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Synergies Connecting the Photovoltaics and Solid-State Lighting Industries

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Synergies Connecting the Photovoltaic and Solid-State Lighting Industries

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ABSTRACT

Recent increases in the efficiencies of phosphide, nitride, and organic light-emitting diodes (LEDs) inspire a vision of a revolution in lighting. If high efficiencies, long lifetimes, and low cost can be achieved, solid-state lighting could save our country many quads of electricity in the coming years. The solid-state lighting (SSL) and photovoltaic (PV) industries share many of the same challenges. This paper explores the similarities between the two industries and how they might benefit by sharing information.

1. A Shared Vision

The SSL and PV industries share the vision of reducing our reliance on electricity. Even though both of these industries are growing at a healthy rate, neither technology has begun to reduce electricity demand in a meaningful way. Currently, for SSL, only colored-light (e.g., traffic lights) and low-wattage (e.g., flashlights) applications are more efficiently serviced by LEDs than by traditional lighting. For most lighting applications, fluorescent and high-intensity discharge lamps provide the most efficient options. However, LED efficiencies are increasing and, with more research, promise to equal or surpass those of fluorescent lights [1]. Currently, both SSL and PV products are too expensive to compete for mainstream applications. These industries are building manufacturing experience and market share by selling into niche applications. Both are growing at a healthy rate, even in a depressed economy (see Fig. 1) [2].

In general, industries make and sell products in order to make a profit, whereas society may benefit from products with improved energy efficiency. The United States reliance on foreign oil is often argued to be the single biggest threat to national security. Government programs that increase energy efficiency can be the foundation of any national security program. Yet, extrapolation of the current growth curves for SSL and PV imply that both are years away from providing significant energy savings. Thus, the role of the DOE Solar Program has been to accelerate the deployment of PV and the Building Technologies Program has recently begun a program to accelerate the deployment of SSL. In both cases, the programs must choose whether to support market development in order to increase the slopes of the curves shown in Fig 1, accelerate incremental improvements in the technology, and/or to investigate new technologies that could revolutionize the industry and provide a dramatically faster growth curve. As difficult choices are made for limited funding, the Solar Program and the Office of Building Technologies may benefit by leveraging their limited resources. The purpose of this paper is to explore the synergies between these two technologies so that this synergy may be effectively exploited by the Solar Program as well as the developing Solid-State Lighting Program to their mutual advantage.

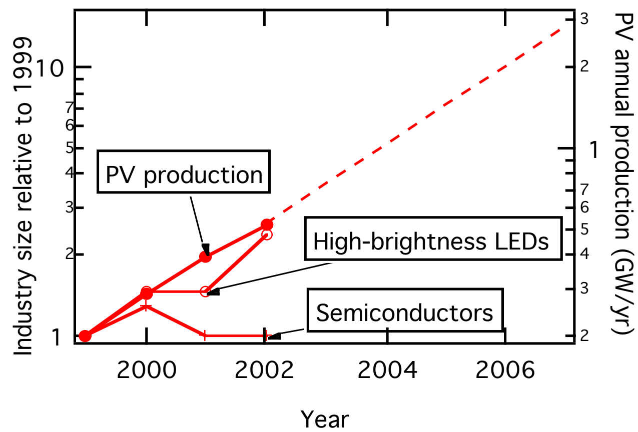

Figure 1. Industry worldwide-growth data [2]. The extrapolation assumes a 40% annual growth rate. PV production is also shown on the right-hand axis in GW/yr. For comparison, the United States has typically installed ~20 GW/yr new electricity generating capacity [3].

2. Shared Technical Issues

Solar cells and LEDs have fairly similar structures in that both are diodes (usually p-n junctions) with the carriers confined to an active region. Both are designed to allow light to pass efficiently between the semiconductor and its surroundings. A solar cell generates electricity when light is absorbed and the resulting photocarriers are collected, and then are used as electricity in an external circuit. An LED works like a solar cell in reverse: carriers are injected, and then emit light when they recombine radiatively. It is common practice to forward bias direct-gap solar cells (causing the cell to act as an LED) to inspect for nonuniform illumination. Dark or bright spots usually indicate a defect in the solar cell and quickly isolate the origin of shunting of the solar cell. This is a specific example of how the similarities between LEDs and solar cells can be exploited.

