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Beyond blue LED

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Abstract

After reviewing the development of GaN-based blue light emitting diodes (LEDs), new GaN-on-Si technology and nanowires/nanorods technology are outlined. The fundamental growth technology as well as the application of these structures for laser diodes (LDs) and LEDs are discussed in detail.

1. Introduction

Let me explain how blue LEDs have changed our lives. Portable games machines and cellular or smartphones are very familiar items, particularly to young people. The world's first portable games machine was released in 1979 and cellular phones first became commercially available in 1984. However, until the end of the 90s, all the displays of portable games machines and cellular phones or smartphones were monochrome. People can now enjoy full-color portable games and cellular/smartphones because of the emergence of blue LEDs, although some people are now concerned about the increase in the number of people addicted to their smartphones or cellular phones. The applications of blue LEDs are not limited to displays. In combination with phosphors, blue LEDs can act as a white light source and are also used in general lighting.

For general lighting, it is important to explain how InGaN-based blue LEDs can contribute to improving the electricity situation and saving energy, especially in Japan. Many people remember the great earthquake of east Japan and the meltdown of the nuclear power plants in 2011. Before 2011, about 30% of Japan's electricity was generated by nuclear reactors. Therefore, energy saving is one of the top priority issues in Japan. The US Department of Energy predicted that about three-quarters of lighting will have been replaced with LED lighting systems by the year 2030 in the United States, resulting in a 7% reduction in electricity use. In Japan, the penetration of LED lighting systems into the market is expected to be much faster. A research company in Japan has predicted that by 2020 more than 70% of general lighting systems will have been replaced with LED lighting. More importantly, we can develop and supply compact lighting systems to the people, especially children, in remote areas without access to electricity. Using an LED lighting system with a solar cell panel and a battery, children can read books and study at night.

The successful application of blue/white LEDs in displays and general lighting, LDs in blu-ray discs, and high-power/high-frequency HEMTs in smartphone base stations has motivated researchers to apply nitrides in another fields such as DUV LEDs and lasers, high-power transistors for inverters/converters, multi-junction solar cells, and yellow/red LEDs and LDs. For example, the replacement of Si-based IGBT power device with nitride devices is expected to reduce electricity consumption by 9.8%. Therefore, in combination with LEDs lighting, a 16 to 17% reduction in electricity consumption may be possible by developing future electronic devices based on nitrides. The development of new growth technology is essential for the widespread use of future nitride-based electronics.

In this presentation, the recent development of GaN-on-Si technology and GaN-based nanowires/nanorods technology are discussed.

2. GaN on Si

Si(111) is usually used as the substrate for the growth of GaN(0001) by metalorganic vapor phase epitaxy (MOVPE) [1,2]. To combine the functionality of nitride devices with that of Si LSI, however, the substrate should be Si(100). In addition, in the growth of InGaN quantum well layers by MOVPE, indium incorporation is strongly dependent on the crystal plane. The semipolar (1-101) has higher In incorporation than the conventional (0001) plane, making it promising for use in long-wavelength light emitters. For solar cell applications, the use of a semipolar, nonpolar, or (0001) N face is essential because the effect of the piezoelectric field is too strong when using the (0001) Ga plane. A large number of trapezoidal bars of semipolar (1-101) were grown on patterned 8° -off Si(001) substrate using an AlN interlayer by MOVPE [3]. Each bar has separated confinement heterostructure having three InGaN quantum wells for use as a violet laser. A vertical mode with a mode spacing of 0.46 nm was clearly observed when the optical excitation density exceeded 5 MW/cm^2. The formation of a ridge stripe structure was found to be effective for the clear observation of near-field and far-field patterns.

In the case of the MOVPE of GaN on a just cut Si(100) substrate, there are four equivalent crystal orientation relationships. Therefore, if Si(100) is used as the substrate, polycrystalline GaN is usually grown. Recently, it has been found that the directional sputtering of a thin AlN (sp-AlN) layer on a just Si(100) is effective for controlling the crystal orientation of the overlying GaN. During directional sputtering, the Si substrate was not rotated and an AlN target was placed parallel to the Si[110] direction. Single-domain semipolar (10-13) GaN with an optically flat surface can be grown on an sp-AlN-coated Si(100) substrate. The optimum V/III ratio was found to be as low as 36. Cross-sectional transmission electron microscopy revealed that the GaN layer followed the crystal orientation of the sp-AlN layer. Defects with a high density were generated at the initial stage of growth, although the density was greatly reduced when the thickness exceeded 2 microns.

These results are promising for the realization of nitride/Si hybrid LSI devices.

3. GaN nanowires and nanorods

Nitride researchers are facing the problems such as the green gap and efficiency droop in conventional two dimensional quantum-well-based blue LEDs. The one-dimensional nanowire structure is promising for overcoming these problems because of the limited area of the heterostructure, which minimizes the generation of misfit dislocations. The nanorod structure is also promising for reducing the electric field at the pn junction in power electronic devices meaning that it can be used in the high-voltage vertical structure of pn junction diodes and transistors.

Out-of-plane GaN nanowires of 50 μm in length and 30 - 100 nm diameter can be grown by catalyst-assisted halogen transport vapor phase epitaxy (CA HVPE) using a Ni/Au catalyst. Also, horizontal nanowires can be grown on a different planes of sapphire substrate. In the case of horizontal nanowires, Ni/Au catalyst should be rolling over on the surface of the substrate. These ultralong and smart nanowires can be applied to LSI chip-to-chip interconnection and also nanowire lasers.

The rate of GaN nanorods growth by MOVPE is lower than that by CA HVPE. This is because a vapor-liquid-solid mechanism is dominant in CA HVPE whereas vapor-solid mechanism is dominant in MOVPE. Pulsed-mode MOVPE has been found to be effective for growing Ga-face GaN nanorods [4-6]. The growth processes of GaN nanorods and InGaN core-shell structures have been studied in detail. Moreover, nanoimprint technology has been used for the selective growth of GaN nanorods. The growth rate was approximately 10 nm per cycle in the initial stage and became 5 nm per cycle when the vertical height exceeded 1 μm. Nanorod LEDs having InGaN core-shell structures have also been fabricated. The inter-planer diffusion of precursors caused a difference in the color emitted at the top and the middle to the bottom regions of the m-plane sidewalls.

These three-dimensional core-shell structures should be effective for reducing the current density by increasing the effective pn junction area, thus solving the problem of efficiency droop in conventional two-dimensional LEDs.

4. Conclusion

Examples of new technologies for the growth of GaN on Si substrates and GaN nanowires/nanorods have been reviewed. We hope that these new technologies will expand the range of applications of nitride semiconductors contributing to a better quality of life for humans.

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