

# I. GaAs Material Properties

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GaAs is a III–V compound semiconductor composed of the element gallium (Ga) from column III and the element arsenic (As) from column V of the periodic table of the elements. GaAs was first created by Goldschmidt and reported in 1929, but the first reported electronic properties of III–V compounds as semiconductors did not appear until 1952 [1].

The GaAs crystal is composed of two sublattices, each face centered cubic (fcc) and offset with respect to each other by half the diagonal of the fcc cube. This crystal configuration is known as cubic sphalerite or zinc blende. Figure 3-1 shows a unit cube for GaAs and Table 3-1 provides a listing of some of the general material characteristics and properties.

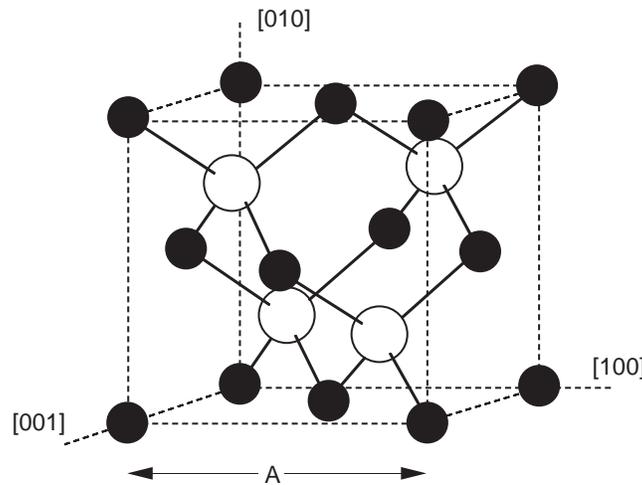


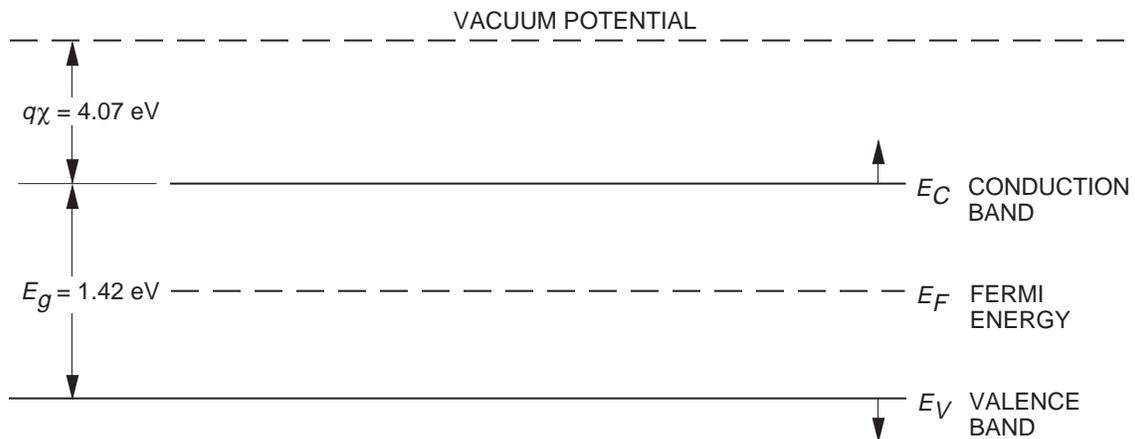
Figure 3-1. Unit cube of GaAs crystal lattice.

## A. Energy Band Structure

As a result of the laws of quantum mechanics, electrons in isolated atoms can have only certain discrete energy values. As these isolated atoms are brought together to form a crystal, the electrons become restricted not to single energy levels, but rather to ranges of allowed energies, or bands called the valance and conduction bands (Figure 3-2). These two bands are separated by an energy band gap, which is a very important characteristic of the semiconductor material. At zero kelvin, all the electrons are confined to the valance band and the material is a perfect insulator. Above zero kelvin, some electrons have sufficient thermal energy to make a transition to the conduction band where they are free to move and conduct current through the crystal. The probability of an electron having enough energy to make the transition is given by the Fermi distribution function. The Fermi level shown on Figure 3-2 is the energy level at which the probability function is equal to one half. For pure semiconductors, the Fermi level is approximately in the center of the band gap. Note, though, that no electron actually has an energy of  $E_F$ , since they are not permitted to exist at energies in the band gap. The amount of energy required for an electron to move from the valance band to the

