Novel Nitride Semiconductor Devices

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Abstract

Nitride semiconductors are best known as materials for blue light emitting diodes, but they have unique characteristics applicable to other devices. This paper describes three such novel nitride devices that NTT Basic Research Laboratories has developed: (1) a nitride heterojunction bipolar transistor, which shows a very-high power density of 270,000 W/cm^2, (2) a nitride field emission display, which is promising for an efficient, reliable, and bright flat panel display, and (3) a nitride surface emitting laser diode, which should lead to micro optical devices and optoelectronic integrated circuits.

1. Introduction

Over the last five decades, research on the conventional semiconductors Si, GaAs, and InP has advanced steadily and these semiconductors have been applied to various optical and electronic devices. In contrast, in the early stages of research on the nitride semiconductors GaN, InGaN, and AlGaN, progress was slow because these semiconductors were very difficult to grow. However, the situation changed in 1986 with the development of a growth method that produced high-quality nitride semiconductors [1]. Since then, this research has accelerated.

The bandgaps of nitride semiconductors are wider than those of the conventional semiconductors, so they are suitable materials for short-wavelength optical devices such as blue light emitting diodes (LEDs) [2], [3]. In addition to their wide bandgaps, nitride semiconductors have several unique characteristics, such as high crystal hardness, a high breakdown field, high saturation velocity, and low electron affinity. These characteristics make them applicable to other devices in addition to simple blue LEDs, so NTT Basic Research Laboratories has taken advantage of these unique characteristics to develop novel nitride devices. This paper describes three of them: a nitride heterojunction bipolar transistor (HBT), a nitride field emission display, (FED), and a nitride surface emitting laser diode (SELD).

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2. Nitride heterojunction bipolar transistor for very-high power operation

High-power radio-frequency (RF) devices are necessary for the base station transmitters of cellular phone systems, satellite transmitters, and high-definition television (HDTV) transmitters and for the power modules of phase-array radars and surveillance and traffic control radars. However, it has not been possible to design and fabricate solid-state transistors that can yield RF output power of the order of the hundreds of watts that would be necessary to compete with microwave vacuum tubes. This is mainly because Si, GaAs, and InP have low breakdown fields. Since nitride semiconductors have high breakdown fields, these materials are suitable for high-power electronic devices that can operate at high voltages.

As an electronic device an HBT has several advantages over a field effect transistor (FET), such as high current density and good threshold voltage uniformity. Considering these characteristics in terms of both materials and device type, an HBT composed of nitride semiconductors should exhibit a very high power density. However, it is difficult to fabricate good nitride HBTs because their structure is rather complicated.

At other research institutions, AlGaN/GaN HBTs have been fabricated using a p-GaN base [4]-[7], but their current gains were low. In contrast, GaN/InGaN HBTs using a p-InGaN base have been developed by NTT Basic Research Laboratories [8]-[10]. **Figure 1** illustrates their typical structure, which consists of an n-GaN emitter, a p-InGaN base, and an n-GaN collector. In bipolar transistors, the current flows from the emitter to the collector; that is, the collector current is controlled by the base current, and the current gain is defined as the change in collector current divided by the change in base current. The p-InGaN base shows higher conductivity than a conventional p-GaN base [11], which means that it is easy to control the collector current. In addition, the collector is GaN instead of InGaN. This double heterojunction structure is preferable for high-power operation. **Figure 2** shows an example of the common-emitter current-voltage (I-V) characteristics. The offset voltage, i.e., the turn-on voltage of the collector current, is less than 1 V, which is one-fifth that of other HBTs [10]. **Figure 3** shows the trend of current gain for nitride HBTs. The maximum current gain of our HBT exceeds 2000, which is 100 times the previous record. Research on nitride HBTs started in 1998. At that time, the current gain of the first nitride HBT was just 3. But, in 2003, as a result of considerable effort dedicated to increasing the current gain, NTT Basic Research Laboratories reported a record-high current gain of 3000 for a GaN/InGaN HBT.

Figure 4 shows breakdown fields of HBTs com-

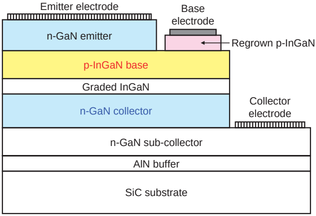


Fig. 1. Illustration of a typical HBT structure, which consists of an n-GaN emitter, a p-InGaN base, and an n-GaN collector.

