

GaN: from fundamentals to applications

Jacques I. Pankove

ASTRALUX, 2500 Central Ave., Boulder, CO 80301, USA

Abstract

The fundamental differences between GaN and SiC are reviewed, then the problems of doping GaN are explored. The range of energy band gaps obtainable with alloys of all the III-Nitrides extends from 1.9 to 6.2 eV. Finally, various applications of the III-Nitrides are described with emphasis on solar blind UV detectors, light-emitting and modulating devices, cold cathodes and, in more detail, a heterojunction bipolar transistor that uses a SiC base layer and operates above 500°C. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

Although SiC has the longest history of all the wide bandgap semiconductors, and is one of the most thermally stable compounds, GaN and other III-Nitrides have recently captured the spot-light. This is due to the fact that the III-Nitrides can have a higher bandgap than SiC and their gap is direct. Also success with extremely bright light emitting diodes (LEDs) and other potential applications have encouraged new activities at a furious pace.

2. Fundamental considerations

First the fundamental differences that favorably distinguish GaN from SiC need to be considered: GaN has a direct bandgap of 3.4 eV. A direct bandgap increases the optical transition probability by at least one order of magnitude compared to an indirect gap such as in SiC. This statement applies to both absorption and emission of photons. On the other hand, SiC is endowed with a long carrier lifetime that may be important in some applications.

Of course, optical transitions through deep levels are very efficient in all materials, direct or indirect, because deep levels mean that the electron is very localized and therefore spread out in momentum space, which helps conserve momentum for any optical transition involving a deep level.

GaN has no inversion symmetry because the Ga–N bond is highly polarized with the electrons located mostly near the nitrogen atom. The polarization makes GaN strongly piezoelectric and optically nonlinear.

3. Doping problems

Now the dopants that allow control of the carrier type and the carrier concentration are considered. These are the donors and acceptors. The most common donors are oxygen atoms. Oxygen in a nitrogen site provides one extra electron that is donated to the conduction band.

Oxygen is very abundant as an adsorbate on the walls of the reactor chamber and often as H₂O in the ammonia used to synthesize the nitride [1]. Hence it is difficult to control the concentration of O in GaN. For this reason it is preferable to use Si as a donor that can be added controllably during the growth of GaN [2].

The choice of acceptors is more difficult. All the divalent elements that could be substituted for the trivalent Ga are looked at systematically [3]. Of these the shallowest appeared to be Mg, but the technique used indicated a level 0.3 eV above the valence band edge—too deep to make conducting p-type material. Zn was concentrated on because, being 0.7 eV above the valence band it gave a bright blue luminescence [4]. Carbon, that is so successful in making conducting p-type GaAs, is a deep level in GaN.

The discovery that all acceptors are deep discouraged all the GaN researchers from continuing the search for conducting p-type GaN, i.e. all except Isamu Akasaki. Professor Akasaki continued and his perseverance was rewarded with an accidental discovery. Akasaki and his team put a sample of GaN:Mg in a scanning electron microscope equipped with an optical window through which they could see the blue cathodoluminescence. They noticed that the luminescence kept getting brighter the longer they scanned (Fig. 1). When the brightness seemed to saturate they took the sample out and measured the Hall effect.

To their great surprise and to the world's astonishment, the previously insulating sample had become conducting p-type [5]. This breakthrough was tentatively explained by Van Vechten who proposed that perhaps hydrogen was passivating a shallow acceptor level of Mg; the electron beam provided enough energy to break away the H and free the shallow acceptor [6]. Shuji Nakamura made the definitive experiment that showed by thermal annealing that above 700°C the passivating H was dissociated from Mg, rendering GaN conducting p-type (see Fig. 2). H could be reintroduced by heating in NH_3 making GaN:Mg insulating again [7].

4. III-Nitride alloys

The most important III-Nitrides and their bandgap values are listed in Table 1 with their bandgaps.