To further explore these similarities, we discuss here three key areas that show significant parallels between PV and SSL: (1) high-brightness LEDs and III-V concentrator cells, (2) organic LEDs (OLEDs) and thin-film solar cells, and (3) PV systems and SSL systems.

2.1. High-brightness LEDs and III-V space and concentrator cells

Today s highest-efficiency LEDs and solar cells are made from III-V materials. $Ga_{0.5}In_{0.5}P$/GaAs/Ge cells are currently in production for space applications [4] and are being investigated for terrestrial concentrator applications [4]. High-brightness LEDs are currently fabricated from $Al_xGa_{0.5-x}In_{0.5}P$ or from $Ga_{1-x}In_xN$. For both SSL and PV, the three critical elements of success are (1) high efficiency, (2) low cost, and (3) reliability. These are interrelated, but are discussed here separately.

2.1.1 Perfect materials for high efficiency

Fundamentally, high-efficiency devices require materials of high crystalline quality. The best solar cells and LEDs are made from single-crystal materials that are relatively free from defects and have carefully passivated surfaces. In many material systems, defects (e.g., dislocations or free surfaces) are sites for nonradiative recombination. In a solar cell, photogenerated carriers that recombine nonradiatively at defects do not contribute to electricity generation. Similarly, in an LED, carriers that recombine nonradiatively at defects do not emit light.

A key difference between solar cells and LEDs is that radiative recombination is the goal for LEDs, but is avoided in solar cells. For a direct-gap material, the radiative recombination is controlled mostly by the dopant concentration, but indirect-gap materials present a very different situation. Strictly speaking, radiative recombination is forbidden for indirect transitions. This effect is not a problem for solar cells, but decreases the efficiency of LEDs. Thus, some good solar cell materials do not make good LEDs.

Regardless of the role of an indirect gap, both solar cell and LED efficiencies are improved by perfecting the material quality. Although there are many factors (e.g., device design) determining the device efficiency, for both solar cells and LEDs the most fundamental *material* property that affects efficiency is crystalline perfection (including the perfection of terminating the surfaces of the crystal). Once basic material studies provide a near-perfect crystal, this material must be engineered into an efficient and low-cost device structure.

2.1.2 Low cost

Today s solar cells and LEDs are functional, useful devices. However, they do not provide the lowest cost sources of electricity and light, respectively. If lower cost options were *not* available, the functionality provided by solar cells and LEDs today would easily justify their current price and both would be sold to the larger market. If the price of electricity were much higher, the payback time for PV and energy-efficient LED products would be reduced and sales would increase. Unless the price of electricity increases, the success of these technologies toward significantly reducing our electricity usage requires a substantial cost reduction; this is a primary goal of supportive government programs. The importance of low cost also underscores the need to develop new materials and processes that are scaleable for large-volume manufacturing.

As described above, the highest-efficiency solar cells and LEDs are made from single-crystal semiconductors. Associated with the high crystal quality is high cost. Reduction in cost can occur by identifying a low-cost substrate, reducing the cost of the epitaxial growth, reducing the cost of device processing, or improving the manufacturing yield. Cost breakdown for LED products is not readily available, but evaluations for III-V solar cells have shown that the substrate and epitaxial growth may be about $210 per 4-inch Ge wafer (assuming 90% yield and 10 m/hr growth rate) [5]. This can also be used as a rough estimate for the cost of substrate and epitaxial growth of GaInP LEDs and translates to three cents per square mm.

The costs of epitaxial growth, device processing, and low yield will fall as the manufacturing volume and experience are increased. In this way, parallel growth of the III-V PV and SSL industries may help to bring costs down for both industries.