**Table 3-1. Room-temperature properties of GaAs.**

Property	Parameter
Crystal structure	Zinc blende
Lattice constant	5.65 Å
Density	5.32 g/cm <sup>3</sup>
Atomic density	4.5 × 10 <sup>22</sup> atoms/cm <sup>3</sup>
Molecular weight	144.64
Bulk modulus	7.55 × 10 <sup>11</sup> dyn/cm <sup>2</sup>
Sheer modulus	3.26 × 10 <sup>11</sup> dyn/cm <sup>2</sup>
Coefficient of thermal expansion	5.8 × 10 <sup>-6</sup> K <sup>-1</sup>
Specific heat	0.327 J/g-K
Lattice thermal conductivity	0.55 W/cm-°C
Dielectric constant	12.85
Band gap	1.42 eV
Threshold field	3.3 kV/cm
Peak drift velocity	2.1 × 10 <sup>7</sup> cm/s
Electron mobility (undoped)	8500 cm <sup>2</sup> /V-s
Hole mobility (undoped)	400 cm <sup>2</sup> /V-s
Melting point	1238°C



**Figure 3-2. Energy band diagram for GaAs.**

conduction band (energy band gap) depends on the temperature, the semiconductor material, and the material's purity and doping profile. For undoped GaAs, the energy band gap at room temperature is 1.42 eV. The energy band diagram is usually referenced to a potential called the vacuum potential. The electron affinity,  $q\chi$ , is the energy required to remove an electron from the bottom of the conduction band to the vacuum potential. For GaAs,  $q\chi$  is approximately 4.07 eV [2,3].

GaAs is a direct band gap semiconductor, which means that the minimum of the conduction band is directly over the maximum of the valence band (Figure 3-3). Transitions between the valence band and the conduction band require only a change in energy, and no change in momentum, unlike indirect band-gap semiconductors such as silicon (Si). This property makes GaAs a very useful material for the manufacture of light emitting diodes and semiconductor lasers, since a photon is emitted when an electron changes energy levels from the conduction band to the valence band.

