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The Spectrum of
Clean Energy Innovation

Fundamental Science
Market-Relevant Research
Systems Integration
Testing and Validation
Commercialization
Deployment

Green Light-Emitting Diode Makes Highly Efficient White Light

Scientists at the National Renewable Energy Laboratory (NREL) have invented a deep green light-emitting diode (LED) that can lead to higher efficiency white light, which is of prime value in the indoor lighting world.

LEDs are fundamentally solar cells operating in reverse—that is, when an electrical current is applied to a thin-film semiconductor, the result is the emission of light. These devices are a key technology for producing a new generation of efficient lighting, in which the amount of light generated far outweighs the amount of heat produced.

But at the moment, LEDs that emit white light are produced using an inefficient process known as phosphor conversion. In this process, light from a blue- or ultraviolet-emitting LED energizes a phosphorescent substance to produce white light indirectly, similar to the process used in fluorescent lamps. So, one challenge is to improve the Color Rendering Index (CRI) of this white light while maintaining a device that has high efficiency. The higher the CRI value, the closer a light source reproduces the colors of an object illuminated by a natural light source.

A more efficient process—known as the "Red-Green-Blue (RGB)" process—mixes the light from red, green, and blue LEDs to produce white light directly. The result is a white light with much improved CRI values. However, to date, RGB research has not produced high-quality white light because of a lack of deep green LEDs. This Achilles heel is commonly known as the "Green Gap," referring to the inability of current LEDs to produce light in the wavelength range of 530 to 570 nanometers (nm).

The bottom line when it comes to LEDs, then, is that we need greener green light to produce whiter white light.

Through deep technical expertise and an unmatched breadth of capabilities, NREL leads an integrated approach across the spectrum of renewable energy innovation. From scientific discovery to accelerating market deployment, NREL works in partnership with private industry to drive the transformation of our nation's energy systems.

This case study illustrates NREL's innovations in Fundamental Science.

Light-emitting diodes, or LEDs, are emerging as an efficient solid-state light source, able to replace incandescent and compact fluorescent light bulbs in many applications. A new green LED from NREL may yield more efficient solid-state lighting.


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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL to the Chromatic Rescue

Although reasonable red and blue LEDs are available for the RGB scheme, using the green LED for generating RGB white light poses a significant technological challenge.

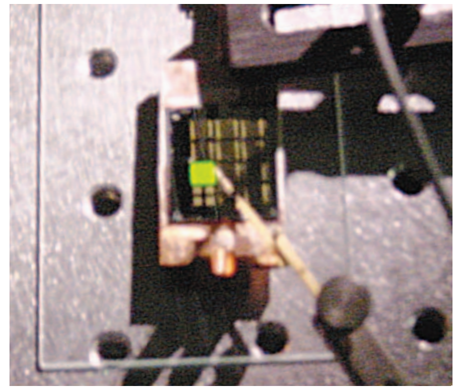
An NREL team of researchers is using an approach radically different from other research groups to create an LED that emits light with a wavelength of 562 nm. Their approach uses a gallium indium phosphide (GaInP) alloy grown on a gallium arsenide (GaAs) substrate. This type of lattice-mismatched GaInP/GaAs tandem device (see sidebar for details) has been in development by several NREL scientists studying high-efficiency solar cells, and they have been very successful in demonstrating it.

NREL's 562-nm LED is thus capable of producing a deep green light close to the peak of the spectral sensitivity of the human eye and overcomes the Green Gap deficiency.

Enabling a Lighting Revolution

The beauty of LEDs is that they are much more energy efficient than incandescent and even compact fluorescent lights. For example, whereas conventional devices may generate energy as 10% light and 90% heat, LEDs turn these numbers around—90% light and only 10% heat. Thus, in indoor applications, LED devices can provide high-quality light while reducing building cooling loads because of lower heat generation.

The lack of an efficient green light emitter has limited the adoption of LEDs for indoor lighting applications. However, when NREL's new green LEDs are combined with red and blue LEDs, the resulting white light is substantially more efficient than existing light sources. Ultimately, this innovative design could lead to a low-cost, manufacturing-friendly process for high-value, energy-efficient LED lighting that generates much less heat than today's products.



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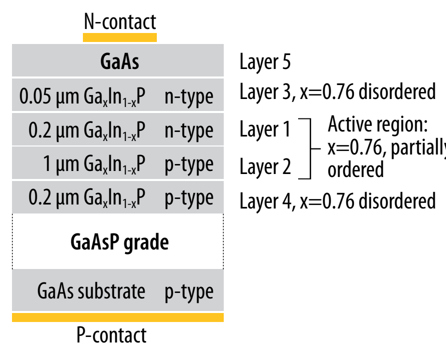
This NREL device, shown here within an experimental setup, can function as an LED that emits green light with a wavelength at 562.3 nm (or 2.205 eV), which is within the Green Gap. In 2009, the NREL team received $1.8 million in American Recovery and Reinvestment Act funds from the U.S. Department of Energy to continue developing the device.



This schematic shows the basic layer compositions of NREL's green LED device, which uses a GaAsP compositionally graded layer to reduce the strain of the lattice mismatch with the active GaInP layers.

What's the Science Behind the Green LED?

For over a decade, scientists have extensively researched so-called wide-bandgap III-V alloys that use gallium (Ga), aluminum, and indium (In) as cations, and nitrogen (N) as the anion, for synthesis of ultraviolet (UV), blue, green, and red LEDs. But their spectacular success in making UV and blue LEDs using this approach has not been paralleled in efforts to synthesize green or red LEDs. The primary obstacle has been very poor material quality when substantial In is added to GaN to shift the light emission into the Green Gap, or when substantial Ga is added to InN to shift the emission toward red. It is very difficult to obtain decent green LEDs even at 520 nm using this approach. And raising the operating wavelength into the 530 to 570 nm Green Gap poses a formidable challenge.

NREL's approach solves this conundrum by approaching the Green Gap from the upper limit (570 nm) using a GaInP alloy grown on conventional GaAs substrates (see schematic). The current workhorse material for synthesizing red LEDs is GaInP alloy on GaAs substrates grown lattice-*matched*, which means that the spacing between atoms in the two materials is similar. NREL has demonstrated that GaInP alloy grown lattice mismatched—having dissimilar atomic spacing—to GaAs can produce LED emission well inside the Green Gap.

LED samples are grown by atmospheric-pressure organometallic vapor-phase epitaxy. The GaInP layer having the target composition is significantly lattice-mismatched from the GaAs substrate. Thus, poor material quality will result if the mismatch is not adequately bridged to relieve the strain. To do that, scientists carefully adjust the elemental composition of various very thin layers to control the distortion of the atomic crystal lattices. Specifically, NREL researchers grow a thick compositionally step-graded layer of GaAsP, where the phosphorus fraction is incrementally increased so that the mismatch per step is very small. For LED structures with 76% gallium, a grade of ten steps, each 1 micrometer thick, adequately bridges the total mismatch. The GaInP active layers are then deposited nearly strain-free.

The NREL approach enables the design of an efficient LED operating inside the Green Gap. Red LEDs operating within the Red Gap (~615 to 625 nm) are currently unavailable but can be designed using a process analogous to that used for green LEDs.

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