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Non-radiative energy transfer leads to high-efficiency color conversion in LEDs

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A new color conversion process for light-emitting diodes is more than twice as efficient as traditional techniques.

Phosphorescent materials that emit light when exposed to certain wavelengths of radiation are traditionally used for color conversion in light-emitting diodes (LEDs). The device emits a high-energy photon, the phosphor absorbs it and then re-emits a lower-energy and thus differently colored photon. If the light source activates the phosphor directly via non-radiative energy transfer (ET), significant amounts of energy can be saved.[1] This requires the direct interaction of donor and acceptor, but it eliminates several intermediate steps in color conversion (see the 'efficiency budget' diagram in Figure 1a). Recently we demonstrated the first practical implementation of this approach using an electrically driven GaN/InGaN quantum well (QW) that was *ET-coupled* to a single monolayer of semiconductor nanocrystal (NC) quantum dots, which served as color-selectable phosphors.[2]

The feasibility of noncontact pumping of nanocrystals using ET from a proximal QW was first demonstrated with optical excitation of charge carriers.[3] But two conflicting requirements complicate the practical implementation of this pumping scheme in an electrically driven device. On one hand, ET coupling sharply decreases with increasing QW-nanocrystal separation, d, since coupling scales as d^{-4} here.[4] This dictates the use of exceedingly thin QW barrier layers. On the other hand, relatively thick barriers are needed to reduce non-radiative carrier losses and to enhance injection efficiencies because reduced carrier mobilities in thin barriers limit current spreading.

As a compromise solution to this problem, we used an *inverted* LED design. In a traditional design, the QW is fabricated on top of an n-doped layer. But, as shown in Figure 1b, we grew an InGaN QW on top of a thick, p-doped GaN barrier using metal-organic chemical-vapor deposition.[5] The structure was further capped with a thin, 3nm, n-type GaN layer, and electrical contacts were applied by plasma etching using a flip-chip mask (see Figure 1b). As such, we took advantage of the much higher mobility of n-GaN compared to p-GaN as well as obtained significant current spreading (ca. $\sim$80μm) despite the thinness of the n-type injection layer. The structure was completed with a monolayer of CdSe/ZnS core/shell NCs, which was assembled on top of the n-type barrier.

Using a microscope coupled to a spectrometer, we spatially and spectrally resolved the electroluminescence from the area around the n-contact. In addition to the QW band at $\sim$420nm, the acquired spectra (see Figure 1c) clearly show a nanocrystal band near 590nm. The ratio between the nanocrystal and the LED emission intensities, η_{cc}, approximately determines the color conversion efficiency. In this case η_{cc} is 13%. This η_{cc} does not depend significantly on the driving current (see Figure 1c) and, hence, on the excitation density in the QW. In a traditional conversion scheme one would expect $\eta_{cc} < 4\%$, as estimated based on the excitation of nanocrystals by both the light emitted by the QW and waveguided modes in GaN. The much larger η_{cc} in this experiment indicates that the ET mechanism for NC activation is in effect. This mechanism is further confirmed by quantitative analysis of the color conversion efficiency for the ET scheme.[4]

This ET mechanism can be used to improve the absolute external quantum efficiency of phosphor-based emitters. For example, it can reduce losses resulting from non-radiative recombination in the LED and incomplete absorption by the phosphor (see Figure 1a). Furthermore, because this ET process is very efficient, even for thin, optically transparent acceptor layers, it can also eliminate losses caused by re-absorption and/or scattering of secondary photons in the phosphor medium itself.

Another attractive feature of this ET scheme is that it can improve efficiency compared to a stand-alone LED (see Figure 1a). Specifically, if the ET rate is sufficiently high compared to the rate of nonradiative losses in the QW, the majority of excitations can

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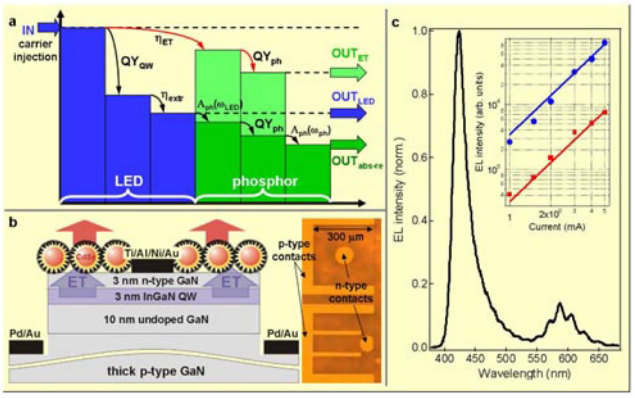

Figure 1. We created a nanocrystal-based energy-transfer LED. (a) This 'efficiency-budget' diagram illustrates the different steps (and associated losses) in color conversion using either a traditional absorption-re-emission process (black arrows) or non-radiative ET (red arrows). (b) A schematic cross-section of the ET-LED structure is on the left, and the contact geometry of a real device is on the right. (c) The electroluminescence spectra (2mA driving current) display both QW (420nm) and NC (590nm) emission bands; oscillations in the spectra are due to interference in the LED multilayer structure. Inset: A graph of QW and NC emission intensities vs. driving current indicates that the color conversion efficiency (approximately the ratio of the two intensities) is independent of current. η_{extr}: Light extraction efficiency from the LED. $A_{ph}(\omega_{LED})$ and $A_{ph}(\omega_{ph})$: Phosphor-layer absorbances at the LED and phosphor emission frequencies, respectively.

be 'rescued' from non-radiative recombination by transferring them into the phosphor, which then efficiently converts them into photons. This implies that the ET approach can produce high overall quantum efficiencies even for moderately efficient LEDs with thin QW barriers adjusted to optimize the ET rate.

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