The smallest bandgap of 1.9 eV (corresponding to red emission) belongs to InN, and the largest, 6.2 eV, belongs to AlN. These three nitrides have direct gaps and are miscible in all proportions. Hence it is possible to make binary and ternary alloys with a bandgap in

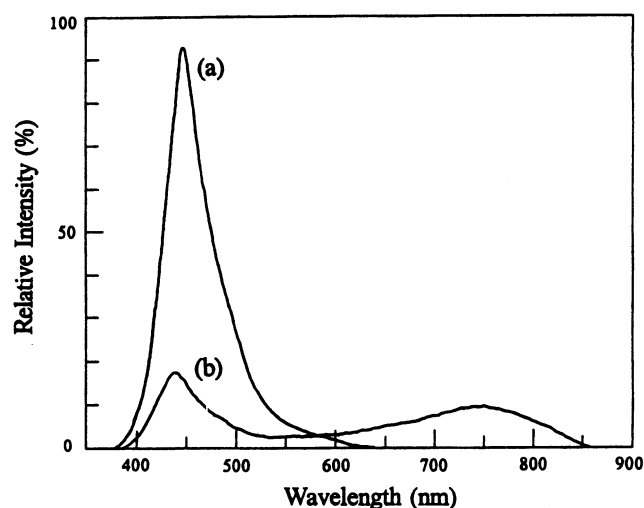


Fig. 1. Photoluminescence spectra of GaN:Mg (b) before and (a) after the electron beam treatment. The ratio of the two peaks is 100 [5].

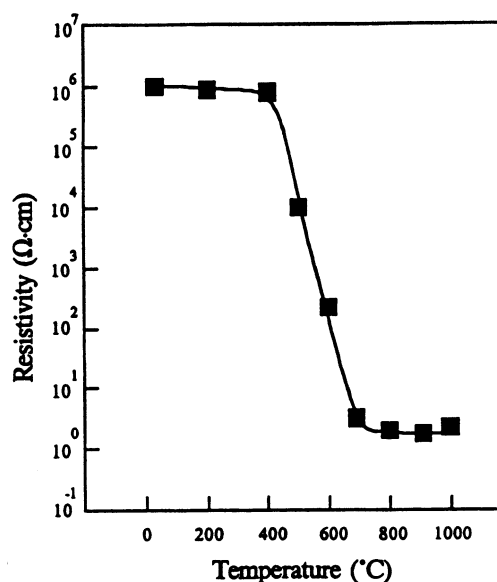


Fig. 2. Resistivity of GaN:Mg after annealing at various temperatures [7].

the 1.9–6.2 eV. Table 2 lists the two main binary alloys and their bandgap ranges.

Of these the InGaN is most widely used to make wells or quantum wells when inserted between GaN barriers (GaAlN is used to make higher barriers). In-GaN is not stable at high temperature because of spinodal decomposition whereby the InN phase separates and tends to cluster together. It turns out that this InN clustering is beneficial to lasers because the clusters are so small that they form 3-D quantum boxes or dots within the intended 1-D well, thus increasing the carrier confinement and hence their recombination efficiency. Furthermore, a 3-D quantization provides more quantized states than 1-D quantization.

Table 1
Energy bandgap of binary III-N compounds

Material	Energy bandgap (eV)
InN	1.9
GaN	3.4
AlN	6.2

Table 2
Energy bandgap of tertiary III-N compounds

Material	Energy bandgap (eV)
InGaN	1.9–3.4
AlGaIn	3.4–6.2

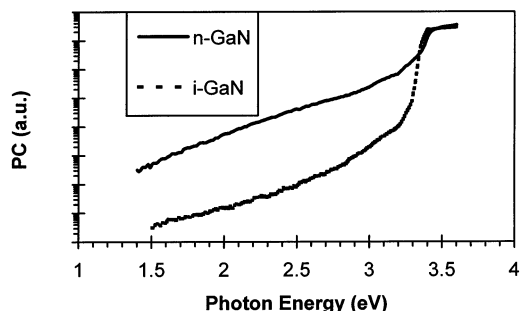


Fig. 3. Photoconductivity spectra of metal-organic chemical vapor deposition (MOCVD)-grown n-type (solid line) and insulating (dotted line) GaN.

