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Editorial

Advances in GaN Crystals and Their Applications

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Abstract: This special issue looks at the potential applications of GaN-based crystals in both fields of nano-electronics and optoelectronics. The contents will focus on the fabrication and characterization of GaN-based thin films and nanostructures. It consists of six papers, indicating the current developments in GaN-related technology for high-efficiency sustainable electronic and optoelectronic devices, which include the role of the AlN layer in high-quality AlGaN/GaN heterostructures for advanced high-mobility electronic applications and simulation of GaN-based nanorod high-efficiency light-emitting diodes for optoelectronic applications. From the results, one can learn the information and experience available in the advanced fabrication of nanostructured GaN-based crystals for nano-electronic and optoelectronic devices.

Keywords: GaN; AlN; InN; AlGaN; InGaN; MOSFET; LED

1. Applications of GaN-Based Compounds

Reviewing the application of semiconductor compounds, it stemmed from the replacement of vacuum tube by transistors in electronics [1,2]. The first "point-contact transistor" was invented by J. Bardeen and W. H. Brattain with "three-electrode elements" utilizing semiconductor materials, *p*-type, and *n*-type germaniums [1]. As the germanium crystal was substituted by silicon crystal to make a *p-n-p* bipolar junction transistor [3] or metal-oxide-semiconductor field effect transistor (MOSFET) [4], the electronic property of transistor was tremendously enhanced and the silicon-based electronic industry was then established. However, the VI-elements (i.e., Ge, Si) are basically indirect band structure, which is not suitable for the application of photo-electronic devices. When the IV-elements (Si or Ge) are replaced by GaAs-based III-V compounds, the electron mobility of MOSFET can be significantly increased [5] and quantum effects (e.g., normal and fractional quantum Hall effects) can be clearly detected [6,7]. In addition to the high-speed transistor applications, the direct band structures of GaAs-based III-V compounds extended the semiconductor materials to photo-electronic applications, in which the IV-elements (Si or Ge) are exclusive due to the indirect band structure. In such a way, the GaAs-based heterostructures were successfully utilized in the information and communication technology [8]. Moreover, many opto-electronic devices were invented with GaAs-compounds such as light-emitting diodes (LED) and laser diodes (LD). In other words, GaAs-based III-V compounds can be designed to apply in both electronic and opto-electronic devices. However, the light-sources made of GaAs-based compounds (group III-arsenides) were limited to the emitting photon wavelength greater than 760 nm (red light) due to the bandgap energy (i.e., E_g = 1.424 eV of GaAs). On the other hand, the direct bandgap energy of group III-nitrides can cover the range from 0.7 eV (InN), 3.4 eV (GaN), to 6.2 eV (AlN). Therefore, the III-nitrides can offer a simple material system, replacing III-arsenides to integrate both electronic and opto-electronic technologies with the optical properties from the wavelength of far infrared to deep ultraviolet. For instance, the present opto-electronic application of GaN-based compounds is in light-emitting diodes (LEDs) for white light sources. Today, energy-savings and environmental-friendliness are two important criteria to evaluate sustainable light sources. In 2014, Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura received the Nobel

Prize in Physics "for the invention of efficient blue light-emitting diodes which have enabled bright and energy-saving white light sources". A new energy-efficient white light source was created in a revolutionary way by using the blue InGaN-based light-emitting diode. The incandescent light bulb was prohibited by United Nations after the year of 2014; indicating that "incandescent light bulbs lit the 20th century and the 21st century will be lit by LED lamps" [9]. A smart selection of materials can merit the energy-saving and environmentally-friendly criteria to integrate both nano-electronic and opto-electronic technologies by one material family: GaN-based compounds.

