

Nanostructured, luminescent solar concentrators

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Narrow-band-gap quantum dots emitting at IR wavelengths may be ideal materials for solar-energy harvesting.

Luminescent solar concentrators¹ (LSCs), a class of solar-energy-harvesting devices, operate slightly differently from traditional photovoltaic (PV) solar cells. Irrespective of the exact nature of the active materials used for their manufacturing, solar cells generate electrical carriers and, hence, a photocurrent. In contrast, LSCs absorb solar photons and re-emit them over a narrow band at longer wavelengths. This downshifted radiation is transported to the edge of the LSC, where it illuminates a solar cell. In principle, the active material of LSCs can be any fluorescent substance, either inorganic (such as semiconductors) or organic (e.g., dyes). Figure 1 shows a schematic LSC, where the fluorescent medium consists of a collection of nanoscale semiconducting particles, also known as quantum dots (QDs).

In the 1970s, the main impetus behind the initial design and development of LSCs was the idea that—when attached to a large, inexpensive glass- or polymer-based LSC operating at optimal efficiency—the photocurrent generated by the edge solar cells may increase relative to the same cell facing the sun (because of the concentration effect at the LSC edges). This would reduce operational costs substantially by requiring less PV material. Today, this holds true for the thin-film and multi-junction cells that remain prohibitively expensive to fabricate. However, for silicon cells (which account for over 85% of commercially produced solar cells), the cost factor has been mitigated to a large extent. What makes LSCs still appealing is their ability to perform very well under both direct and diffuse lighting. This negates the need for any tracking mechanism, thus reducing the infrastructural support essential for any array of traditional solar panels. This, in turn, enables unique building-integrated applications. For instance, currently available solar panels can only be roof-mounted to accommodate the tracking components, while typical commercial areas in cities consist of buildings with very small footprints. LSCs can be incorporated in windows, sidings,

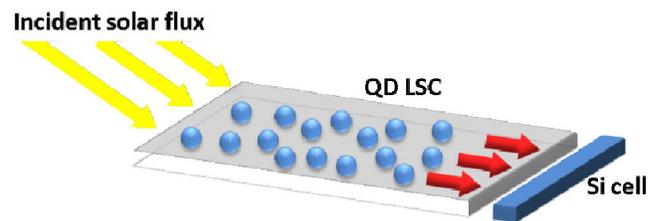


Figure 1. Schematic of a quantum-dot (QD)-embedded, luminescent solar concentrator (LSC). The incident sunlight consists of photons with energy ranging from the UV to the IR spectral range. The QDs re-emit these over a narrow range limited to the IR regime. This re-emitted radiation (red arrows) is captured by the silicon (Si) photovoltaic cell, which converts it to electrical power. The LSC is typically glass or polymer doped with QDs.

and other vertical areas, using large amounts of available but unused space for electrical-power generation.

Despite their ease of manufacturing and the possibilities they offer, LSCs have not quite achieved the requisite efficiencies to make them commercially viable.^{2,3} An LSC's performance is almost entirely determined by the properties of the fluorescent material, which needs to satisfy a number of criteria. It must offer broadband absorption (that is, absorb as much of the solar spectrum as efficiently as possible), have a high quantum yield (defined as the ratio of the number of photons emitted to those absorbed, thus reducing losses during the downconversion process), exhibit low self-absorption (the fluorescent material must not re-absorb its emitted photons, because they will not reach the PV at the edge and, thus, reduce the device efficiency), and offer spectral compatibility with the attached PV cell: if the emitted radiation is close to the PV material's band gap, the cell's external quantum efficiency will be higher, and the cell will thus generate more current.

The earliest LSCs were doped with organic dyes. However, dyes are very susceptible to photobleaching, so that their deployment is impractical. Recently, semiconductor QDs emerged as attractive candidates for development of stable and functional

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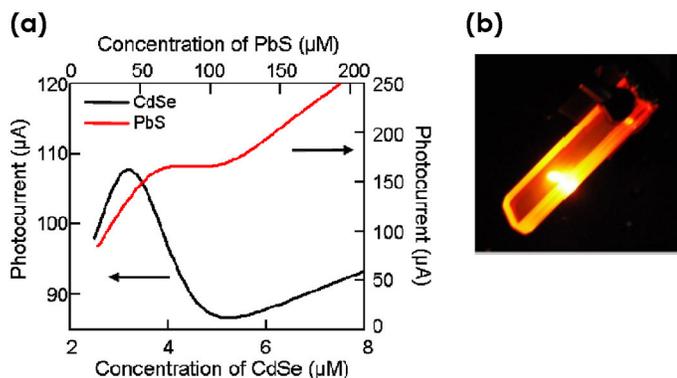


Figure 2. (a) Photocurrent for cadmium selenide (CdSe) and lead sulfide (PbS) LSCs as a function of QD concentration. The efficiency of CdSe concentrators is limited by self-absorption, which causes the generated current to decrease beyond a concentration of $3.2\ \mu\text{M}$. The PbS samples do not appear to suffer from such a limitation, because output current keeps increasing with QD density. (b) LSC showing light emission.

LSC devices. Most research on QD-based LSCs has centered on II-VI cadmium selenide (CdSe)/zinc sulfide core-shell nanoparticles coupled to silicon-PV cells. Varying the core diameter from 2 to 6 nm tunes the emission band from blue to red (450 to 640 nm) and stable samples with quantum yields on the order of 50–60% are relatively easy to grow. However, since QDs can only absorb solar photons with energies equal to or greater than their band gap, absorption is also limited to visible or shorter wavelengths. Almost 60% of solar photons have energies in the IR regime, so all that energy is unused. In addition, self-absorption is quite high, thus making these LSCs inefficient.

Our research focuses on developing efficient LSCs using lead sulfide QDs that emit at IR wavelengths.⁴ They absorb over a very broad spectral range ($<800\text{nm}$). At high enough QD concentration, these samples are very efficient absorbers of solar photons. Their emission is in the range 850–1000 nm, which energetically matches the band gap of silicon PV cells. This is a major advantage, since any excess energy from photons incident on PV cells contributes to heating, which may degrade cell performance. Finally, the QDs' Stokes shift is larger than for most other fluorescent materials commonly used in LSCs, in turn reducing the detrimental effects of self-absorption. Figure 2(a) compares the photocurrent generated in silicon-PV cells (attached to the edges of an IR LSC) to the performance of CdSe QDs emitting at $\sim 640\text{nm}$. For the latter sample (black curve), the current increases over a narrow range of QD concentration before decreasing as dominant self-absorption cancels the advantage of higher illumination. In comparison, the PbS sample (red curve) shows

much better performance. The associated photocurrent is higher and the output keeps increasing for higher QD concentrations.

For any solar-energy-harvesting device to perform well, it has to absorb as much of the solar spectrum as possible. Increasing absorbance of LSCs is easily achieved by increasing the concentration or density of the fluorescent material. However, the main problem is that self-absorption also increases when the QDs are packed more tightly, with as net result that the total intensity of the downconverted radiation reaching the PV cells exhibits a nonmonotonic dependence on concentration: see Figure 2(a). High self-absorption also limits the device size. The results obtained from our PbS LSCs are, therefore, very encouraging, because they demonstrate that for applications in solar cells (where efficient absorption is paramount) or silicon-coupled LSCs (where emission close to the silicon band gap is preferred), IR-emitting QDs are very suitable as active material. We will continue to carefully tailor our IR QDs to push the power-conversion efficiency of QD LSCs to the estimated theoretical limits, so that durable, stable LSCs with high power-conversion efficiencies can become a reality. This will lead to more cost-effective and user-friendly solar-power devices.

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