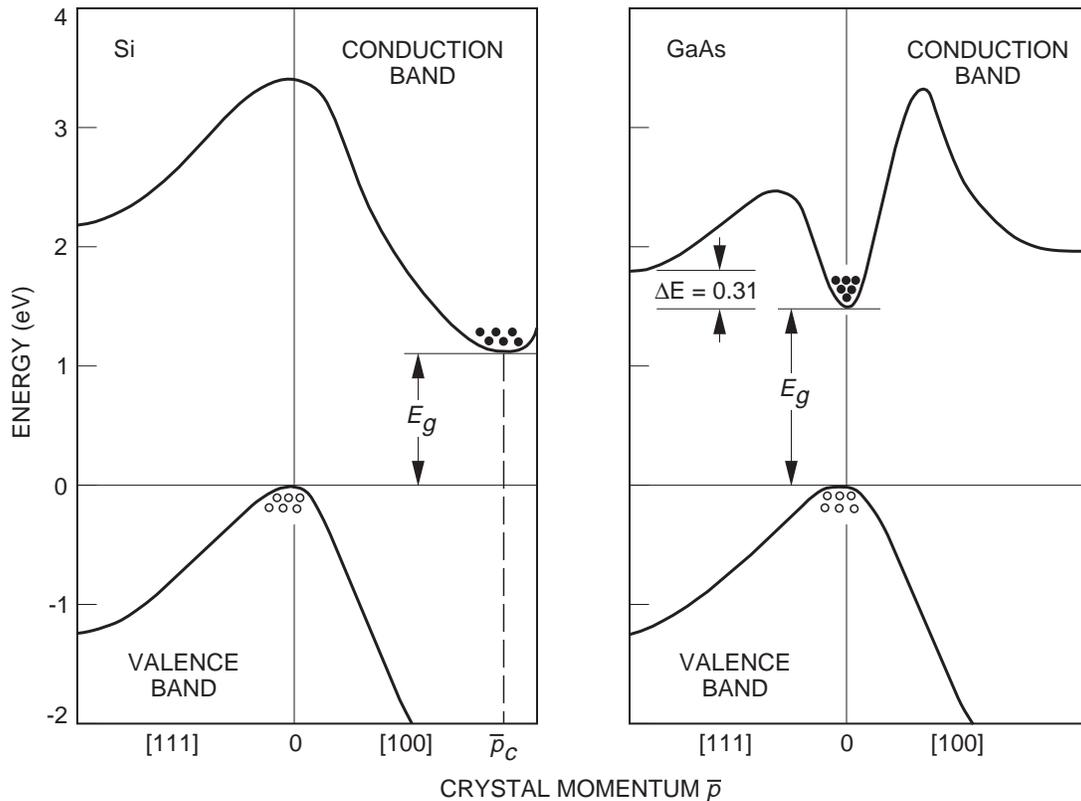


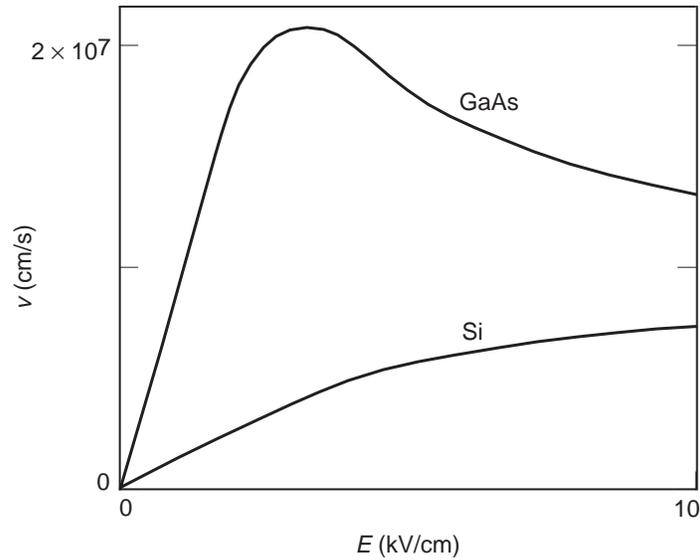
Figure 3-3. Energy band structure of Si and GaAs.

Alternatively, an incident photon can excite an electron from the valence band to the conduction band, allowing GaAs to be used in photo detectors.

## B. Mobility and Drift Velocity

GaAs has several advantages over silicon for operation in the microwave region—primarily, higher mobility and saturated drift velocity and the capability to produce devices on a semi-insulating substrate.

In a semiconductor, when a carrier (an electron) is subjected to an electric field, it will experience a force ( $\mathbf{F} = -q\mathbf{E}$ ) and will be accelerated along the field. During the time between collisions with other carrier ions and the semiconductor lattice, the carrier will achieve a velocity that is a function of the electric field strength. This velocity is defined as the drift velocity ( $v$ ). From the conservation of momentum, it can be shown that the drift velocity ( $v$ ) is proportional to the applied electric field (Figure 3-4) and can be expressed as



**Figure 3-4. Drift velocity of electrons in GaAs and Si as a function of the electric field.**

$$v = -\left(\frac{q\tau_c}{m^*}\right)\mathbf{E} \quad (3-1)$$

The proportionality factor depends on the mean free time between collisions ( $\tau_c$ ) and the electron effective mass ( $m^*$ ). The proportionality factor is called the electron mobility ( $\mu$ ) in units of  $\text{cm}^2/\text{V}\cdot\text{s}$ .

Mobility is an important parameter for carrier transport because it describes how strongly the motion of an electron is influenced by an applied electric field. From the equation above, it is evident that mobility is related directly to the mean free time between collisions, which in turn is determined primarily by lattice scattering and impurity scattering. Lattice scattering, which is a result of thermal vibrations of the lattice, increases with temperature and becomes dominant at high temperatures; therefore, the mobility decreases with increasing temperature. Impurity scattering on the other hand, which is a result of the movement of a carrier past an ionized dopant impurity, becomes less significant at higher temperatures [2].

Although the peak mobility of GaAs in the linear region can be as much as six times greater than that of silicon (Si) at typical field strengths, the advantage of GaAs may be only as much as a factor of two [4]. This still translates to the fact that GaAs devices can work at significantly higher frequencies than Si. The exact increase in the speed of operation depends on factors such as the circuit capacitance and the electric field regime in which the device operates.

### C. Semi-Insulating GaAs

The importance of semi-insulating GaAs is based on the fact that devices made of it by direct ion implantation are self-isolating, so that it is ideally suited to integrated circuit fabrication. Moreover, the semi-insulating substrate provides greatly reduced

parasitic capacitances, thus faster devices, and allows for integration and the implementation of monolithic microwave integrated circuits (MMIC).

