Solid-State Lighting Devices – White LEDs and Solar PV Cells: Status and Roadmap for Improvement of their Efficiencies

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ABSTRACT Application of white LEDs and solar PV cells will revolutionize in near future low-cost solid-state lighting (SSL). However, their efficiency must improve significantly if these devices are to become useful for general lighting for household and industrial purposes. Majority of photons, around two-third, generated within a LED are trapped and absorbed, and are converted into heat. Phosphors commonly used in white LEDs backscatter more than half of the down-converted light, of which a significant portion is eventually lost within the package, thus reducing the overall efficiency. Some developmental work lead to design of high efficiency nitride-based SSL-LEDs. Gallium nitride (GaN) based micro-cavity fabrication was employed. A new packaging method, called scattered photon extraction (SPE), produced an average efficiency of 36 lm/W for prototypes, and 23 lm/W for a similar commercial white LED package; whereas theoretical potential is nearly to 375 lm/W.

Presently, the promising solar PV cells versions are: mono crystalline Si-PVs, dye sensitized PVs, amorphous Si-PVs, polymer PVs, and few other material and technological variations. Their conversion efficiency can be improved by several innovations. Some are improvements on existing devices (by surface passivation), light trapping (surface treatments like anisotropic grooves and pyramids etching, antireflective coating), light concentration (use of mirrors, fresnel lenses, holographic concentrators), wavelength transformation from UV to IR and IR to UV regions (use of fluorescent coatings and anti-stokes pigments), multi-junction devices (sandwiching of semiconductor layers), and use of multi-band gap materials.

Current values of luminous efficiency of various light sources, as reported in 2006, range: 10-18 lm/W for incandescent bulb, 35-60 lm/W for compact fluorescent lamp (CFL), 22-35 lm/W for warm light white LED 3300K, and 45-55 lm/W for cool light white LED 5000K.

Conversion efficiency of solar PV cells employing different materials and technologies range nearly 15% to 25%, under mass-production. With solar concentrator, the efficiency is of the order of 33%.

The paper presents and discusses the current gaps and roadblocks, and directions to improve the efficiency of SSL devices. Young researchers pursuing postgraduate and doctoral studies and research may adopt some of the topics pertaining to these roadblocks in their work plan, and workout viable solutions to overcome the current gaps in SSL device technologies for their better and more efficient performance.

Key words: Solid-state lighting (SSL), white LED, solar photovoltaic cell, luminous efficiency, conversion efficiency, performance improvement.

1. PREAMBLE

Illumination industry is optimistic that the LED will revolutionize in near future low-cost solid-state lighting (SSL). The luminous efficiency* of white LEDs must improve significantly if LEDs are to become useful for general lighting for household and industrial purposes (*Luminous Efficiency: the total luminous flux emitted by a light source divided by total power input to the light source; expressed in lumens per watt, lm/W). Majority of photons, around two-third, generated within a LED are trapped and absorbed, and are converted into heat. Phosphors commonly used in white LEDs backscatter more than half of the down-converted light, of which a significant portion is eventually lost within the package, thus reducing the overall efficiency. Previous developmental work lead to design of high efficiency nitride-based SSL-LEDs. Gallium nitride (GaN) based micro-cavity fabrication was employed. A new packaging method, called scattered photon extraction (SPE), produced an average efficiency of 36 lm/W for prototypes, and 23 lm/W for a similar commercial white LED package [6, 7].

Luminous efficiencies of various light sources, as reported in 2006, range: incandescent bulb 10-18 lm/W, compact fluorescent lamp (CFL) 35-60 lm/W, warm light white LED 3300K 22-35 lm/W, and cool light white LED 5000K 45-55 lm/W. Conversion efficiency* (*defined as the ratio between the electric power generated by the cell and the total photo power incident on cell's sensitive surface, expressed in per cent) of solar photovoltaic cells employing different materials and technologies range nearly 15% to 25%, under mass-production; with solar concentrator, the efficiency is of the order of 33% [1, 2, 3, 4, 17].

2. CURRENT STATUS – GLOBAL SCENIEARO OF SSL R&D

2.1 Patents applied for or awarded, since 2000

Since U.S. Department of Energy began funding SSL research projects in 2000 (a major global initiative for SSL), about 31 patents have been applied for or awarded [8]. Some of them are:

Agiltron, Inc.

- Light Emitting Diodes with porous SiC substrate and method for fabricating ultra-thin ohmic contacts for p-type nitride light emitting devices.

Cree, Inc.