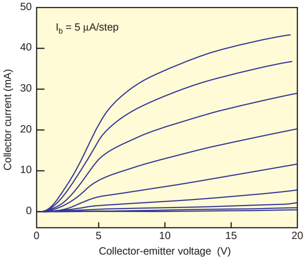


Fig. 2. Example of common emitter I-V characteristics of the HBT developed by NTT Basic Research Laboratories.

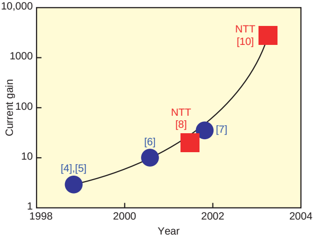


Fig. 3. Trend of current gain for nitride HBTs. Numbers in brackets are references.

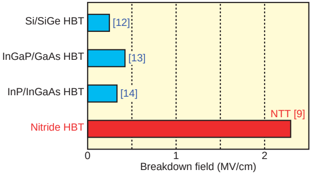


Fig. 4. Breakdown fields of HBTs composed of Si/SiGe [12], InGaP/GaAs [13], and InP/InGaAs [14] semiconductor material systems. Numbers in brackets are references.

posed of Si/SiGe [12], InGaP/GaAs [13], and InP/InGaAs [14] semiconductor material systems. The breakdown field of the nitride HBT is much higher than those of HBTs composed of other materials. This high breakdown field is comparable to the theoretically expected value [15] and it results from the wide bandgap of the nitride semiconductors. The maximum operating voltage is limited by the product of this breakdown field and the collector thickness, so a high breakdown field at a fixed collector thickness is necessary for high-power operation. On the other hand, we have reported that the maximum collector current of a GaN/InGaN HBT is proportional to the emitter area and increases with a slope of 7000 A/cm^2 [16]. This means that a nitride HBT with a large emitter area operates at high voltage with high current, resulting in a very-high power electronic device. Up to now, we have obtained a maximum DC power of 10 W and corresponding power density as high as 270,000 W/cm^2 [16].

Research on nitride HBTs has only just started and their characteristics have been getting better. Higher power will be easily obtainable by increasing the emitter area in GaN/InGaN HBTs because the collector current is proportional to the emitter area. Further investigations of high-frequency characteristics and device reliability are necessary to determine their suitability for practical use.

3. Nitride field emission for an efficient, reliable, and bright flat panel display

There is strong demand for a flat panel display that is efficient, reliable, and bright. Field emission, which is a phenomenon where electrons are emitted from a semiconductor surface into a vacuum by an electric field, is applicable to such a display. For this purpose, we need high-performance electron field emitters. Since aluminum nitride (AlN) has a wide bandgap of 6.2 eV, its electron affinity is expected to be nearly zero. Therefore, AlN is a promising material for field emitters because electrons in materials with nearly zero electron affinity can be easily extracted from the surface into a vacuum by a small electric field. However, the reported field emission current for AlN is still too low and the turn-on electric field too high for device application [17], [18]. This is probably because the electron concentration in the undoped AlN samples is so low that the electrons necessary for field emission cannot be efficiently supplied to the surface.

Recently, NTT Basic Research Laboratories has reported that heavy Si doping is very effective in improving the field emission properties of AlN [19]. As the Si doping concentration increases, the turn-on voltage decreases, resulting in an increase in the field emission current. Two factors that contribute to the field emission properties of the heavily Si-doped AlN [20]-[23] are the formation of a Si impurity band below the conduction band and nearly zero electron affinity. A third one is the field enhancement afforded by the nano-scale pyramid structure formed by Si doping. The tip of the pyramid decreases the effective energy barrier of field emission and thereby enhances field emission efficiency. **Figure 5** illustrates field emission from the pyramid tips. Electrons are easily extracted from the tip of a pyramid by the electric field.

An AlN FED device was fabricated to investigate its luminescence characteristics. As illustrated in **Fig. 6**, it has a vertical triode structure consisting of heavily Si-doped AlN, a mesh grid, and a phosphor-coated anode screen. The heavily Si-doped AlN was set on the cathode electrode. The mesh grid was separat-

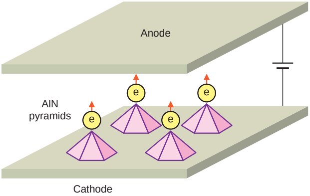


Fig. 5. Illustration of field emission from the tips of AlN pyramids.

