【Grant-in-Aid for Scientific Research (S)】

# New development of Semiconductors Intracenter Photonics



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## Purpose and Background of the Research

**● Outline of the Research**

Our surroundings are filled with light of various colors emitted from semiconductors. All of this light is generated by electronic transitions between the conduction band and the valence band (interband transitions) formed within the semiconductors. As such, the color of the light is determined by the width of the forbidden band or bandgap energy. The bandgap energy is a function of the ambient temperature and decreases with increasing temperature. That is, in terms of wavelength, the wavelength is lengthened (red-shifted). Therefore, today's light-emitting devices using interband transitions have a critical drawback, which is a wavelength "fluctuation" depending on the ambient temperature, and this cannot be avoided in principle.

We propose "rare-earth-doped semiconductors," which are hybrid materials comprised of rare-earth phosphors and semiconductors, as a new family of functional optical materials. These devices will rely on a new type of photonics called "semiconductors intracenter photonics," which focuses on emission due to the intra-4*f* shell transitions that are particular to the rare-earth elements. We aim to integrate and develop semiconductor science and rare-earth science in a cross-sectional and multi-layered manner. By making full use of the world's only technology that controls rare-earth elements at the atomic level and dopes them into semiconductors, we have achieved several breakthroughs. Among them, in 2009, we focused on europium (Eu), which is widely used in red phosphors, and doped a very small amount (0.08%, about 1/100 compared to ordinary rare-earth phosphors) into GaN. In doing so, we have invented a narrow-band red LED that emits red light when current is injected.

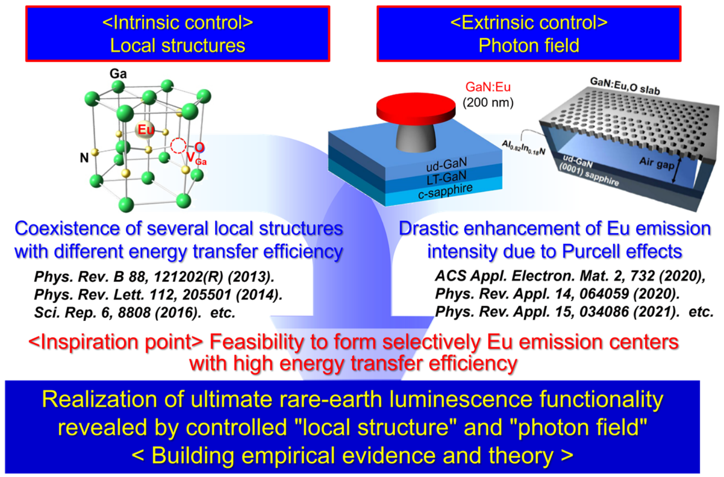


Fig. 1 Flow and challenge of this project

In this research, using Eu-doped GaN as a subject, we combine two previous approaches: "intrinsic control" which focuses on the local structure around Eu ions, and "extrinsic control" which focuses on the photon field "sensed" by the Eu emission center. Next, we will selectively form only the Eu emission center with extremely high energy transfer efficiency from the GaN host and strive to extract the ultimate emission properties. The microscopic structure will be clarified experimentally and theoretically.

- **[Objective 1] Reconstruction of the Eu emission center:** Based on the relationship between the local structure around the Eu ions in Eu-doped GaN and the resulting emission properties, we will establish a method to selectively form Eu emission centers with high luminous efficiency. This will be achieved by advanced Eu doping technology controlled at the atomic level and new post-growth processing technology.
- **[Objective 2] Theoretical/experimental identification of the Eu emission center:** We will clarify, theoretically, the local structure of selectively formed Eu emission centers using first-principles calculations. In addition, we will also clarify the local structure around the Eu ions, experimentally, using synchrotron radiation.
- **[Objective 3] Realization of ultimate Eu emission property:** We will utilize photon field control using 1) a vertical-cavity-type optical cavity, 2) a microdisk cavity, and 3) a two-dimensional photonic crystal optical cavity. These cavities will be formed from Eu-doped GaN with selectively formed Eu emission centers with high luminous efficiency. This will allow us to realize the optimum Eu emission properties under electric current injection, as well as photoexcitation.

## Expected Research Achievements

Previous studies have revealed that the energy transfer efficiency (luminous efficiency) from the GaN host strongly depends on the local structure around the Eu ion, but the Eu emission centers with high luminous efficiency only account for a few percent of the total. In this research, we will reconstruct the Eu emission centers into ones with high luminous efficiency through post-growth processes. In doing so, we will extract the ultimate potential of Eu-doped GaN. Furthermore, we aim to theoretically determine the local structure of the most efficient Eu center and use this as a design guideline for its practical realization.

- **[Ripple effect 1] Mastering rare-earth elements:** Previous rare-earth materials science related to rare-earth phosphors and rare-earth magnets has been based on "trial and error" using "intuition and experience." By scientifically studying the new luminescence functionality that arises from the combination of rare-earth elements lightly doped into semiconductors at the atomic level, and the intentional control of the external photon field, we will provide the world with guiding principles in the search for rare-earth phosphors that enable ultra-high brightness.
- **[Ripple effect 2] Core technology for next-generation micro-LED displays:** Towards the realization of a "super smart society" (the 6th Science and Technology and Innovation Basic Plan), there is a high social demand for ultra-compact, high-definition micro-LED displays that can be applied to ultra-compact LED projectors and head-mounted displays, and various efforts are being made to realize them. The red emission due to the intra-4*f* shell transitions of Eu ions has outstanding advantages, such as color purity and wavelength stability, which cannot be obtained with conventional LEDs. In addition, Eu-doped GaN red LEDs can be integrated with conventional blue/green LEDs on the same sapphire substrate, enabling the realization of three primary colors of light on a single chip. It is a key technology for next-generation micro-LED displays.

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| Homepage Address, etc. | http://www.mat.eng.osaka-u.ac.jp/mse6/<br>https://www.youtube.com/watch?v=G9fMdSX7n7k |