- A mechanically flexible OLED light source with increased external quantum efficiency.
- Thin electrodes with a collection grid for organic light emitting diodes.
- Luminaries for light extraction from a flat light source.
- Organic light-emitting devices with integrated series connection.
- Efficient and stable operation of organic light emitting diodes.
- Hybrid electroluminescent devices.
- Organic electroluminescent devices having improved light extraction array for area illumination by organic light emitting diodes.
- Light-emitting device with organic electroluminescent material and photoluminescent material.

Lumileds Lighting U.S., LLC

- Cantilever epitaxial process.

Maxdem Incorporated

- Polymer matrix electroluminescent materials and devices.
- Integrated fuses for organic LED lighting device.
- Organic light emitting diodes with phosphors.
- Novel method to generate high efficient devices.

OSRAM Opto Semiconductors, Inc.

- Hybrid light source.

Pacific Northwest National Laboratory

- Thin films based on organic phosphine oxide compounds for electronic applications.
- Light emitting device having selenium-based fluorescent phosphor.
- Light emitting device having silicate fluorescent phosphor.

PhosphorTech Corporation

- Light emitting device having sulfoselenide fluorescent phosphor.
- Semiconductor micro-cavity light emitting diode.

- Horizontal emitting, vertical emitting, beam shaped, distributed feedback lasers by growth over a patterned substrate.

University of California, Santa Barbara

- Single or multi-color high efficiency light emitting diode by growth over a patterned substrate.
- Silicone resin encapsulates for LEDs.

Rensselaer Polytechnic Institute

- Novel package for producing white light with short-wavelength LED / RCLEDs and down conversion phosphors.
- Organic light emitting device structure for obtaining chromaticity stability.

Universal Display Corporation

- Organic light emitting devices for illumination.

2.2 Major breakthroughs in SSL devices technologies

In recent few years, research and developmental efforts have lead to significant progress in SSL devices technologies for white LEDs and solar cells [2, 9]. Some breakthroughs are:

a. *Advances in LED chip technology and packaging, breakthrough in performance and quality of white LEDs*: white LEDs with luminous efficiency of the order of 80 lm/W at 350 mA and 160 lm/W at 700 mA (Cree's New XLamp 7090 LED on EZBright 1000 LED chip www.cree.com).

b. *World's brightest LED - 240 lumens single die light source*: P4 type LED with a single die produces 240 lumens at 1 A (100 lm/W); planned luminous efficiency up to 135 lm/W in 2007 and up to 145 lm/W in 2008 (Seoul Semiconductor, 05 Dec. 2006, www.zled.com) [14].

c. *High efficiency white LEDs*: small sized (240×420 μm^2) 5450 K 138 lm/W at 20 mA / 3.11 V, and larger sized (1×1 mm^2) high-power white LED 5200 K 91.7 lm/W at 350 mA / 3.29 V (Nichia Corporation, Japan) [10]. LLF announced, *28 April 2006*, white LED fixtures using less than 15% of the power of standard 65W incandescent bulbs and 50% of the power of compact fluorescent bulbs, while delivering equivalent warm white light. The fixture produced virtually no heat, and can provide 50,000 hours of light, as compared to the average 2,000 hours provided by conventional 65W bulbs, www.ledlightingfixtures.com.

d. *New efficiency record for white organic LED*: 25 lm/W, the highest known efficiency achieved so far for a polymer-based white OLED (Osram Opto-Semeconductors, Inc.).

e. *Low-voltage white phosphorescent OLED*: high efficiency low-voltage phosphorescent OLED (PHOLED), 20 lm/W, operating at 6.3 V.

f. *Materials for white LED*: use of semiconductor nanoparticles (quantum dots) as luminescent down-converting materials for white LEDs, conversion yield up to about 75% - a world record (Lumileds Lighting and Sandia National Laboratories).

g. *Large-area photonic crystal LED*: uniform light emission from large-area photonic crystal LED for low-cost, high-volume manufacturing (Lumileds Lighting, University of New Mexico and Sandia National Laboratories).

h. *Large sized OLED light panel*: panel producing 1200 lm of white light at 15 lm/W efficiency – at par with current incandescent bulb technology, a world record (General Electric Global Research and Cambridge Display Technologies).

i. *Multi-junction solar cells*: multi-junction solar cells with optical concentrator, breaking the 40% conversion efficiency barrier [15]. This breakthrough leads to the possibility of solar systems generating electricity at 8 to 10 US cents per kWh. In 1980s multi-junction gallium arsenide solar cell achieved about 16% efficiency; in 1994 the 30% barrier was crossed, and now in 2006 the 40% barrier. Ultra-triple-junction solar cells, average efficiency *28.3%*, are now under mass-production < www.spectrolab.com >.

j. *Photovoltaic cell efficiencies in the illumination level 1W/m2 to 1000 W/m2*: PV cell efficiencies 17.4% to 24.7%, illumination level range of 1W/m2 to 1000 W/m2 [3].

