LIGHT-EMITTING DEVICES

Turning the tables on surface plasmons

The coupling of energy to surface-plasmons in the metal contacts of a light-emitting diode is usually considered detrimental to optical efficiency. A new study suggests that the opposite could be true.

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With the growing popularity of ultrabright light-emitting diodes (LEDs) for applications including bicycle headlights, advanced electronic displays and even traffic lights, there is increasing speculation that they could one day replace fluorescent tubes for domestic lighting. Before LEDs could even begin to challenge such low-cost and well-proven technology, however, there are many practical challenges that must first be resolved. Of these, one of the most crucial is the need to improve the efficiency with which light generated within an LED can be extracted from it. On page 601 of this issue, Okamoto and colleagues[1] report results that suggest that exploitation of optical modes known as surface plasmon-polaritons (SPPs) might offer one way to improve efficiency, perhaps helping LEDs challenge more conventional sources of light.

There are two broad classes of LED, those based on organic semiconductors and those on inorganic semiconductors, such as the blue-emitting InGaN used by Okamoto and colleagues. In both cases, electrons and holes are injected into the semiconducting layer where they combine to form excitons. In turn, when these excitons decay, photons are produced thus generating light. Improving an LED's efficiency usually relies on ensuring that as many of these excitons as possible are allowed to recombine to produce photons. In most LEDs, however, a metal contact layer usually bounds one side of the semiconducting layer in which these excitons are produced, often resulting in much of the energy being lost to SPPs at this interface.

SPPs are collective excitation modes that propagate across a metal's surface, and comprise an electromagnetic field coupled to oscillations of the conduction electrons at this surface. For most LED designs, to facilitate efficient electron inject it is necessary to place a metal contact in close proximity to the semiconducting layer where excitons are generated. This means that the probability of losing energy through coupling to SPPs associated with this contact is high[2]. Moreover, because of the large momentum carried by SPPs they are unable to generate light directly. Consequently, any energy that becomes trapped in them is usually dissipated as heat, thereby reducing the LED's luminescent efficiency.

Fortunately, there are ways that the energy trapped in SPP modes can be recovered. By introducing grating structures of just the right period into a device, these SPP modes can be made to scatter and thereby lose much of their momentum, increasing their ability to couple to light — a principle that has already been used to enhance the luminescent efficiency of organic LEDs[3]. Okamoto *et al.* exploit similar mechanisms to recover energy trapped in SPP modes, but instead of introducing periodic structures to scatter the SPPs, they find that the inherent surface roughness of an evaporated film can give a similar result[1]. But what makes their work important, however, is that they go well beyond just trying to recover power lost to SPP modes — they increase the amount of energy that is coupled into these modes, a step that could, perhaps counterintuitively, allow still greater enhancement of a device's efficiency.

The authors have achieved this feat by exploiting the dispersion relation of the SPPs at the interface of a metal contact grown in close proximity to an InGaN quantum well. A typical SPP dispersion relation — which defines the relationship between an SPP's momentum

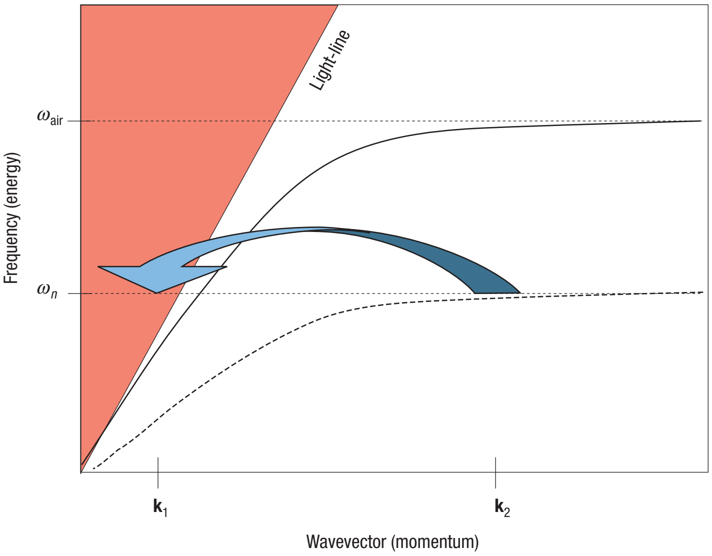

Figure 1 The SPP dispersion relation. The solid line shows how the momentum (wavevector, **k**) varies with its energy (frequency, ω) for SPPs at a metal/air interface. The dashed line shows the same for SPPs at a metal/semiconductor interface. By choosing the combination of metal and semiconductor appropriately, the asymptotic limit of this relation can be engineered to lie within the emission band of the semiconductor, thereby increasing the coupling between excitons and SPPs. Roughness allows SPPs of high momentum ($\mathbf{k}_2$) to scatter and lose momentum (to $\mathbf{k}_1$) as indicated by the arrow, so bringing them inside the light-line (the red region) and thus able to couple to light.

(wavevector, **k**) and its energy (frequency, ω) — for a metal/air interface is given by the solid line in Fig. 1. The important thing to notice about this is that with increasing energy/frequency, this relation hits an asymptotic limit. The position of this limit depends not only on the properties of the metal, but also on the refractive index of the medium on which it rests. The dotted curve shows how a material of higher refractive index than air, such as the InGaN used in the LED experiment, alters the dispersion relation to lower this asymptotic limit from ω_{air} to ω_n. Moreover, because the density of SPP states is inversely proportional to the slope of the dispersion relation, this density reaches a maximum as the asymptotic limit is approached. Consequently, by selecting a metal so that the asymptotic limit for SPPs falls close to or within the emission band of the semiconductor, the coupling between excitons and SPPs — and therefore the chances that the former will decay into the latter — can be increased. And by combining this with a rough metal interface to scatter the resulting SPPs to produce photons, the luminescent efficiency can be enhanced.

The idea of arranging the asymptotic limit of the SPP dispersion relation to be within the emission band of a semiconductor has been proposed before, but the present work is the first to demonstrate that it can be used effectively. This demonstration relies on the very high refractive index of the inorganic semiconducting materials ($n \approx 2.5$) to bring the asymptotic limit into the visible part of the spectrum. For lower-index light-emitting materials, such as the conjugated polymers, is it possible recent developments in surface metamaterials may offer a similar route to SPP-engineering efficiency enhancements — though at this stage such possibilities are very speculative.

Although the results reported at this stage are preliminary — Okamoto *et al.* demonstrate enhancement of the photoluminescence of an optically pumped multilayer device, rather than an electrically pumped LED — they do offer the possibility of turning what might initially be perceived as a problem (losses to surface plasmon-polariton modes) into an advantage. Whether it proves to be a commercially viable proposition remains to be seen, but regardless, it certainly adds a fascinating extra dimension to the exploration of surface plasmon-polariton related phenomena along the road to ultra-efficient LEDs.

References

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