Semi-insulating GaAs must meet the following requirements to provide semiconductor quality material:

- (1) Thermal stability during epitaxial growth or anneal of ion-implanted active layer.
- (2) Absence of undesirable substrate active layer interface effects, such as back-gating and light sensitivity.
- (3) No degradation of active layer properties by outdiffusion of impurities from substrate during thermal processing.
- (4) Lowest possible density of crystalline defects, such as dislocations, stacking faults, and precipitates.

To achieve some of these requirements, buffer layer technology was developed. A buffer layer is a relatively thick, high-resistivity epitaxial layer grown on the semi-insulating substrate. Another epitaxial layer is then grown on the buffer layer and used for the active layer. The buffer layer provides a physical barrier for undesirable substrate impurities and imperfections.

GaAs bulk resistivity can range from  $10^{-6}$   $\Omega$ -cm to about  $10^{22}$   $\Omega$ -cm, with the practical range being  $10^{-3}$   $\Omega$ -cm to  $10^8$   $\Omega$ -cm. This high resistivity is about six orders of magnitude greater than that of silicon and provides excellent isolation and substrate insulation. Undoped GaAs can be made semi-insulating by the addition of either oxygen or chromium to the melt. The resistivity of the semiconductor can be controlled by counter doping with a deep-level impurity that has a conductivity type opposite to that of the impurities introduced during growth.

## **D. Crystal Defects**

No semiconductor crystalline material is perfect, and GaAs crystals, in spite of the efforts to control crystal growth, contain a number of crystal defects, dislocations, and impurities. These defects can have either desirable or undesirable effects on the electronic properties of GaAs. The natures of these defects and the observed effects are determined by the method of their incorporation into the material and the general growth conditions.

### **1. Point Defects**

Localized defects of atomic dimensions, called point defects, can occur in an otherwise perfect crystal lattice. These point defects can include vacancies, interstitials, misplaced atoms, intentionally introduced dopant impurities, and impurities introduced inadvertently during the material growth process. The study of point defects is important because of the effect these defects have on the electronic properties of the material and the strong relationship between diffusion and the number and type of defects in the crystalline material. The electrical properties of a semiconductor can be manipulated by the deliberate insertion of chemical defects (impurities) into the material during the growth and processing steps. However, intrinsic defects present in the material also play an important role in the electronic behavior of GaAs.

Many intrinsic defects are observed in GaAs. The concentration and effect of these defects are determined by the manner in which the material is grown. Intrinsic defects in GaAs include both arsenic and gallium vacancies, their concentration being determined by the overpressure of arsenic during processing. The effect of these vacancy defects has been observed to be neutral [5], deep donor-like, and deep acceptor-like [6].

EL2, an important defect in GaAs, is present in material grown from an arsenic-rich melt. This defect is donor-like in character and is located at the middle of the energy gap [7]. It is thermally very stable and can withstand processing temperatures up to 900°C, and acts as an electron trap. The importance of this defect lies in its ability to convert p-type GaAs to semi-insulating material, and its thermal stability.

## 2. Dislocations

A dislocation is a one-dimensional array of point defects in an otherwise perfect crystal. It occurs when the crystal is subjected to stresses in excess of the elastic limit of the material. Dislocations interact with chemical and other point defects. This interaction exists between the localized impurity atoms and the strain field in the vicinity of the dislocations. The presence of a dislocation is usually associated with an enhanced rate of impurity diffusion leading to the formation of diffusion pipes. This effect translates to the introduction of trapping states in the band gap, altering the etching properties of the wafer, and, most importantly, altering the electrical properties of the devices. Studies have shown detrimental effects of dislocations and dislocation densities on the source drain current and threshold voltage of field-effect transistors FETs [8,9], carrier concentration, and sheet resistance [10].

Dislocations generally are introduced as a result of a temperature gradient present during crystal growth. Modern crystal growth methods can routinely produce 7.6-cm (3-in.) wafers with dislocation densities of  $10^4$  to  $10^5$   $\text{cm}^{-2}$  for the Liquid Encapsulated Czochralski (LEC) and 8000 to 25,000  $\text{cm}^{-2}$  for Horizontal Bridgeman (HB) techniques.

## 3. Impurities in GaAs

Chemical point defects (doping impurities) can be introduced to the crystalline material either deliberately or inadvertently as contamination during processing. In general, substitutional impurities are electronically active, whereas many contaminants are interstitial in nature and are electronically inactive. Dopants are classified as either donors or acceptors. A donor has one more electron than the atom it is replacing in the crystal. This extra electron is easily removed or donated to the conduction current. An acceptor, on the other hand, has one less electron than the atom it is replacing. Thus, an acceptor can easily capture an electron and prevent it from adding to the conduction current. Regardless of the type or character of the impurity, the electrical properties of the semiconductor are altered.