k. *Work on solar cells at Fraunhofer Institute*: 100 cm2 solar cells on czochralski silicon with an efficiency of 20.2%; fresnel lens concentrator technology based high concentration III-IV multi-junction solar cells gave 33.5% efficiency [1, 4].

l. *Multi-band semiconductors for high conversion efficiency of photovoltaic cells*: use of multi-band gap semiconductor compounds (such as: ZnMnOTe, GaNAsP [13]) exhibited conversion efficiency potential of 56% with single-junction, full-spectrum (absorbing full range of IR to UV, photon range of 0.4 to 4 eV) solar cells, and this could be further enhanced to nearly 73% with quad-band semiconductor [5, 12].

3. GAPS AND ROADMAP FOR IMPROVEMENT OF EFFICIENCY

3.1 Gaps

While the semiconductor devices emitting infrared light have recently (as in 2005) demonstrated an efficiency of the order of 75%, there is no known fundamental opto-electronic and quantum processes barrier in achieving higher efficiencies approaching the theoretical limit of 100% (equivalent nearly to 375 lm/W) for white SSL-LEDs. To achieve this, practically every electron injected into the material must result in a photon. In addition, the voltage required to inject and transport the electrons to the light emitting region of the LED must be near that corresponding to the energy of the resulting photon. The distribution of photon wavelengths must match the spectrum perceived by human eye to render colors accurately. The emitted photons must lie within the visible range. Besides, the entire characteristic must be realizable by the device with operating lifetime of several thousands of hours, at a cost lower than that of existing lighting technology.

With technologies available to date, a large gap exists between the currently achievable efficiency and the theoretical 100% [11]. The challenge is to mass-produce white SSL-LED that is high in efficiency, high in color rendering quality, and low in cost [16]. This calls for better understanding of the opto-electronic and quantum processes within the materials and major breakthroughs in device architecture and packaging. Similar challenges are there for mass-production of photovoltaic solar cells with high conversion efficiency.

3.2 Roadmap for improvement of efficiency

To approach theoretical potential of efficiency and high-color-quality at low-cost, the sub-systems, regions and materials of the white LEDs and the solar PV cells will have to be redesigned so that the losses in the light-emission and light-electricity conversion processes are minimized. This will need, *inter alia*:

1. Better understanding of the fundamental properties of light emitting inorganic, organic, hybrid materials, and their nanostructures.

2. Control of decay pathway that compete with light emission – electrons to produce light but not heat.

3. Deep understanding of how light interacts with matter and removal of roadblocks in developing and adopting ultrahigh efficiency light-emitting materials.

4. Integration of novel, heterogeneous building blocks, such as carbon nanotubes, quantum dots and exploration on properties to optimize performance of SSL devices (both WLEDs and solar photovoltaic cells).

5. Improved architectures and packages to maximize the efficiency of light extraction in LEDs and conversion of light to electricity more efficiently in solar cells.

6. Improvement in efficiency of photovoltaic solar cells – by technology options [17] such as: multi-junction cell, use of organic materials and nano-composites, use of nano-crystals (quantum dots) and nano-tube technology [18], light trapping (anti-reflective coating, surface treatments like anisotropic grooves and pyramids etching), light concentration (mirror, fresnel lens), wavelength transformation (use of anti-stokes pigments to absorb infrared radiation and convert it into visible wavelength),.

7. Development of new theoretical, experimental and computational tools, and mass-production techniques to enhance the quality and performance of SSL devices.

8. Cost affordable and environment friendly mass manufacturing processes.

Young researchers pursuing postgraduate and doctoral studies and research may adopt some of the topics pertaining to these roadblocks in their work plan, and workout viable solutions to overcome the current gaps in SSL device technologies. With theoretical potentials/limits of near 375 lm/W [11] for white LEDs and conversion efficiency range of 56% to 73% [13] for solar photovoltaic cells, goals for white LEDs attaining luminous efficiency of the order of 150-200 lm/W and solar PV cells attaining conversion efficiency nearing 50%, in cost-effective, market-ready systems, appear to be realizable in near future.

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Dr. Agarwal actively participated in many national and international conferences. In 2005, on invitation of AvH, DAAD and TUI, he attended the 11th International Congress on ‘Germanistik’, at Paris / France, from 26 Aug – 03 Sept 05; the 50th International Scientific Colloquium on ‘Micro and Nano Technologies’, at Ilmenau / Germany, from 19 – 23 Sept 05; and the 7th International Conference on ’Lighting Engineering - Lux jr. 2005’, at Doernfeld / Germany, from 23 – 25 Sept 05.

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