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Inserting Eu-doped GaN surface-smoothing layers improves the emission homogeneity of InGaN quantum wells on vicinal (0001) substrates

Innovative Atomic-Level Surface-Planarization Technology was Developed for the Semiconductor Industry and is Expected to be used to Mass-Produce Micro-LEDs

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summary

- **A surface-planarization technology that eliminates “macrostep” structural defects, which are bottlenecks in the LED manufacturing process, has been developed for fabricating atomically flat crystal surfaces.**
- **Film-thickness control using europium, a rare-earth element, improves luminescence properties in a quantifiable manner.**
- **This research contributes to improving yields in semiconductor-device-based industries as a whole, including for the manufacture of micro-LEDs, which are expected to be produced on large (market) scales.**

A research group led by Reo Yamato, Shuhei Ichikawa (concurrently at the Research Center for Ultra-High Voltage Electron Microscopy, Osaka University), Atsushi Takeo, Jun Tatebayashi, and Yasufumi Fujiwara of the Graduate School of Engineering, Osaka University, has quantitatively demonstrated that gallium nitride (GaN:Eu) doped with europium, a rare-earth element, can be used to eliminate structural defects on crystal surfaces that occur during LED production. The group has quantified the elimination of “macrosteps,” which are structural defects on crystal surfaces formed during the LED-manufacturing process, as well as improvements in LED luminescence properties. The atomic-level surface-planarization technology developed in this study is expected to benefit the semiconductor industry, which includes the fabrication of micro-LEDs.

detail

Crystal surface roughness determines LED performance

LEDs are light sources that are indispensable in today's virtual and real spaces, including televisions, smartphones, next-generation wearable displays in VR devices, and lighting that feature in our daily lives. LEDs are luminous semiconductors and their performance is supported by technology that precisely controls their atomic-level structures.

Single crystals, such as gallium nitride (GaN), are grown on substrates, such as sapphire, during LED manufacturing to form an (epitaxial) light-emitting LED layer that forms the heart of the device. Reducing “through-dislocation” defects during crystal growth, which are detrimental to the device, is important. One way of reducing such defects involves growing crystals on finely tilted (or “micro-tilted”) substrates. However, minute roughness (“macrosteps”) is formed on the surface of crystals grown on micro-tilted substrates using the conventional method, resulting in uneven LED luminescence and performance degradation, which have been long-standing issues.

An LED emits light when tiny crystals on the LED chip quantum-mechanically exchange electrons. Macrosteps endow the surfaces of these tiny crystals with minute roughness. The wavelength of the emitted light is affected if such macrosteps are formed in LEDs that require nano-level film-thickness control. A rough crystal surface will emit energy that is inconsistently distributed; such inconsistencies affect the wavelength (and the color) of the emitted light: a higher energy corresponds to a shorter wavelength, leading to blueish light, whereas lower energy corresponds to a longer wavelength leading to reddish light. In other words, LED crystals with inconsistent surfaces emit light with various energies and wavelengths, resulting in muddy colors and poor performance. On the other hand, an ideal LED has a perfect crystal surface that emits light with consistent energy and wavelength; i.e., pure monochromatic light. To achieve this, the macrosteps on the crystal surface need to be reduced to create a flat crystal surface.

The Miracle of Europium, a Rare-Earth Element

A research group in the Graduate School of Engineering, Osaka University, which has published multiple research results related to group-III nitride semiconductors that are used in optical devices, has developed surface planarization technology for eliminating macrosteps that involves adding europium (Eu) to produce an atomically flat crystal surface, which successfully improved luminescence consistency.

“The macrostep is a very fine irregularity with a height difference of several tens of nanometers, which causes the emission wavelength to fluctuate. Industry would Ideally like to manufacture flat semiconductor surfaces that produces the same wavelength regardless of which part of the surface is used. However, the current situation is not ideal, which affects the yield rate as a result. We have shown that europium eliminates macrosteps and have revealed how it changes the luminescence properties of LEDs," says Reio Yamato of the research group.

The team found that macrosteps were eliminated by inserting a 40-nanometer layer of europium-doped gallium nitride (GaN:Eu) into the bottom of the gallium nitride crystal (Figure). Yamato measured the unevenness of the macrostep formed when gallium nitride is grown by conventional methods on a finely tilted substrate. The group also found that peak luminescence energy depended on the measurement location.

“The difference between the minimum and maximum peak luminescence energies was found to be 0.22 eV when energies were measured across the surfaces of crystals prepared by the conventional method,” he said. “However, the difference was reduced to 0.02 eV when europium was added and macrosteps were eliminated, which indicates that luminescence fluctuations are reduced. Furthermore, the luminescence intensity was found to have increased, which quantitatively confirms that luminescence properties had improved.”

