AlGaAs

Sue Lindsay

Department of Physics
University of Cincinnati
Cincinnati, Ohio 45221

Abstract

AlGaAs has many properties which make it a very useful material. The ability to fabricate AlGaAs/GaAS thin films and bulk crystals allows the study of this material. It can be used in $Al_xGa_{1-x}As$/GaAs heterostructure systems such as optical waveguides, lasers, infrared detectors, high speed digital devices and more.

STRUCTURE

Many III-V mixed alloys form crystals with zinc-blend structures. Both GaAs and AlGaAs form crystals with the zinc-blend arrangement with eight atoms in a unit cell. The lattice atoms are tetrahedrally bound in network arrangements. AlGaAs is made of two face centered cubic lattices that are displaced from one another by a quarter of a body diagonal where one lattice has the Aluminium and Gallium atoms, and the other has the Arsenic atoms.

GaAs has a lattice constant of $5.6533\mathring{A}$ and AlAs has a lattice constant of $5.6611\mathring{A}$[1]. Because these values are so close, the lattice match between these two is very good. They are relatively easy to grow epitaxially, So $Al_xGa_{1-x}As$ layers, grown on a GaAs substrate at 900degC, have a perfect lattice match for all the values of x[2].

The crystal density ρ of $Al_xGa_{1-x}As$ varies as a linear function of the composition x, where the calculation of ρ is given by ρ(x) = 5.36 - 1.6x[1]. The lattice constant of $Al_xGa_{1-x}As$ obeys Vegard's law, which states that the lattice constant varies as a function of the composition x.

BAND STRUCTURE

$Al_xGa_{1-x}As$ has both direct and indirect energy gaps. The compositional dependence of the energy gaps are[3]

Γ direct gap $E_g^\Gamma = 1.424 + 1.247x$ $(0 \leq x \leq 0.45)$

Γ direct gap $E_g^\Gamma = 1.424 + 1.247x + 1.147(x-0.45)^2$ $(0.45 < x \leq 1)$

X indirect gap $E_g^X = 1.900 + 0.125x + 0.143x^2$

L indirect gap $E_g^L = 1.708 + 0.642x$

There is a crossover from the Γ-L-X in GaAs to X-L-Γ in AlAs, so $Al_xGa_{1-x}As$ is a direct gap semiconductor below a compositional x=0.47, and an indirect gap semiconductor above it[4].

For alloy compositions x close to 0.47 (the direct crossover), the carriers will be distributed among several conduction bands[5]. The apparent Hall electron concentration, n_H, is obtained from the equation $n_H = -1/eR_H$ where R_H is the Hall constant. For all practical values of the magnetic field, n_H will be smaller than the actual total electron density as in Fig. 1, due to multivalley conduction.The electron mobility of $Al_xGa_{1-x}As$ alloys decrease with increasing Al content.

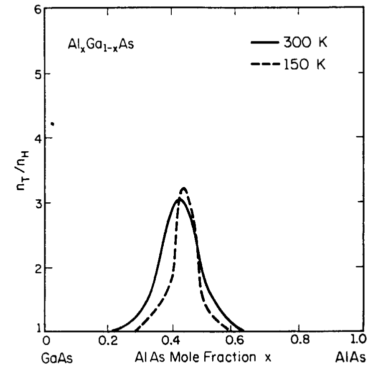

Figure 1: The ratio of true electron concentration,n_T, and the measured n_H is plotted as a function of composition x. (From Ref. 5)

ELECTRICAL PROPERTIES

GaAs has been widely studied, and there is much information on the transport properties of it, but there is less information on AlGaAs, though this is changing rapidly. Often AlGaAs is grown as thin epitaxial films on a GaAs substrate. The electron, donor, and acceptor concentrations (n, N_d, N_a respectively) and the activation energy(E_d) are related through the charge-neutrality condition

$$\frac{n(N_a+n)}{N_d-N_a-n}=\frac{N_c}{g}\exp\frac{-E_d}{k_b}T$$

r where g=2 is the donor spin-degeneracy factor. $Al_xGa_{1-x}As/GaAs$ grown by molecular beam epitaxy(MBE) can be doped with silicon, tellurium, selenium and tin for example. The high activation-energy points in Fig. 2 correspond to low doping concentrations which lead to an increase in E_d.

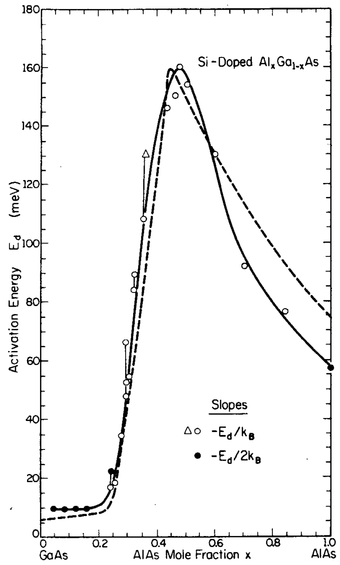

Figure 2: Compositional dependence of the ionization energy E_d of the dominant Si donor level in $Al_xGa_{1-x}As$. (From Ref. 5)

In a layer of n-type AlGaAs grown on semi-insulating GaAs substrate, electrons will transfer from the donors in the AlGaAs into the GaAs, and form a quasi two dimensional electron gas(2DEG) with a sheet density of approximately $10^{12}cm^{12}$[6]. This 2DEG will have a high mobility because the GaAs has a low concentration of ionized impurities, so the 2DEG dominates Hall measurements made at low temperatures or in the dark. A 1 μm undoped AlGaAs buffer layer grown between the substrate and the AlGaAs can suppress the formation of a 2DEG.

