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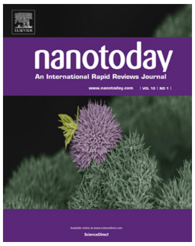

REVIEW

Transparent dielectric nanostructures for efficient light management in optoelectronic applications

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Summary Since light management is crucial for the performance of optoelectronic devices, extensive efforts, such as texturing semiconductor layers and implementing plasmonic metal nanostructures or transparent dielectric structures, have been made to enhance the optical properties of the devices. It is advantageous that the implementation of transparent dielectric structures in the devices enables us to improve optical properties with minimized parasitic absorption loss and little deterioration of electrical property in the active layer. By properly designing geometry of structure and appropriately selecting dielectric material property, we can effectively control the efficiency of light transmission, extraction, scattering, or reflection. Hence, efficient light management using lossless dielectric structures gives great potential for improving the performance of the optoelectronic devices such as photovoltaic cells, photodetectors, light emitting diodes, and displays. In this review article, we will summarize the latest research progress on light management strategies for high-performance optoelectronic devices using transparent dielectric micro and nanostructures.

Introduction

Light management strategies can significantly improve the performance of various optoelectronic devices such as photovoltaic cells, photodetectors, light-emitting diodes, and displays. For example, enhancement of light absorption in photovoltaic devices can result in high photon-to-electron conversion efficiencies. Since the amount of light absorption is proportional to the thickness of semiconductor (active) layer, the layer should be thick enough to harvest light efficiently.

However, since only the photocarriers generated near the junctions are efficiently collected, the thickness of

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semiconductor layer is limited by the carrier diffusion length, which is the average distance that a carrier can travel before it recombines [1]. Compared to monocrystalline silicon (c-Si), amorphous silicon (a-Si) has a very short carrier diffusion length of 300 nm or less [2]. Typical organic semiconductor also has a very short exciton diffusion length of 5–10 nm [3,4]. Therefore, the thickness of active layer in thin-film solar cell is supposed to be very thin for efficient collection of photocarriers. Unfortunately, the cell's ability to absorb incident light greatly decreases when the thickness of the active layer in thin-film solar cell is equal to or thinner than the carrier (exciton) diffusion length. Hence, efficient light management schemes such as reduction of surface reflection and enhancement of light trapping are required to improve absorption in such thin active layers. Several light management strategies implementing micro and nanostructures made of semiconductors, metals, and dielectric materials have been proposed to manipulate light in the devices.

Numerous semiconductor micro and nanostructures which have the geometry of micro-pyramids [5], photonic crystals [6], nanocones [7,8], nanowires [9–11], and nanodomes [2] have been extensively investigated for light absorption enhancement in thin-film solar cells. Surface texturing of a semiconductor or depositing of a semiconductor thin-film on textured substrate can significantly enhance the light absorption via increase of light traveling path within the semiconductor or decrease of Fresnel reflection at the surface of the semiconductor. However, a large surface area and high crack density, which are both induced by the fabrication process, increase recombination loss of a solar cell [12,13]. As a result, the improved optical property is balanced by degraded electrical property.

Metallic nanostructures such as nanoparticles [14–16], nano-pyramids [17], nano-grating [18–20], and nano-mesh [21] have gained a lot of attention for their ability to enhance the light absorption in thin-film solar cells. The metallic nanostructures can support surface plasmon resonance, which is a resonant photon-induced collective oscillation of surface electrons at a metal–dielectric interface. Metal nanoparticles can enhance the light absorption through resonant light scattering or resonant field enhancement. Metal nano-grating excites propagating surface plasmon resonance, thus traps and guides the light which can improve the absorption efficiency in semiconductor layers [1]. Additionally, altering the types, sizes, and shapes of metal, can tune the plasmon resonance band over the entire solar spectrum [22]. However, the generally narrow plasmon bandwidth and the large absorption of light by plasmonic metal nanostructures called parasitic absorption are detrimental to light absorption in the solar cell [23,24]. For these reasons, the improved optical property of plasmonic solar cell is balanced by the parasitic absorption loss and narrow bandwidth of the plasmonic metal nanostructures.

Implementation of transparent dielectric structures is an effective method in solving the issues we mentioned above. There are two advantages to using transparent dielectric micro and nanostructures for enhancing light absorption in solar cells. First, the structures are lossless, and thus can improve the optical property of the cells without parasitic absorption loss. Second, the structures do not deteriorate the electrical property of the cells since the scheme does not texture the active layer.

On the other hand, enhancement of light extraction is one of the most important factors in light-emitting devices such as light-emitting diodes (LEDs) or scintillator based devices. The trapped light within a high-refractive index semiconductor limits light-extraction efficiency of the devices. A considerable amount of light emitted from the active layer experience total internal reflection and hence is trapped in the layer. The trapped light is eventually reabsorbed in the active layer and converted to heat. The process significantly deteriorates the performance and durability of the device [25]. Therefore, the implementation of effective light management schemes is required to extract more light and consequently enhance the external quantum efficiency and durability of devices. Many different light management schemes using transparent dielectric micro and nanostructures have been developed and applied to organic or inorganic LEDs [26–28] and scintillators [29].

In this review, we will focus on transparent dielectric micro and nanostructures which can manipulate reflection, extraction and propagation of light with negligible parasitic loss and without degradation of the device's electrical property. We will discuss recent research advances in light management structures for optoelectronic applications. We will explain various light management strategies, interference type antireflection, graded index antireflection, scattering enhancements, photonic crystals- and whispering gallery mode resonator arrays-induced light trapping/extraction, and hybrid methods-combining different strategies. Mechanism of enhancements and fabrication process of the structures will also be discussed in detail. Table 1 summarizes the recent light management strategies using transparent dielectric structures. The details of the geometries, fabrication schemes, and their applications can be found in the references cited.

Interference-type antireflective structures

Antireflective coating techniques that effectively reduce surface reflection are vital in improving the performance of optical and optoelectronic devices. Interference-type antireflective coating with single planar dielectric film is the most simple and widely used method for reducing Fresnel reflection losses at the material interface.

The reflected light from the front and back sides of the transparent dielectric film can destructively interfere with each other when the thickness of the film is equal to one-quarter of the wavelength. In addition, refractive index of the film material should satisfy the following equation in order to obtain minimum surface reflection: $n_{AR} = (n_{substrate} \cdot n_{air})^{1/2}$ [30].

In the case of high-index semiconductor material such as c-Si ($n_{substrate} = 4.0$) or Ge ($n_{substrate} = 5.2$), which is commonly used as an active layer of photovoltaic devices, there is a wide choice of materials (SiO_2, $n_{AR} = 1.4$; Al_2O_3, $n_{AR} = 1.8$; Si_3N_4, $n_{AR} = 2.0$; TiO_2, $n_{AR} = 2.3$) available for manufacturing efficient antireflective coatings [31].

However, plastic or glass used as cover or encapsulating material for optoelectronic devices has relatively low refractive index ($n_{substrate} = 1.4$–1.6), hence antireflection