MIT & Brookhaven show that In-rich clustering does not drive efficiency in InGaN LEDs

Aberration-corrected STEM plus EELS enables non-destructive analysis of LED function.

A contentious controversy surrounds the high intensity of indium gallium nitride (InGaN) LEDs, with experts split on whether or not indium-rich clusters within the material provide their remarkable efficiency. Now, researchers from the Massachusetts Institute of Technology (MIT) and the US Department of Energy (DOE)'s Brookhaven National Laboratory claim to have demonstrated that clustering is not the source ('Revisiting the "In-clustering" question in InGaN through the use of aberration-corrected electron microscopy below the knock-on threshold' by Baloch et al, Applied Physics Letters 102, 191910 (2013).

"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 coauthor Silvija Gradecak, MIT associate professor of Materials Science and Engineering.

CFN's Kim Kisslinger, here with a focused-ion beam instrument, thinned the InGaN samples to 20nm for electron microscopy.

Higher-efficiency bulbs

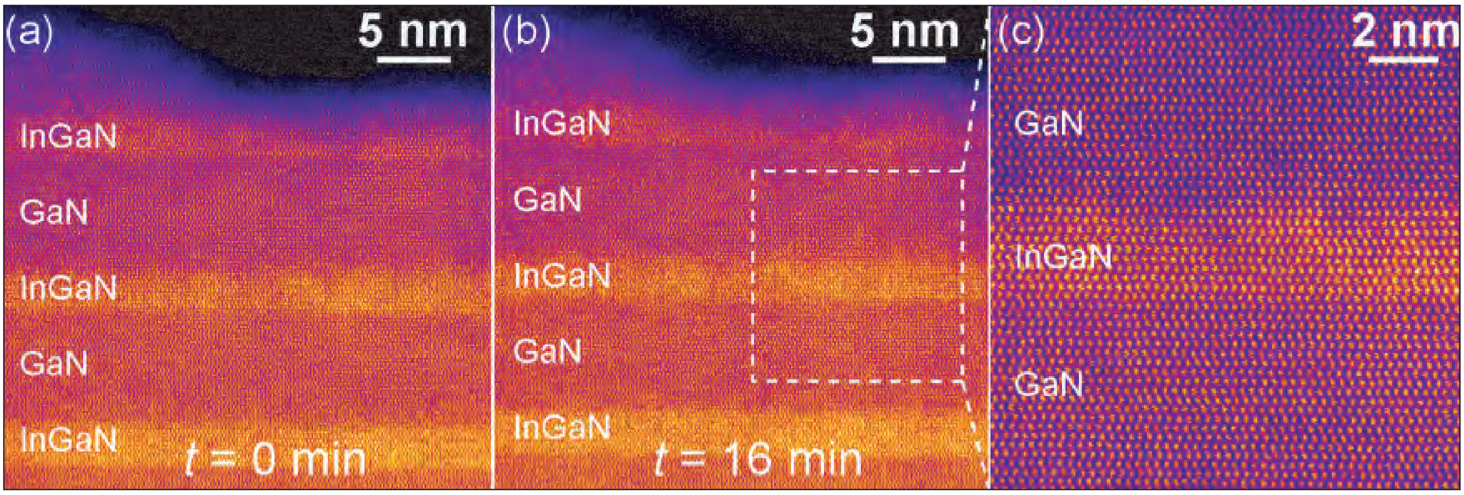
Incandescent lights convert only about 5% of electricity into visible light, with the rest lost as heat. Fluorescent lights push that efficiency up to about 20%, but still waste 80% of the electricity. In both of these cases, light is only the byproduct of heat-generating reactions rather than the principal effect. "Solid-state lights convert electric current directly into photons," notes co-author Eric Stach, leader of the Electron Microscopy Group at Brookhaven Lab's Center for Functional Nanomaterials (CFN). The efficiency of the electroluminescence light-generating process in LED bulbs could, in theory, be nearly perfect, but experimental realization has not reached those levels. "That disconnect helped motivate this study," adds Stach.

InGaN alloys contain dislocations in the crystal lattice, which can inhibit electricity flow and light production, but despite this the alloy performs exceptionally well. Understanding the light-emitting mechanism requires an understanding of what is happening on the atomic scale.

Controversial clusters

"Years ago, a team of researchers used electron microscopes to examine InGaN samples, and they identified a surprising phenomenon — the material appeared to be spontaneously decomposing and forming these isolated indium-rich clusters," Stach says. "This behavior could explain the efficient light emission, as the clusters might help electrons avoid the structural problems in the InGaN," he adds. "But then things became really interesting when another group proposed that the electron microscope itself caused that clustering decomposition. We had a real divide in the semiconductor field."

Rather than using light to examine materials, electron microscopes bombard samples with finely tuned beams of electrons and detect their interactions when they pass through a sample to reveal atomic structures. To achieve high enough resolution to examine the InGaN alloys, the electron microscopes used in the older experiments needed high-voltage beams. The controversy revolved around whether or not the experiment itself produced the clusters, rather than discovering the mechanism behind efficient light emission.



Images of InGaN samples produced by CFN's low-voltage STEM reveal a lack of structural changes over time. After 16 minutes of scanning, no damage or decomposition is visible. Higher magnification (c) exhibits none of the clustering previously theorized to be central to LED efficiency.

Improved imaging

"The state-of-the-art instruments available at Brookhaven Lab's CFN changed the way we could test these promising materials," Gradecak says. "The CFN's aberration-corrected scanning transmission electron microscope (STEM) opened a new and non-destructive window into the LED samples. For the first time, we could get Ångstrom-level details without the risk of the device affecting the sample."

Non-destructive STEM imaging of specific InGaN samples demonstrates that indium-rich clustering does not drive the efficient light emission.

The researchers combined the STEM techniques with high-resolution electron energy-loss spectroscopy (EELS), which measures the energy lost by electrons as they passed through the sample. MIT post-doctoral researchers Kamal Baloch (lead author of the study) and Aaron Johnston-Peck of CFN applied these imaging techniques to the same samples that first launched the controversy over clustering, with the aim of helping to settle 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. "While clustering may still occur in other samples, which may be prepared in different ways, the important point is that we've established a foolproof method for investigating InGaN materials. We can use these non-destructive imaging techniques to explore the fundamental relationship between cluster formation and light emission."

Beyond the advanced imaging instruments, researchers used the expertise of Brookhaven Lab physicist Kim Kisslinger, who specializes in nanoscale sample preparation. The InGaN samples were thinned to just 20nm (essential for priming the materials for STEM and EELS). The samples were also cleaned and polished to eliminate artifacts that might impact image resolution.

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