Gallium Nitride

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Abstract

Gallium Nitride is a direct band gap III-V semiconductor. Because of its wide band gap (3.4 eV) it has promise in applications such as blue and UV detectors and emitters. Its electrical properties and thermal stability show potential for use in high temperature electronics. The two main problems GaN faces are lack of a good substrate material and difficulty in achieving p-type doping. This paper is a review of GaN's physical, electical, and optical properties.

I. PHYSICAL AND THERMAL PROPERTIES

GaN used in devices is generally grown epitaxially as a thin film on some sort of a substrate. The choice of substrate material and the plane on which GaN is grown affect the crystal structure and physical properties. The electrical properties and to a lesser extent the optical properties of GaN are dependent on this choice of substrate material and orientation, but thermal properties are largely unaffected.

The equilibrium crystal structure of GaN is the wurtzite structure. The wurzite structure consists of interpenetrating hexagonal close-packed sublattices of the group III (Ga) and the group V (N) elements which are displaced from one another. Each atom is surrounded by four atoms of the opposite type in a tetrahedral arrangement. The lattice constants are a = 3.189 Angstroms and c = 5.185 Angstroms [1].

In addition to the wurzite phase a zinc-blende phase is often observed. The zinc-blende structure is similar to the wurzite structure. It consists of interpenetrating face-centered cubic sublattices of each element displaced by one quarter of a body diagonal. Again each atom of one element is surrounded by four atoms of the opposite element in the tetrahedral arrangement. The zinc-blende and wurzite structures differ only in the stacking sequence of the close packed (111) planes. The zinc-blende structure stacks in an ABCABC... arrangement while the wurzite structure stacks in an ABABAB... arrangement. The lattice constant of the zinc-blende phase is 4.50 Angstroms [1].

Figure 1 summarizes some of the important properties of wurzite phase GaN [2]. It is very stable thermally, and the width of the band gap has only a small temperature dependence. The coefficients of thermal expansion given in Figure 1 are for room temperature, but are approximately constant to 900 K. GaN has a high thermal conductivity, experimentally measured at k = 1.3 W/cm•K. Theoretical calculations are reasonably close, with k = 1.7 W/cm•K [3]. Since GaN is a nonmetallic crystal, it transports heat primarily by phonons. Phonons scatter from impurities and defects, so the thermal conductivity is lower for heavily doped or low quality samples.

GaN is a hard material, and very chemically stable. It has superior radiation hardness to GaAs and Si. Other properties not listed in Figure 1 include the density (6.05 g/cm^3) and the sound velocity (4.75 x 10^5 cm/sec for the wurzite phase and 4.33 x 10^5 cm/sec for the zinc-blende phase) [1].

II. ELECTRICAL PROPERTIES

GaN is an intrinsic n-type semiconductor. The purest samples show an electron concentration of approximately n = 4 x 10^{16}/cm^3 . No impurity is present in high enough concentration to account for this carrier density, so it is attributed to native defects (probably nitrogen vacancies). The electron mobility has been found to vary as 1/T^2 in the 300 - 900 K range. The highest recorded mobilities of undoped GaN to date are μ = 600 cm^2/V•sec (with n = 4 x 10^{16}/cm^3) at room temperature and μ = 1500 cm^2/V•sec (with n = 8 x 10^{15}/cm^3) at liquid nitrogen temperature [2].

Until recently, no one has been able to fabricate p-type GaN. Reliable p-type doping remains one of the major hurdles to overcome in developing GaN applications. However, several groups have recently achieved p-type GaN by using various methods of magnesium doping. The most recent effort reported a hole concentration of 2 x 10^{17}/cm^3 at room temperature [4].

FIGURES

TABLE II. Properties of wurtzite GaN.

Band gap energy	E_g (300 K) = 3.39 eV E_g (1.6 K) = 3.50 eV
Band gap temperature coefficient ($T > 180$ K)	$dE_g/(dT) = -6.0 \times 10^{-4}$ eV/K
Band gap pressure coefficient ($T = 300$ K)	$dE_g/(dP) = 4.2 \times 10^{-3}$ eV/kbar
Lattice constant ($T = 300$ K)	$a = 3.189$ Å $c = 5.185$ Å
Coefficient of thermal expansion ($T = 300$ K)	$\frac{\Delta a}{a} = 5.59 \times 10^{-6}$/K $\frac{\Delta c}{c} = 3.17 \times 10^{-6}$/K
Thermal conductivity	$\kappa = 1.3$ W/cm K
Index of refraction	$n(1\ \text{eV}) = 2.33$ $n(3.38\ \text{eV}) = 2.67$
Dielectric constants	$\epsilon_0 = 8.9$ $\epsilon_0 = 9.5$ $\epsilon_\infty = 5.35$
Electron effective mass	$m_e^* = 0.20 \pm 0.02 m_0$
Phonon modes ($T = 300$ K)	A_1(TO) = 532 cm^{-1} E_1(TO) = 560 cm^{-1} E_2 = 144,569 cm^{-1} A_1(LO) = 710 cm^{-1} E_1(TO) = 741 cm^{-1}

FIG. 1. *Properties of wurzite GaN [2].*

III. OPTICAL PROPERTIES

The optical of properties of GaN are of primary interest since the most promising applications are blue and UV LED's and diode lasers. The band gap at room temperature is about 3.4 eV. The gap at 1.6 K is 3.503 +/- .0005 eV. The band gap has been found to obey the emperical relation $E_g = 3.503 + (5.08 \text{ x } 10^{-4}\ T^2)/(T - 996)$ eV
See Figure 2 for the temperature dependence of the principle emission peak. The slope of this curve is linear above 180 K, and thus the band gap temperature coefficient in this range is constant:
$dE_g/dT = -6.0 \text{ x } 10^{-4}$ eV/K [2].