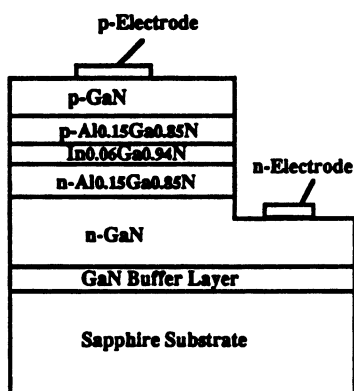


Fig. 4. Structure of III-Nitride light emitting diodes (LEDs) (after Ref. [11]).

5. Practical applications for III-nitrides

The main applications for GaN are listed below.

- UV detectors (solar-blind)
- X-ray detectors
- LEDs/laser diodes
- Surface acoustic wave devices
- Cold cathodes (NEA)
- Heterojunction bipolar transistors

6. UV detectors

UV detectors take advantage of the efficient direct optical transition of GaN in the UV. An extensive study has been carried out on the photoconductivity of GaN from various sources, many n-type and some p-type. They all show the spectral dependence of the top curve in Fig. 3. One recognizes the across-the-bandgap transitions above 3.4 eV, the nearly abrupt Urbach exponential edge below 3.4 eV and a long tail through the visible part of the spectrum [8].

At 2.5 eV, in the blue, the response is about 1% of the across-the-gap response. Note that the photoconductivity spectrum is an absorption spectrum where the sample is its own detector of absorption. Every electron

promoted to the conduction band by the absorption of a photon is detected as photocurrent in the presence of an applied field. The absorption throughout the visible spectrum indicates that there are electron-occupied states in the energy gap. These could be tails of valence or conduction bands or a broad distribution of gap states.

In December 1997, a GaN sample was received from Professor S. Porowski of Unipress in Warsaw, Poland. This sample was grown from a Ga solution at high pressure and high temperature as described in Ref. [9]. The photoconductivity of this insulating sample is similar to the lower curve in Fig. 3. Its response at 2.5 eV is 10^{-5} that at 3.4 eV, i.e. its solar blindness increased by three orders of magnitude. A reason for this behavior is proposed in Ref. [10]. More recently another insulating sample of GaN grown by metal-oxide chemical vapor deposition (MOCVD) was received from Dr S. Nakamura. This sample produced the lower curve of Fig. 3, exhibiting also a three order of magnitude increase in solar blindness.

A UV detector can also detect X-rays and cosmic particles. It is generally believed that a high energy photon or particle will produce n electrons if their energy is n times larger than the GaN bandgap. For space applications these radiation-hard detectors are valuable because they do not require any cooling, unlike lithium-drifted Ge detectors that must remain cooled from the time they leave the factory.

7. Light-emitting devices

The most spectacular application and the first commercial GaN product is the LED [11]. Nakamura et al. have produced the brightest LEDs using GaN pn junctions that include a Zn-doped well as shown in Fig. 4. The purpose of the well is to confine the carriers in a small volume, the purpose of the Zn is to introduce an efficient blue or green luminescent center. Later the well was replaced by one or more quantum wells.

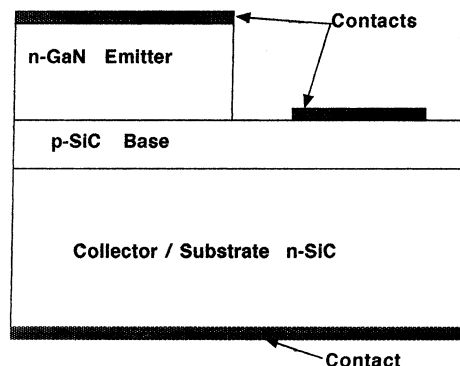


Fig. 5. Structure of GaN/SiC heterojunction bipolar transistor (HBT).