OPTICAL PROPERTIES

The composition x can be varied to get different values for the index of refraction. The refractive index also varies with increasing temperature. The temperature coefficient of GaAs was measured to be dn/dt $3x10^{-4}K^{-1}$ in the 0.7 - 1.4eV range of photon energy[6]. The dielectric function ϵ determines the optical properties at all photon energies, and is given by $\epsilon=\epsilon_1$ + iϵ_2. The complex refractive index is given by n^* = n + ik, where n is the real refractive index and k is the extinction coefficient. The two are related by the following equations, $\epsilon_1 = n^2$ - k^2, ϵ_2 = 2nk. The absorption coefficient, α, is given by $\alpha = 4\pi k/\lambda$ where λ is the wavelength of the light in vacuum.

Free carriers that are present in semiconductors affect its optical properties, causing it to differ from the properties of the intrinsic material. An important parameter is the plasma frequency which is $\omega_p = 4\pi e^2 N/m^*\epsilon$ where N is the carrier concentration, m* is the free carrier effective mass[6]. Free carrier absorption results from the excitations of electrons occupying states in the partially filled band, when carriers remain in the same minimum of this band. There is not much experimental data for $Al_xGa_{1-x}As$ related to free carrier absorption or plasma effects.

APPLICATIONS

The ability to vary the index of refraction of $Al_xGa_{1-x}As$ by changing the composition x is very useful in the fabrication of waveguides, which can consist of a core with a higher refractive index and smaller energy gap than the surrounding cladding regions as in Figs. 3 and 4. Waveguides in which multiple quantum wells(MQW) or heterostructures of $Al_xGa_{1-x}As/GaAs$ make up the core as in Fig. 5 are widely applicable to lasers, modulators and nonlinear optical devices[7]. Typical parameters for $Al_xGa_{1-x}As/GaAs$ heterostructures are 3nm $Al_{0.3}Ga_{0.7}As$/3nm GaAs[6]. This allows a significant penetration of the ground state electron wave function into the wide gap barrier region with the lower index of refraction. The study of $Al_xGa_{1-x}As$ MQW structures with varying well and barrier thicknesses and alloy compositions has generated much literature and important recent advances in this subject.

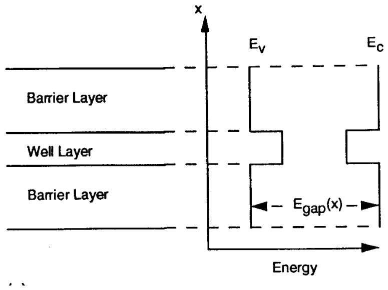

Figure 3: Schematic drawing of a single quantum well. (From Ref. 7)

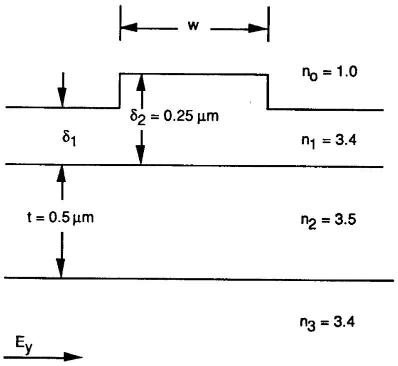

Figure 4: Cross section of AlGaAs channel waveguide formed by etching ridge in cover layer. (From Ref. 7)

Additionally, heterostructures made of $Al_xGa_{1-x}As/GaAs$ have great potential for many high speed electronics on optoelectronic devices, because the lattice constant between

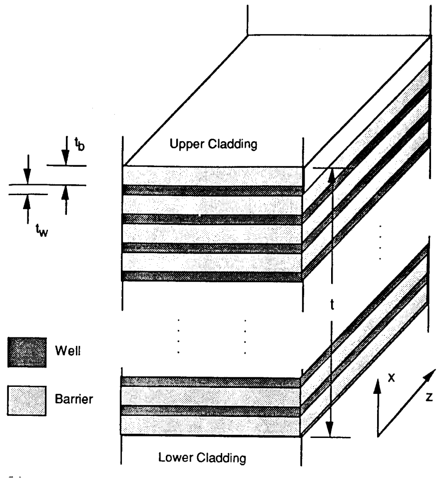

Figure 5: Schematic drawing of multiple quantum well planar optical waveguide. From Ref. 7)

the two are so close that there are a minimum of interface states which affects the mobility and the formation of 2DEG.

References

[1] S. Adachi, J. Appl. Phys. **58**, R1-R29 (1985).

[2] S. Adachi, *Physical Properties of III-V Semiconductor Compounds*, Wiley, New York, 1992.

[3] H.C. Casey Jr and M.B. Panish, *Heterostructure Lasers*, Academic, New York, 1978.

[4] A.K. Saxens, Phys. Status Solidi(b) **105**, 777(1981).

[5] N. Chand et al, Phys. Rev. B, (USA), **30**, 4481(1984).

[6] S. Adachi, *Properties of Aluminium Gallium Arsenide*, INSPEC, England, 1993.

[7] R.G. Hunsperger, *Photonic Devices and Systems*, Optical Engineering; 45, New York, 1994.