GaN has several photoluminescence peaks. At 2 K, the principle (free exciton) peak is at 3.47 eV. There is a doublet at 3.38 eV with 7.8 meV spacing and a weak doublet at 3.29 eV. The doublets are longitudinal optical phonon replica peaks of the free and bound exciton peaks. There is a donor-acceptor transition peak at 3.36 eV, and a broad, midgap optical transition at 2.2 eV. At 300 K, the free exciton peak is at 3.39 eV. Doping leads to additional impurity levels ranging from 1.8 to 2.9 eV [2].

Morkoc and Strite report A_1 and E_1 transverse optical (TO) phonon modes at 533 and 559 cm^{-1} respectively, and E_2 TO modes at 144 and 569 cm^{-1}. They report A_1 and E_1 longitudinal modes (LO) at 710 and 741 cm^{-1} respectively [2]. Kozawa et al report A_1 and E_1 TO modes at 534 and 563 cm^{-1}, an E_2 mode at 572 cm^{-1}, and A_1 and E_1 LO modes at 736 and 745 cm^{-1} [5]. All values were determined using Raman Spectroscopy.

Other important propeties include the refractive index, absorption coefficient, and ϵ_o. The refractive index has been determined using transmission and absorption measurements:

n(3.38 eV) = 2.67 and n(1.0 eV) = 2.33. Measurements of ϵ_o range from 8.9 to 9.5. Measurements of the absorption coefficient at room temperature as a function of photon energy are given in Figure 2 [2].

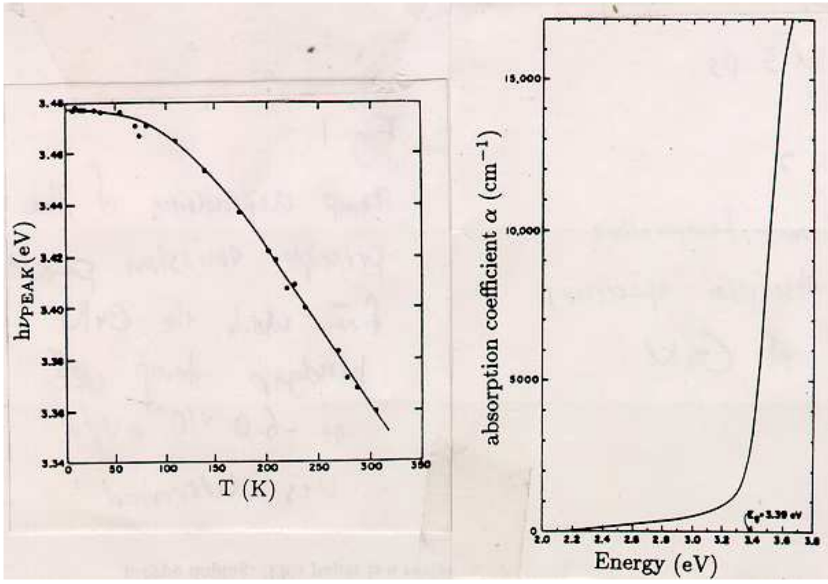

FIG. 2.

Graph 1 - Temperature Dependence of the Principle Emission Peak

Graph 2 - Room Temperature Absorption Spectrum of GaN [2].

III. CONCLUSION

GaN has the potential for many useful applications. Its thermal and chemical stability make it attractive for high temperature and high power electronics applications. It has superior radiation hardness to GaAs and Si, which is a useful property for space applications. It has better electrical properties and ohmic contact resistance than more developed wide band gap materials such SiC.

The primary interest in GaN is towards blue and UV detectors and emitters. A Japanese company is already producing bright, reliable, efficient blue GaN LED's [6]. Blue LED's are needed for use in full color LED displays. A full color display requires LED's of the three primary colors: blue, green, and red. Suitable green and red LED's already exist, but blue has been a problem. Since the human eye is less efficient at detecting blue wavelengths than green or red, the blue LED's used in displays need to be bright.

A blue diode laser would be useful in optical memory applications. The amount of information that can be optically stored on a 2-D surface is diffraction limited, which goes as the square of the wavelength. A blue laser with half the wavelength of the red/IR lasers currently used would be able to read and store four times as much information on a disc of the same size. One group has been able to get GaN to lase at 3.45 eV (at 2 K). It has also been observed to lase at 80 K and even at room temperature [2]. There is also considerable interest in using GaN as a UV detector.

Recent research indicates GaN is a promising material, but problems remain. Already discussed is the difficulty of p-type doping. Another major obstacle is the fact that other wide band gap semiconductors such as SiC have been more thoroughly studied and developed. The last and possibly most difficult obstacle is the lack of a good substrate material. There are no substrate materials with a good lattice match and a good thermal match (saphire is the most common choice). Because it is so hard, GaN films often crack the substrate as the temperature changes because the two expand or contract at different rates. The lattice mismatch causes strain and defects in the crystal, and films must be grown thick to get a good quality sample. Despite the problems, research continues and GaN applications will continue to develop until the problems are resolved or a better wide band gap material is found.

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