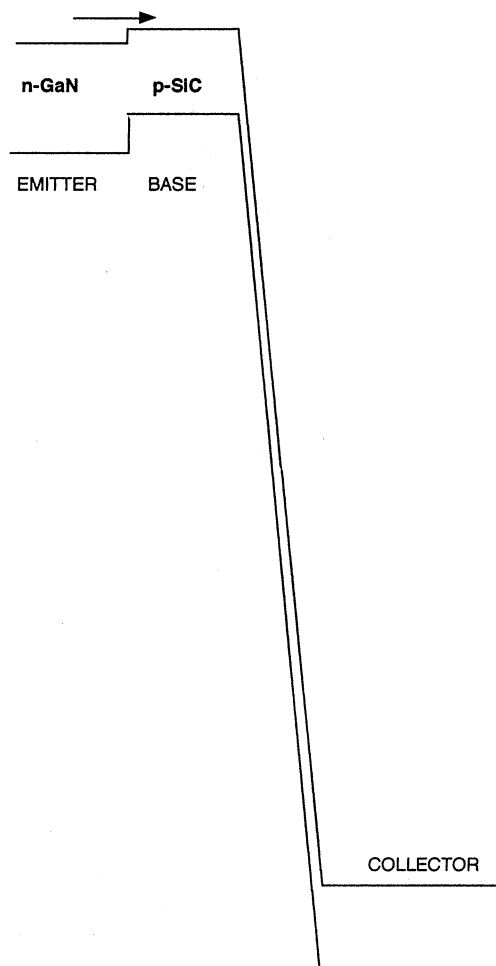


Fig. 6. Band structure of heterojunction bipolar transistor (HBT) under biased conditions.

Laser diodes emitting blue or green light were made with structures similar to that of Fig. 4 using multiple quantum wells and no doping. These short wavelength lasers will be used to store optical data on compact disks (CDs) with a five times greater information capacity than present CDs. Already lasers with a cw operating life of 10 000 h have been achieved. Their commercial availability is imminent.

8. Light modulator

Since GaN is piezoelectric, one should expect the emergence of an acousto-optic modulator. By placing interdigitated fingers on the surface of GaN it is possible to launch a surface acoustic wave that may either propagate or remain stationary [12]. The acoustic wave consists of an alternation of densified and dilated regions of GaN. The denser regions have a higher refractive index than the dilated regions. These alternating regions form a grating that can deflect a laser beam traversing the GaN layer. Changing the frequency of

the acoustic wave will cause a different deflection of the laser beam, i.e. a sweeping beam.

9. Cold cathode

It has been shown that by treating the surface of an insulating GaN with a low work function element, it is possible to place the vacuum level at the surface below the conduction band edge. This is called negative electron affinity (NEA), a condition that allows any electron in the conduction band of the i-GaN layer to escape into vacuum [13]. Therefore NEA allows the making of a solid state cold cathode.

10. Heterojunction bipolar transistor (HBT)

A most promising project is the HBT that can operate at high temperatures ($> 500^{\circ}\text{C}$) [14]. The structure which has been studied is shown in Fig. 5. It consists of a p-SiC base on an n-SiC collector. The emitter is made of n-GaN forming a heterojunction to the base. The band structure diagram of Fig. 6 shows the HBT under biased conditions: a forward bias across the heterojunction, allowing the injection of electrons from the wider bandgap GaN into SiC. These electrons are sucked out of the base by the electric field of the reverse biased collector. Power gain results from the fact that electrons enter the base with just a few volts of bias and exit to the collector at several hundreds or thousands of volts. Hence the power gain of each electron is the ratio of output to input voltages. Note that Singh et al. [15] have shown the possibility of operating reverse biased SiC pn junctions with a breakdown voltage exceeding

