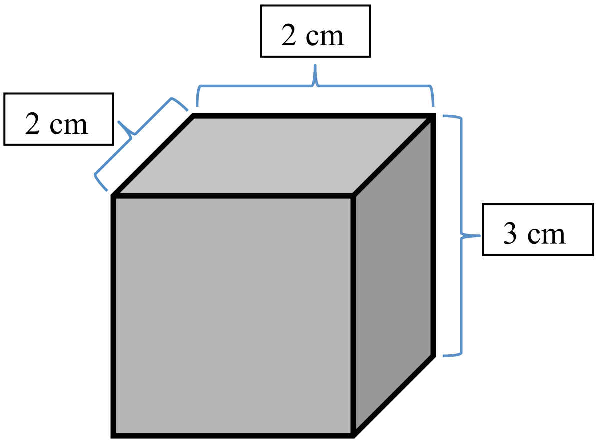
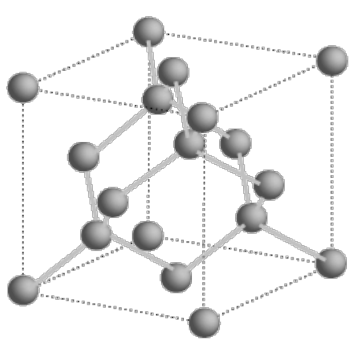
The block of single crystal silicon pictured below would have a mass of 28 grams and would contain over 10^{23} atoms. That is nearly a quadrillion billion atoms.



A block of single crystal silicon.

Examination of the block of silicon under a very powerful electron microscope will reveal that the atoms are arranged in a very definite pattern called the lattice structure.

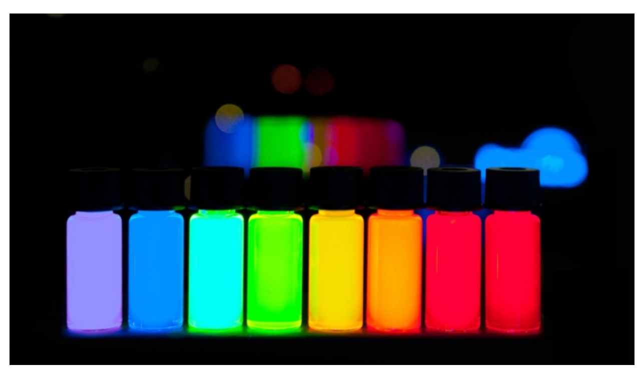


The lattice structure of single crystal silicon.

If we were to divide the block in half, then divide one of those pieces in half and repeat the process for a total of 65 times we would end up with a piece of silicon with an average side about 3 nanometers (one billionth of a meter) long and it would contain roughly 200 atoms. This tiny piece of silicon we call a quantum dot. Silicon quantum dots with dimensions as small as 1 nanometer have been made. When the pieces of silicon get to the quantum dot size they start to no longer look like cubes but more like little pyramids or the caps of hemispheres, hence the name quantum dot.

The remarkable thing about silicon quantum dots is that they essentially retain the same lattice structure as the larger block with which we started. The much smaller size, however, means that the usual electronic properties we would see with the larger block of silicon are changed in some very dramatic ways. One of the changes has to do with how silicon interacts with light. Ordinary silicon does not emit radiation in the visible part of the spectrum at all and emits only weakly in the longer wavelength, or infrared, part of the spectrum. All that changes in the quantum dot size regime.

Adjusting the dimensions of a silicon quantum dot will enable it to emit light in the visible part of the spectrum. Each one of the vials in the figure below contains silicon quantum dots,



with the smallest size quantum dot on the left (violet color) and the largest on the right (red color.) What is important, however, is that the different quantum dots will also absorb the same color they emit. Not only that, the quantum dots in any given vial can also absorb the shorter wavelengths of light as well, though with diminishing capability as the wavelengths get shorter. It is this property – the ability to "tune" the quantum dots to absorb different regions of the solar spectrum by changing their size- that makes them useful for solar energy conversion.

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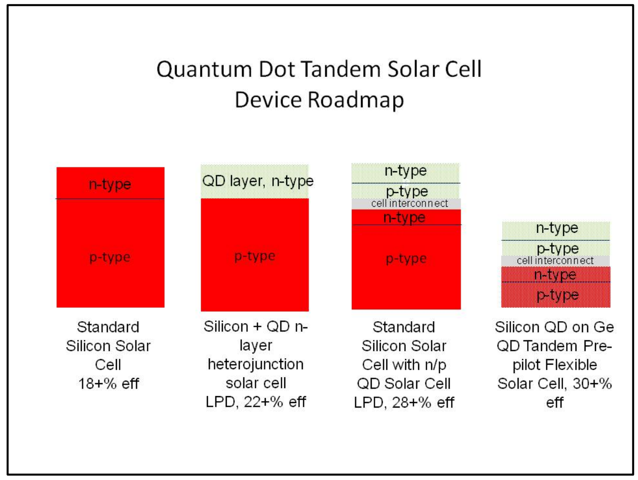
The technical name for this ability to change the wavelengths of light absorbed by the quantum dots is ”bandgap engineering.”

In order for light to be absorbed by a solar cell the energy of the incoming light must be greater than the energy bandgap of the absorbing material. A silicon solar cell starts absorbing at a wavelength slightly greater than1100 nanometers and the absorption reaches its maximum value for wavelengths below about 900 nanometers. The absorption typically starts to decrease as the wavelength of the incoming light gets shorter. Making silicon quantum dots with dimensions on the order of 2 nanometers results in a bandgap of about 1.71eV and the corresponding wavelength where absorption starts is about 725 nanometers, a wavelength considerably considerably shorter than the turn-on wavelength for regular silicon solar cells.

If a solar cell made of quantum dots is placed on top of an ordinary silicon cell, its absorption starts to “kick in” where the silicon cell absorption starts to fall off. Such a cell configuration is called a tandem solar cell because the two devices work in series. The result is that the overall efficiency goes up because more light is absorbed. Theoretical estimates of the efficiency such a device could exhibit are in the range from 30% to 35% in terrestrial sunlight.

The figure at the right above presents a roadmap of sorts for the steps to go through to make an all quantum dot solar cell. The progression passes through the various cell combinations starting with an ordinary silicon solar cell to a full quantum dot tandem solar cell. It should be pointed out that tandem solar cells are not a new invention. Such devices have been used on space satellite solar arrays for two decades or more. The space cell is made of exotic, very expensive materials that make it impractical for terrestrial solar arrays, but the all quantum dot tandem solar cell can be made from readily available materials such as silicon and germanium in roll-to-roll film processing equipment and has the potential to be extremely low cost as well as highly efficient.



How soon can such devices be available to consumers? It may not be as long as previously thought. The past half dozen years has seen an explosion in the number of research papers being published by research groups the world over and rapid progress is being made in academic and industry research laboratories. Low cost, 30%+ efficient thin film tandem solar cells could start showing up in the marketplace in the next 3 to 5 years.

The US Department of Energy has set a target for the consumer cost of electrical energy from solar arrays at 5 cents per kilowatt-hour. This price will put solar array generated electricity on a par with fossil fuel power sources. When that happens, the world demand for solar cells and arrays will grow to hundreds to gigawatts (a gigawatt is one billion watts of output) per year, compared to the 35 or so gigawatts now being produced and sold annually. Companies that can address that market with appropriate technology will grow and prosper dramatically.