Solving a semiconductor riddle

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Light-emitting diodes (LEDs) continue to transform technology, whether it's through the high-resolution glow of flat-screen televisions or light bulbs that last for years. The high efficiency and versatility of LEDs make them increasingly popular, but their full potential remains limited, in part because of remaining mysteries about the exact light-emission mechanism in the semiconducting materials.

One significant controversy surrounds the reason for the high-intensity light output from a leading LED semiconductor material, indium gallium nitride (InGaN): Researchers have been split on whether or not indium-rich clusters form within the material and provide the LED's remarkable efficiency. Now, researchers from MIT and Brookhaven National Laboratory have demonstrated definitively that clustering is not the cause. The results, published online in *Applied Physics Letters* [1], advance fundamental understanding of LED technology and could open new research pathways.

"This discovery helps solve a significant mystery in the field of LED research, and demonstrates breakthrough experimental techniques that can advance other sensitive and cutting-edge electronics," says Silvija Gradečak, the Thomas Lord Associate Professor of Materials Science and Engineering at MIT and a co-author on the study. "The work brings us closer to truly mastering solid-state technologies that could supply light and energy with unprecedented efficiency."

Mastering those technologies could have significant consequences: Gradečak points out that about 14 percent of electricity generated in the United States is used for lighting, so a dramatic increase in the efficiency of lighting could help bring about a corresponding reduction in electricity usage.

Building a better bulb

Conventional incandescent light bulbs convert only about 5 percent of their energy into visible light, with the rest lost as heat. Fluorescent lights push that efficiency up to about 20 percent, still wasting 80 percent of the electricity used. In both cases, light is the byproduct of heat-generating reactions, rather than the principal effect, making them inherently inefficient.

"Solid-state lights convert electric current directly into photons," says Eric Stach, leader of the Electron Microscopy Group at Brookhaven's Center for Functional Nanomaterials [2] (CFN) and a co-author on the study. "The efficiency of this process could, in theory, be nearly perfect, but the experimental realization has not reached those levels. That disconnect helped motivate this study."

InGaN is particularly promising for practical LED applications, but there was "a longstanding mystery of why this material was so bright, despite the fact it contains a very high density of structural defects," Gradečak says. Some researchers had analyzed the material with electron microscopes, which use powerful electron beams, and found indium-rich clusters within the material. While some thought those were the cause of the bright emissions, others thought they were artifacts caused by the electron beam itself, and were not normally present in the InGaN layers.

To solve the mystery, what was needed was a way of observing the material that did not use such high-energy beams and could not cause the material to decompose into these clusters. Instruments available at Brookhaven “changed the way we could test these promising materials,” Gradečak says. “The CFN’s aberration-corrected scanning transmission electron microscope opened a new and nondestructive window into the LED samples. For the first time, we could get Angstrom-level details — that’s one-tenth of one nanometer — without the risk of the imaging process affecting the sample.”

No clusters found

Postdocs Kamal Baloch of MIT, the lead author of the study, and Aaron Johnston-Peck of CFN actually applied these imaging techniques to the same samples that first launched the controversy over clustering, helping resolve the issue.

“We found that the indium-rich clusters do not actually exist in these samples, even though they remain efficient light-emitters,” Baloch says. That settled the question of whether they were the cause of the bright emissions.

“The important point is that we’ve established a foolproof method for investigating InGaN materials,” Baloch says. “We can use these nondestructive imaging techniques to explore the fundamental relationship between cluster formation and light emission to help unlock the secrets of this amazing alloy.”

By using this imaging technique, “We showed this process did not produce artifacts,” Gradečak says. That means the real cause of the material’s bright light “remains to be understood,” but one dominant theory has now been ruled out.

Sir Colin Humphreys, a professor and director of research in the Department of Materials Science and Metallurgy at the University of Cambridge, who was not involved in this work, says, “This paper finally solves a longstanding dispute” as to why this type of LEDs are so bright. “This paper definitively shows” that the explanation based on indium clusters was wrong, he says.

“This is an important piece of work which has been carefully and meticulously performed,” he says. “It finally puts an end to this debate, which has raged for the last 10 years.”

InGaN will likely remain a leading material for LEDs, but “even though commercial LEDs are very bright, their efficiency is still below what has theoretically been predicted,” Baloch says. “That’s why there is so much interest in figuring out” exactly what accounts for their superior brightness. “Unless we pin down the mechanism, we will not be able to achieve better efficiency,” Baloch adds.

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