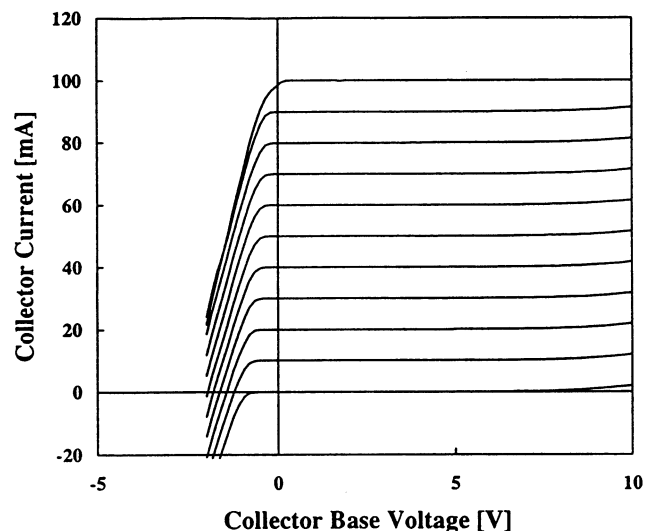


Fig. 7. $I(V)$ characteristics of heterojunction bipolar transistor (HBT) under common base mode at room temperature. The emitter current is in 10 mA increments.

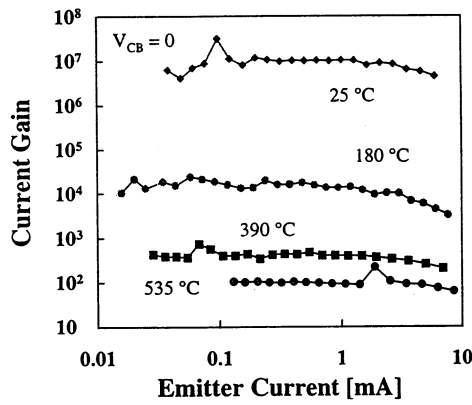


Fig. 8. Differential current gain of heterojunction bipolar transistor (HBT) at various temperatures.

5.5 kV. The $I(V)$ characteristics of Fig. 7 show the behavior of a typical common base transistor at room temperature.

One will note that 100 mA of emitter current results in 100 mA of collector current. A plot of differential current gain dI_C/dI_B , i.e. the change in collector current dI_C for a change in base current dI_B is shown in Fig. 8 for different device temperatures.

At room temperature this current gain has an impressively high value of 10 million at room temperature. As expected, with increasing temperature, the current gain decreases. This decrease is due to the thermal broadening of the Boltzmann tail in the hole distribution in the base layer. Most of the holes in the base are blocked from escaping to the emitter by a barrier that is due to the difference in bandgaps at the heterojunction. However, at high temperatures, the more energetic holes in the Boltzmann tail can overcome this barrier. The emitter current consists of injected electrons and escaping holes. Only electrons contribute to power gain, the holes only reduce the current gain. The above comments explain why the current gain decreases with increasing temperature. An Arrhenius plot of this temperature data (Fig. 9) permits a determination of the activation energy E_A to overcome the barrier to holes at the heterojunction.

From the slope, one obtains $E_A = 0.4$ eV which is the difference between the band gaps of GaN (3.4 eV) and SiC (3.0 eV). Note that a current gain of 100 is obtained at 535°C, which is the typical value of current gain for commercial Si transistors at room temperature. Hence a commercialization of the GaN/SiC HBT device will be a new breakthrough in bipolar transistors.

In conclusion, it is evident that there are still many physical studies to be done with GaN and that numerous new device possibilities will emerge.

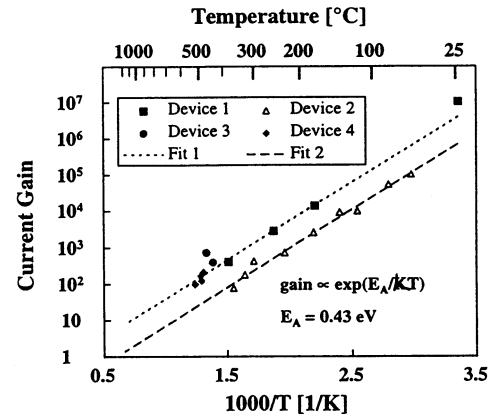


Fig. 9. Arrhenius plot of temperature dependence of GaN/SiC heterojunction bipolar transistor (HBT) (current gain).

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