Figure 3-5 shows the energy band diagram of Figure 3-2 with the addition of impurities. Shallow donor or acceptor impurities have energy levels within  $3kT$  of the conduction and valance band, respectively. Since the energy required for an electron to transition from these impurity energy levels to the nearest band edge is very small, they are typically fully ionized at room temperature. The Fermi level shifts from the band center towards the impurity levels to reflect this. In other words, for donor impurities, the Fermi level shifts towards the conduction band, and  $V_{CF}$  decreases as the donor doping concentration increases. A similar description can be made of acceptor impurities. It is

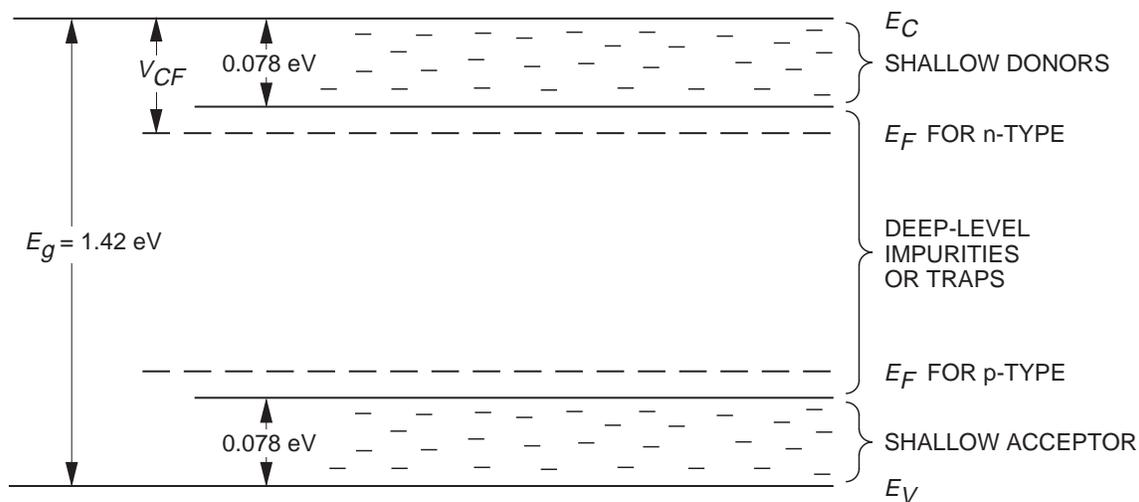


Figure 3-5. Energy band diagram of GaAs with impurities.

these shallow impurities that are used for doping purposes. Impurities with energies in the center of the band gap are called deep impurities. Deep impurities generally degrade device performance by reducing the carrier lifetime.

Both impurity types, deep and shallow, are present in GaAs in the form of complexes with gallium or arsenic. One of the most common is silicon. This group IV element can be used to give either p-type GaAs by incorporating it at low temperatures, or n-type GaAs by processing it at high temperatures. Another group IV element, carbon, is also used extensively to provide p-type GaAs. Chromium (Cr) behaves as an acceptor, with an impurity level close to the center of the energy gap. This property makes it very useful for counterdoping n-type GaAs to make it semi-insulating. Other elements such as copper, oxygen, selenium, and tin are also used in GaAs processing to provide the desired n- or p-like behavior.

## E. Thermal Characteristics

GaAs has a thermal conductivity of 0.55 W/cm-°C, which is about one-third that of silicon and one-tenth that of copper. As a consequence, the power handling capacity and therefore the packing density of a GaAs integrated circuit is limited by the thermal resistance of the substrate. The reliability of GaAs devices is directly related to the thermal characteristics of the device design, the mounting technique used for the die, and the materials used for that interface.

The thermal conductivity of GaAs is related to the temperature of the material over a wide temperature range and varies approximately as  $1/T$ , where  $T$  is the temperature in kelvin. However, thermal conductivity can be considered linear over a very short temperature range [11].

The power handling capabilities, reliability, and performance of semiconductor devices are directly related to the junction temperature of the device during operation. While GaAs has a higher thermal resistivity than silicon, this is somewhat offset by the higher band gap of GaAs, allowing higher operating temperatures. Nevertheless, thermal considerations are extremely important in device design, packaging, and application.

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## Additional Reading

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