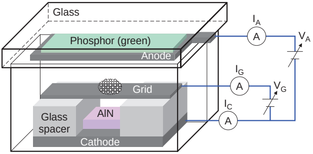


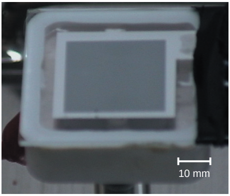
Fig. 6. Illustration of the AlN FED device developed by NTT Basic Research Laboratories.

ed from the AlN surface by a glass spacer and acted as an extraction electrode. The distance between the AlN surface and the grid was about 100 µm. The glass plate was coated with P22-type phosphor for green light, one standard for color cathode ray tubes. A thin Al layer evaporated onto the phosphor-coated glass was used as an anode and positioned about 5 mm from the AlN surface. The field-emitted electrons were accelerated by the anode voltage and passed through the Al thin layer. Then, they excited the phosphor, and the luminescence emitted from the phosphor was observed through the glass.

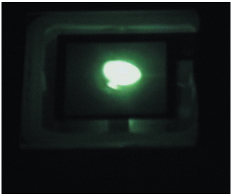
Figure 7 shows photographs of the FED (a) before and (b) during operation. Green luminescence was emitted from the center of the phosphor screen. Scattered light from the surrounding area was also observed. The luminescence area (6 mmϕ) on the phosphor screen is almost the same as the open area of the mesh grid. Uniform and bright luminescence was observed over the entire field emission area. **Figure 8** shows brightness as a function of the applied electric field strength (E_G) [24]-[26]. The brightness increased exponentially with increasing E_G and reached 200 cd/m^2 at E_G = 22 V/µm. The maximum brightness was 300 cd/m^2. This is high enough for display application because conventional displays have values around 200 cd/m^2.

The FED operated in DC mode without a feedback circuit at least for 80 minutes. No significant degradation of the field emission current was observed. During operation, the brightness and uniformity of the luminescence from the phosphor were maintained, indicating that the FED with the AlN field emitter has stable properties. The observed high stability of the field emission current is ascribed to a small change in the emission site density and a low rate of field evaporation of surface atoms, both of which originate from the high physical and chemical stability of the AlN surface afforded by the strong Al-N bond. This is one of the advantages of AlN-based field emitters.

AlN field emission is also expected to find application in electron beam sources for electron-beam lithography, electron microscopy, and X-ray generation. While high stability of the field emission current is one of advantages of AlN-based field emitters, they need higher electric fields than carbon nanotube field emitters because the threshold electric field is closely related to the condition of the AlN surface. Further research is necessary to investigate the relationship between the surface condition and field emission characteristics for practical use.



(a) Before operation



(b) During operation

Fig. 7. Photographs of the FED (a) before and (b) during operation.

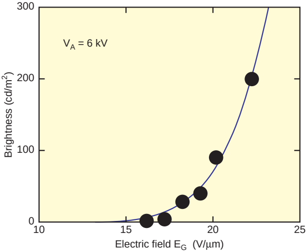


Fig. 8. Brightness as a function of the applied electric field strength E_G.

4. Nitride microstructure for a surface emitting laser diode

NTT Basic Research Laboratories has shown that it is possible to fabricate semiconductor microstructures using the unique characteristics of crystal growth [27]-[30]. These structures will lead to micro optical devices and optoelectronic integrated circuits. As one such microdevice, NTT Basic Research Laboratories has proposed and successfully fabricated a new type of a nitride surface emitting laser diode (SELD).

A conventional SELD emits a laser beam vertically from the substrate surface [31], so it enables the fabrication of a two-dimensional laser array, integration of SELDs with other components, and on-wafer testing compatible to LSI; it also offers high fiber-coupling efficiency. A microlaser array using these SELDs is expected to raise device performance and lead to devices with novel functions. Nitride SELDs have shorter lasing wavelengths than those of conventional semiconductors, such as GaAs and InP, so they are preferable for DVDs and laser printers. A laser array composed of nitride SELDs will allow high-density DVDs to operate at very high speed; it will also let laser printers work at very high speed with higher quality. A conventional SELD consists of an active layer sandwiched by two reflectors parallel to the surface. For nitride semiconductors, however, it has been difficult to fabricate reflectors having both high reflectivity and high electrical conductivity [32], so there have been no reports of current-injected lasing of nitride SELDs until now. Below, I describe the first current-injected lasing of a nitride SELD.