2. Nanotechnology and Fabrication of GaN Crystal

Currently, the competition of Si-based IC technology between industrial manufactories has been reduced to less than 10-nm scales (e.g., Taiwan Semiconductor Manufacturing Company presented an EUV technology for 7-nm FinFET in 2017 International Solid-State Circuits Conference, San Francisco, CA, USA). The selection of smart materials for the next generation of nano-electronic and opto-electronic devices will be more compatible with nanotechnology in advance. III-nitride materials are direct band gaps with a wide range of energy gap from 0.7 eV (far infrared) to 6.2 eV (deep ultraviolet). In recent decades, nanotechnology has been applied to the fabrication of GaN wurtzite crystal for nano-electronic and opto-electronic devices. The carriers in the quantum-devices can be well-confined to two-dimensional, one-dimensional, or even zero-dimensional (quantum dot) systems for spintronic application [10,11] or high-power laser diodes [12], in which the properties of nano-metered optoelectronic devices will be efficiently enhanced by quantum effects for a wide variety of applications. Among the wide bandgap semiconductors, group III-nitrides (GaN, AlN, InN, and their ternary alloys) are expected to be the most suitable material family for the implementation of DUV LEDs and LDs. Moreover, as a white light source, the commercial white-light LED is based on the invention of Shuji Nakamura, which is made of a blue light of $In_xGa_{1-x}N$/GaN quantum-well (QW) mixed with a complementary yellow-green phosphor (e.g., Ce-doped YAG) to create a white light. The phosphor-assisted $In_xGa_{1-x}N$/GaN white-light LED diminishes its luminous efficiency to thermal radiation during the energy conversion. Besides, the thermal radiation will generate heat to degrade the performance and lifetime of the LED. In 2009, Ikai Lo et al. developed a self-assembling nanotechnology to grow a three-dimensional (3D) hexagonal $In_xGa_{1-x}N$/GaN-microdisk from a nanometer-scaled nucleation on $LiAlO_2$ substrate for the application of white-light micro-LED without any assistance of phosphors [13,14]. The phosphor-free white-light micro-LEDs will benefit greatly by a high luminous efficiency and avoid the thermal aging by rare-earth doped phosphors. The red-green-blue micro-LEDs can be utilized not only in the sustainable white light source but also in full-color high-resolution display for the applications of smartphone and virtual reality (VR).

3. Current Perspectives in the Applications of Nanostructured GaN

The trend of GaN-based materials is obviously focused on the nanostructured process and fabrication for nano-electronic and opto-electonic devices to optimize the application of quantum effects. In this special issue, six papers were collected. In the first paper, Y. Kawakami's group studied the interface formation of AlN on sapphire substrate by EVPE, which is a new AlN bulk fabrication method using Al and N_2 as precursors, for AlN bulk crystals that are promising substrates for AlGaN-based deep ultraviolet light emitters and high-frequency electronic devices with high-breakdown voltages [15]. For the second paper, Wuu's group investigated the role of AlN insertion layer in stress control of GaN on Si(111) substrate by metalorganic chemical vapor deposition (MOCVD) for high-frequency and high-power electronic devices [16]. Horng's group studied the effects of a corona-discharge plasma treatment on the performance of an AlGaN/GaN metal-oxide-semiconductor high-electron mobility transistor fabricated on Si substrates [17]. Wu and Jeng presented a simple behavioral model with experimentally extracted parameters for packaged cascode gallium nitride (GaN) field-effect transistors (FETs) [18]. K. Ding, V. Avrutin, Ü. Özgür, and H. Morkoç reviewed the recent progress in growth aspects of group III-nitride heterostructures for deep ultraviolet (DUV) light-emitting diodes (LEDs), with particular emphasis on the growth approaches for attaining high-quality AlN and high Al-molar fraction AlGaN [19]. Finally, Han-Youl Ryu theoretically evaluated the light extraction efficiency (LEE) of GaN-based nanorod blue light-emitting diode (LED) structures using finite-difference time-domain (FDTD) simulations [20].

In light of the results reported in the issue, the readers may have learned the information and experience for the advanced fabrication of nanostructured GaN-based compounds in both nano-electronic and optoelectronic applications. The trend of nano-meter scaled fabrication requires the high quality of GaN-based compounds for device applications to guarantee the mean-free path of carriers longer than the size of device scale. In this special issue, the authors presented the various technologies, theoretically and experimentally, to improve the quality and efficiency of GaN/AlGaN heterostructures for nano-electronic and optoelectronic devices; revealing the perspectives of GaN quantum device applications.

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