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Photonic Structures in LEDs and Solar Cells

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Abstract

In III-V solar cells radiative losses become significant. Consequently, a mismatch between the light emission cone and the solid angle of the illumination source (sun, concentrator) reduces overall efficiency. Similarly, the light cone of an LED has to match the solid angle of an system to omit optical losses. We discuss two strategies to match the emission/absorption cone to the solid angle of an optical system: photonic crystal structures and corrugated Bragg gratings forming angle selective filters. The similarity between III-V solar cells and LEDs in terms of photon management is emphasized.

1. Introduction

Fundamentally, light emitting diodes (LEDs) and solar cells are identical circuits, described by the same physical mechanisms and equations for light propagation, carrier transport and conversion of electrical energy into light and vice versa. Similar strategies were employed towards devices with high conversion efficiency. Thin-film technology is an example of a successful concept to increase efficiency of high power LEDs as well as of solar cells. Both in high power LEDs and in III-V solar cells radiative recombination outnumbers nonradiative recombination. For this case where radiative processes are dominant, photon management has the highest leverage in the task to reach ultimate efficiency. Astonishingly, the efficiency for both classes of devices is limited in the high carrier density range by nonradiative Auger recombination.

Photon management means to control the guided modes in the semiconductor, the propagating modes of the light cone, and the coupling between these modes by scattering mechanisms. In a thin-film LED much of the generated light is emitted into guided modes of the semiconductor slab. With the help of regular (photonic crystal) or irregular (surface roughening) structures, these modes are scattered into the light extraction cone. The corresponding task for thin-film solar cells is to reduce reflection losses at the interface and redirecting light into the plane of the thin-film cell to increase absorption length. Surface texturing as well as metallic and dielectric coatings are used and combined for this purpose.

It is important to evaluate the efficiency not only of the semiconductor device, but of the whole system. This is the light source (sun, concentrator optics) plus solar cell, or the beam shaping or modulating unit together with the LED. In such a system, the cone of emitted or absorbed light, respectively, has to be matched to the solid angle (étendue) of the optical system. The very small solid angle of the sun

$$\pi \sin^2(\theta_{sun}) = 7 \times 10^{-5} \quad (1)$$

can be expanded in a concentrator configuration. As an example for an LED application, we the étendue

$$E = \pi n^2 A \sin^2(\theta) \quad (2)$$

for a projector, which is given by the area A and tilting angle θ of the digital mirror device, a typical number being E = 12.7 mm² sr (with the refractive index n = 1).

We explore two approaches to reduce system losses caused by non-matching étendue (see Fig. 1). In the LED we use a two-dimensional photonic crystal to redirect light from guided modes into outcoupling modes and control the angular spectrum [1,2]. The solar cell is equipped with an angular filter which was realized as one-dimensional corrugated Bragg dielectric mirror [3].

2. Photonic Crystal LED

We explore two-dimensional photonic gratings at the interface between the semiconductor and air. In order not to introduce nonradiative losses by surface recombination or damage due to processing, this is necessarily a shallow photonic crystal, coupling weakly to the modes of the semiconductor slab. It is acting as diffraction grating for the guided modes. The pitch is chosen such that first order diffraction lies within the light extraction cone. To optimize the structure, it is as important to control the guided mode spectrum, i.e. the vertical layer stack, as it is to control coupling between the modes, i.e. the geometry of the photonic crystal structure.

A quantitative comparison shows that photonic crystals LEDs will not outperform LEDs with roughened surface as long as the emission into half space is compared [2]. However, optimizing the photonic crystal, it is possible to almost double the flux into a given solid angle. In the end, light extraction efficiency in the thin-film LEDs depends on two quantities, the extraction and absorption coefficient for light. To increase light extraction, a stronger coupling of the photonic crystal to the guided modes is necessary. Yet, this might be overcompensated by absorption losses introduced by the processing of the photonic crystal LED.

2. Solar Cell with Corrugated Bragg Grating

In the solar cell a one-dimensional corrugated Bragg mirror stack was used as angular and spectral selective filter to reduce reflective losses over a wide spectral range and suppress reemission at the band edge into a large solid angle [4]. A dielectric filter design with 82 layers of different thickness was optimized (using transfer matrix method and a genetic algorithm) for a GaAs solar cell to achieve low reflectivity in the wavelength range from about 950 nm to 400 nm for all angles, and high reflectivity at the band edge for angles from 0° to 90°. Because carriers relax to the band edge before recombining radiatively, such a mirror is capable to selectively suppresses radiative losses while keeping a high transmission throughout the relevant part of the solar spectrum.

Reabsorption of these photons at the band edge leads to an increase in the voltage, and not to an increase of the voltage, as demonstrated in a GaAs thin-film cell with corrugated mirror [5].

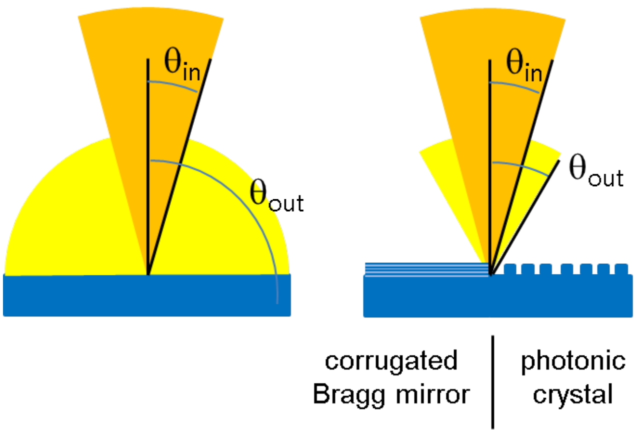

Fig. 1 Light emission into the half space for a planar surface, not matching the solid angle of the incoming light or étendue of the optical system (left); with an angle selective filter (corrugated Bragg mirror) or photonic crystal the light cones can be matched (right).

3. Conclusions

Photonic crystal LEDs have been successfully demonstrated A quantitative understanding of the effect of the photonic crystal structure on mode coupling and extraction efficiency was achieved. However, it is difficult for the photonic crystal LEDs to compete with the highly optimized LEDs with roughened surface which reach light extraction efficiency beyond 90% into half space. With improved processing technology or in the combination with nanorod LEDs with enhanced surface, photonic crystal LEDs may become competitive.

In both classes of devices the efficiency limit is given by the balance of reabsorption and light extraction or absorption, respectively. In the solar cell the increased reabsorption due to the limitation of the solid angle for radiative losses results in an increased voltage. In an ideal solar cell without non-radiative losses, angular confinement, i.e. matching of the emission cone to the étendue of the light source, is thermodynamically equivalent to light concentration. In a real system, non-radiative losses reduce the effect of angular confinement.

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Appendix

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