2.1.3 Reliability

The reliability of III-V LEDs and solar cells is challenged when the operating conditions require very high currents (A/cm^2) and elevated temperatures (~100¡C). Under these conditions, excellent heat sinking is required to prevent thermal runaway and catastrophic failure. For a III-V LED or solar cell operating at a fixed current, as the temperature is increased, the voltage drops by 2 mV/¡C. For the solar cell, this represents a decrease in output power. For the LED, the voltage shift affects the operation of the drive circuit and the temperature can also cause a shift in emission color as well as intensity (especially for the phosphide-based LEDs).

Within a system, the reliability of III-V LEDs and solar cells are often dependent on the device fabrication, particularly the details of the metallization and encapsulation. Although the details of the device mounting are different, the shared requirements (need for excellent heat sinking, conduction of current, and light transmission) imply that progress in this area is likely to be transferable between the SSL and PV industries.

2.2 OLEDs and thin-film solar cells

An alternative approach to reducing cost while still maintaining high performance is to find a material that is less sensitive to crystal perfection. Thin-film solar cells are so called because their active layers are very thin (typically, a few micrometers total thickness) and can be grown on almost any substrate, including relatively low-cost substrates as glass or sheet metal. Although the efficiencies are expected to be somewhat lower than for single-crystal devices, high efficiencies have been obtained for both thin-film solar cells [6,7] and for OLEDs [8]. Again, we will explore the similarities in three sections related to efficiency, cost, and reliability. We also add discussions of flexible substrates, large-area operation, and organic semiconductors.

2.2.1 High efficiency

The achievement of high crystal quality can be useful for OLEDs and thin-film solar cells, but it may not be the overriding concern because some of these materials are relatively insensitive to the presence of grain boundaries and other defects. There are many approaches to forming these devices, but all share the basic structure of TCO (transparent conducting oxide)/active layer/metal, plus encapsulation front and back. The transparency and conductivity [9] of the TCO contribute to device performance, but the optimization of the TCO may be even more complex. The interface between the TCO and the active layer may be chemically or electrically reactive. The roughness of the TCO will affect the structure of the active layer deposited on top of it.

The perfection and uniformity of the active layer(s) are of utmost importance, but can be very difficult to achieve over a large area. For most OLEDs and thin-film cells, the nature of the junction is not as well understood as it is for the III-V, single-crystal devices. The movement of carriers within organic semiconductors and the natures of their interfaces are not yet fully understood.

2.2.2 Low cost

The active-layer materials costs for these thin-film devices are expected to be negligible. However, reducing the total cost can still be challenging. Because the potential for low cost is the key asset of a thin-film solar cell, the cost issues have been thoroughly investigated, concluding that a cost in the range of \$40-50/m^2 should be achievable [10]. These analyses should be helpful to OLED researchers who have targeted a cost of \$20/m^2 [1]. A key selling point of OLEDs is that they are a uniform, low-glare source of light that may be highly valued by the consumer. Thus, for OLEDs, low cost may not be necessary for widespread use if reliability can be improved.

2.2.3 Reliability

In general, the thin-film approaches to PV and SSL are found to have more severe reliability problems compared with single-crystal devices. It is not surprising that the single-crystal devices are more stable, but, with appropriate understanding of the underlying science, it should be possible to create stable thin-film devices. The Solar Program's experience has shown that the issues of high efficiency and reliability must be addressed together.

2.2.4 Flexible substrates

In addition to the possibility of very low-cost devices, a key appeal for the thin-film approaches to PV and SSL is that they may be made in novel configurations. Amorphous-silicon solar cells can be purchased in flexible products such as shingles (for roofing) or light-weight, portable PV arrays (for backpacking trips, etc.) [11]. OLEDs have been demonstrated on flexible substrates, but products are not yet readily available. The manufacturing of both amorphous silicon and OLEDs on flexible substrates starts with a TCO-coated plastic and ends with a flexible encapsulation.