Figure 9 illustrates the new SELD, which consists of a horizontal cavity laser diode (HCLD) with two Fabry-Perot cavity mirrors and an outer micromirror. Both of the Fabry-Perot cavity mirrors are vertical to the surface, while the outer micromirror is inclined to it [33]. The outer micromirror is coated with an Al film to increase its reflectivity to over 90% for blue-ultraviolet light. A laser beam is emitted from the HCLD and is directed upward by the outer micromirror. The angle between the inclined outer micromirror and the surface is 58°, so the laser beam is emitted at an angle of 64° from the surface as shown in Fig. 9. Since these mirrors are formed by crystal growth, they are atomically smooth and have little angular misalignment from the crystallographic viewpoint [34], [35]. Mirrors fabricated by dry-etching, on the other hand, suffer from angular misalignment and etching damage [36]. Note also that the two kinds of mirrors are simultaneously fabricated in one growth step, which means that the SELD fabrication process is simple. **Figure 10** shows a bird's-eye-view scanning electron micrograph of the fabricated SELD. It shows that an HCLD with smooth mirrors was fabricated under the optimal crystal growth conditions.

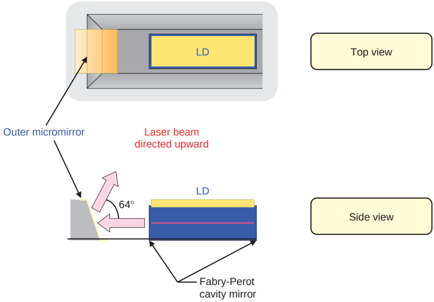


Fig. 9. Illustration of the new type SELD developed by NTT Basic Research Laboratories. The SELD consists of an HCLD with two Fabry-Perot cavity mirrors and an outer micromirror.

The first current-injected lasing of the nitride SELD was observed at a wavelength of 405 nm. **Figure 11** shows emission spectra obtained below (a) and above (b) the lasing threshold (J_{th}) at room temperature. The spectrum width is clearly narrower in spectrum (b). Non-linear behavior was also observed around J_{th} in the light output versus current (L-I) curves [34], [35]. No longitudinal mode was observed in the lasing spectra because of both the long cavity length of 500 μm and the low wavelength resolution (> 1 nm) of the measurement system.

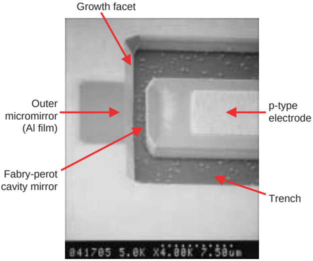


Fig. 10. Scanning electron micrograph showing a bird's-eye view of the fabricated SELD.

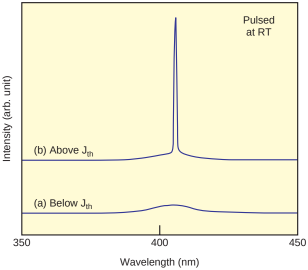


Fig. 11. Emission spectra of SELD obtained (a) below and (b) above the lasing threshold (J_{th}) at room temperature (RT).

For nitride SELDs to become practical, we must decrease their threshold current. Therefore, it is necessary to investigate how device characteristics are affected by surface conditions before regrowth.

5. Summary

The novel nitride devices developed by NTT Basic Research Laboratories utilize the unique characteristics of nitride semiconductors. This paper described three of them: a heterojunction bipolar transistor (HBT), a field emission display (FED), and a surface emitting laser diode (SELD). The nitride HBT has very-high power density, which is preferable for the various transmitters and the power modules of phase-array radars. The nitride FED will make it possible to build efficient, reliable, and bright flat panel displays. AlN field emission is also expected to find application in the electron beam sources. Nitride SELDs can be arrayed on a chip. The nitride SELD arrays will lead to the development of high-speed high-density DVDs and fast high-quality laser printers. Furthermore, semiconductor microstructures fabricated by crystal growth will allow us to connect lasers to waveguides and optoelectronic integrated circuits, which is expected to boost optical device performance and lead to devices with new functions.

These devices developed by NTT Basic Research Laboratories are still at the first stages of research. For nitride HBTs, high-frequency characteristics and device reliability should be investigated. For AlN FEDs and nitride SELDs, further research is needed on the influence of surface conditions on device characteristics. Nevertheless, I believe that some of these devices will be commercialized in the future and that this will lead to the creation of new services that will give the world economy a big boost.

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