The use of europium is a breakthrough LED-performance discovery. In addition to europium, a research group has conducted similar experiments using silicon and magnesium; however, no significant improvements in surface flatness were achieved using these alternative elements. Shuhei Ichikawa, a member of the research group, said, "we were able to obtain previously unreported property improvements by adding europium, a special rare earth element with a large atomic number, which is the major discovery of this study.”

Europium Innovates the Semiconductor Industry

This research group has focused on europium in the past and reported innovative research results. For example, they developed the first red-light-emitting LED by adding europium to gallium nitride. Furthermore, they developed technology that stacks red LEDs on the same substrate used to prepare blue and green LEDs, and applied this technology to "micro-LEDs," which are expected to replace LCDs and organic light-emitting diodes as next-generation displays. This research and development program is expected to reduce the cost of display fabrication to one-tenth that of conventional methods, and may contribute to the realization of lower prices, which has been a bottleneck for micro-LEDs that are expected to be used in a wide range of applications, from wearable VR displays to large-screen products, and are expected to be produced on the large scale for the market.

According to Yasufumi Fujiwara of the research group, surface planarization technology using europium will contribute to improving the yields of GaN substrates used to manufacture LEDs. Mass-produced gallium nitride substrates are used to manufacture highly bright LEDs and lasers. These substrates are produced by forming a single-crystal film of GaN on sapphire and GaAs substrates using the “HVPE,” method, which uses epitaxial and compound semiconductor-processing technologies. However, the substrate material and GaN have different thermal expansion coefficients, which warps the crystal film during crystal growth. Currently, warpage is flattened by polishing; however, this leads to microscopic surface inconsistencies. “Current industries find it extremely difficult to mass-produce atomically flat gallium nitride substrates that emit the same wavelength over their entire surfaces. Flat substrates with minimal wavelength variations can be mass-produced with extremely high precision by applying our developed surface-planarization technology, which we believe will greatly contribute to improving substrate yields."

Although this report focuses on light-emitting devices, this technology can also be applied to electronic devices. Atomic-level surface-planarization technology is expected to become be indispensable in semiconductor industries that will require extremely high precision in the future.

figures

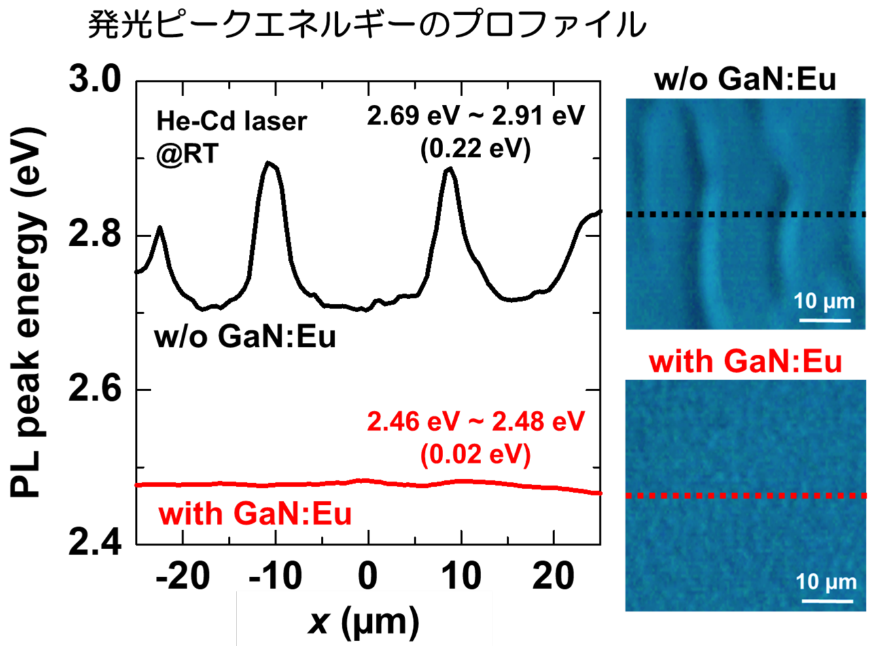

fig. Luminescence energy distribution on the surface of gallium nitride crystals grown using conventional methods (left panel, upper trace). The conventional method leads to large differences in high and low luminescence energies compared to crystals grown with added Eu (GaN:Eu; left panel, lower trace). Crystal surface of gallium nitride grown by the conventional method (upper right). Unevenness due to macrosteps is reduced when europium is added (GaN:Eu) and the macrosteps are eliminated (lower right).