2.2.5 Large-area operation (low voltage/high current)

Large-area solar panels or OLEDs can be envisioned, but just as no one is interested in a 100-watt solar panel that generates 1 V at 100 A, no one wants to run an OLED at low voltage, high current [12]. Manufacturers of thin-film PV modules use laser scribing to create panels that operate at convenient voltages. Laser scribing may also be satisfactory for OLEDs [13]. This is an example of the opportunities that may arise for PV and SSL companies to work together to use old equipment/methods for new products.

2.2.6 Synergy between organic LEDs and organic solar cells

Our understanding of organic semiconductors lags our understanding of inorganic semiconductors. Yet, in the last couple of years, organic-solar-cell and OLED efficiencies have been increasing rapidly [8,14]. Basic studies of organic semiconductor physics will speed the development of not only organic solar cells and OLEDs, but other devices as well.

The fundamental differences between conventional and organic diodes are the role of excitons as the primary light-absorbing/emitting species and charge hopping as the transport mechanism. In an organic solar cell, absorption of a photon produces an exciton. Charge carriers are produced when the excitons are dissociated at an interface between two materials, and the carriers must then hop through their respective layers to reach the electrodes. For a LED, the reverse process can yield emission of light. The great potential for these devices are threefold: they (1) can be made from highly processable (solution) materials (2) are amenable to being engineered on a molecular level, and (3) can be created from sustainable (even biodegradable/recyclable) materials.

2.3 PV systems and SSL systems

Although basic materials research is key to achieving high device efficiencies, the ultimate success of PV and SSL will depend on the quality of the final consumer product. Key considerations that are shared for PV and SSL systems include (1) retaining efficiency so that the system efficiency approaches the efficiency of the diode, (2) well-designed power conditioning, and (3) system reliability.

2.3.1 LEDs are enabling for some PV applications.

PV systems are cost effective today for stand-alone, low-wattage applications such as calculators and walklights. The replacement of an incandescent bulb with an LED can decrease the power needed for colored- and low-wattage lighting applications. In this way, LEDs are an enabling technology for PV: they can open new marketing opportunities. A number of PV-powered SSL systems are already available commercially [15].

2.3.2 Failures in low-tech components.

The weakest link of today s PV systems is usually reported to be the inverter [16]. Anecdotal evidence suggests that SSL systems experience a similar difficulty with the drive circuits used to supply the LEDs with DC current [17]. Other commonly reported failure modes for both PV and SSL systems include encapsulant yellowing, moisture ingress, breakage of wires, and soiling.

2.3.3. Customer acceptance of new products

Customers are hesitant to adopt new products when the upfront cost is high, as is the case for both PV and SSL products. Municipal districts across the United States have been convinced that the reduced maintenance costs associated with LED traffic lights easily justifies the higher upfront cost, but this sort of acceptance requires customer education and experience. Ongoing PV and SSL education programs could benefit by working together.

2.3.4 System benefits may open new markets

The PV industry has found that PV-powered systems are more quickly accepted in the marketplace than plain solar panels. A PV system may be designed to be both a roof and a source of electricity [18]. Such products provide value that offsets the cost differential between PV and conventional electricity. Similarly, comparisons of LED costs relative to incandescent or fluorescent bulb costs imply that substantial cost reductions are needed before LED replacement bulbs can be generally accepted, but consumers regularly buy lighting systems that cost more than $100. For these purchases, the cost differential between a SSL and conventional lighting system may not be a deterrent. The entry of PV and SSL products into the marketplace will be accelerated by incorporation of these into creative consumer products.

3. Conclusions

The similarities between the R&D issues for solar cells and LEDs provide numerous opportunities by which the Solar Program and Solid-State Lighting Programs may learn from each other. Basic studies of materials, and the new physics associated with organic semiconductors can be shared. Existing experience in one technology may benefit the development of the other technology. A new breakthrough in either PV or SSL could be beneficial to the other industry as well. The use of LEDs and solar cells in systems together may open new applications, contributing to industry growth. The two industries share the challenge of competing with very low cost technologies, but both could reduce electricity consumption in a meaningful way if efficiencies are increased and costs lowered. This goal may be achieved sooner if the two industries take advantage of the synergies between them.

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