Photoluminescence of Lattice Matched AlInAs Layers

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ABSTRACT

The photoluminescence spectroscopy of Molecular Beam Epitaxy (MBE) grown AlInAs layers has been used for the detection of optical transition from an excited electronic state to a lower state usually, the ground state. This technique show that it is a very sensitive tool for investigating both the intrinsic electronic transitions and at impurities and defect at low temperatures.

The photoluminescence spectrum consists of a sharp line that is assumed to be a band to band transitions (which is a sample dependent) and, a broad emission band could be due to substrate InP and / or donor-acceptor transitions.

These results suggest that the peak is due to two emission bands, one is dominated at low temperature. The two bands have different power dependence and therefore this could account for different activation energies. In addition the lattice matched of AlInAs, layers has a band gap of 1.55eV.

INTRODUCTION

Photoluminescence is a non-destructive technique used in the analysis of semiconductors and provides information on both intrinsic and extrinsic semiconductor properties. The emission observed is characteristic of the material. Impurities and defects can have a strong effect on the luminescence observed and most photoluminescence is associated with them. There have been several reviews of photoluminescence[1,2].

There are various electron-hole recombination processes which produce an emission spectrum with many different compounded. The most common recombination transitions are shown [3,4,25,27] figure 1. Because of the mutual attraction between electrons and holes produced by laser excitation, they can exist as excitons which move through the
crystal. Free exciton (X) recombination gives rise to sharp transitions generally and are only seen in very pure material at low temperature[5,26,28,31]. Exitons can be trapped at donors or acceptors in either neutral or ionized states. The bound excitons (D\(^0\),X) and (A\(^0\),X) are the highest energy processes observed as the donor or acceptor concentrations increase from very low levels. (D\(^0\),h) is the recombination of a loosely bound electron on a neutral donor with a hole in the valence band. The energy of the transition is \(E_g - E_d\). For the electron–acceptor transition the energy is \(E_g - E_a\). Where \(E_d\) and \(E_a\) are the donor and acceptor binding energies. The energy of the donor-acceptor (D\(^0\),A\(^0\)) recombination depends on the donor-acceptor separation, \(r\), because of the Coulomb interaction between ionized centers and the energy of the transition is given by:

\[
E(r) = E_g - (E_d + E_a) + \frac{e^2}{4\pi\varepsilon_o e r}
\]

When \(r\) is small, the donor and acceptor will occupy pairs of lattice sites with specific crystallographic directions which give specific values of \(r\) and therefore the energies \(E(r)\) will be discrete. As \(r\) increases, the discrete lines merge to form a continuum. Donor-deep acceptor recombination is generally observed as a broad featureless emission. Note too that the recombination kinetics enable the various processes to be distinguished since excitonic emission will have a single lifetime while pair processes are non-exponentials since the recombination time also depends on the separation.

Figure -1: Schematic diagram of the common recombination transitions [3,4,25,31]
Experimental arrangements

A typical experimental arrangement is shown in figure (2)[6]. The sample was mounted using a small spot of low temperature glue at one corner, to prevent strain in the sample, to a copper plate attached to a sample holder. This was inserted into the exchange gas space of an Oxford Instruments CF204 continuous flow helium cryostat with quartz/sapphire windows. The sample temperature could be continuously varied between 4K and room temperature and controlled using the helium flow and the temperature controller with a thermocouple to ±0.1K.

Figure -2: Block diagram of the experimental arrangement for photoluminescence [31]

The luminescence was excited using a Spectra Physics Argon ion laser and a narrow band pass interference filter was placed before the sample to remove the background infrared emission which originates in the laser plasm.

The luminescence was collected at right angles to the excitation, focused onto the entrance slits of a Spax 1402 double grating spectrometer and detected with a cooled North Coast Germanium p~i~n detector. A 1μm grating was used in first order. The luminescence was isolated from the Argon laser line by a long wavelength pass optical filter and chopped at a suitable frequency for the detector response time, typically 300Hz. The detector signal and a reference signal from the chopper were fed into a Brook deal 9503 lock-in amplifier. The output from the lock-in went to a Victor computer, which recorded the luminescence spectrum as it scanned the spectrometer over the wavelength range of interest.
Sample Details:
A series of twelve samples of $\text{Al}_x\text{In}_{1-x}\text{As}$ on n+ sulphur doped InP substrates were grown by MBE at British telecom Research Laboratories using a Vacuum Generators MB288. Three-chamber MBE system with individual Al (6N), In(7N) and As(6N) effusion cells were used. After solvent cleaning and etching of the substrates, the resulting native oxides were removed prior to growth by heating the substrates to 500-510°C in an As4 flux [7,29]. The clean surface showed (2X4) reconstruction as indicated by RHEED. $\text{Al}_x\text{In}_{1-x}\text{As}$ growth was initiated once this pattern had been observed and the growth rates were typically 0.8~0.9μm/h. Ten of the samples were doped with silicon. The AlInAs layers were between 1 and 2μm thick and the carrier concentrations were between $1 \times 10^{15}$ and $8 \times 10^{16}$ cm$^{-3}$. The indium concentration, x, was nominally 0.52, which is the alloy which lattice matches to InP. X-ray measurements were made on some of the samples and these sampler were all. Indium deficient by up to 2%. The growth parameters are listed in Table 1. In addition to some other parameters are: $\Delta E_C=0.21$eV and $\Delta E_V=0.41$eV[2,25]. There has been much interest in the ternary compound AlInAs as a barrier material for 0.48 and 0.52 heterostructure devices lattice matched InP. It has an advantage since it has a large conduction band discontinuity [1,2,24,29,30], a high refractive index and a lower valence band discontinuity.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate temperature (°C)</th>
<th>Silicon Temperature</th>
<th>Arsenide Temperature (°C)</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>2</td>
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<td>Undoped</td>
<td>448</td>
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</table>

Energy gap of lattice matched AlInAs
A range of values for the room temperature and low temperature band gap of $\text{Al}_{0.48}\text{In}_{0.52}$ As lattice matched to InP have been reported. At room temperature, Lorentz and Onton [8] obtained a value of 1.46eV from cathodoluminescence, while 1.45eV was reported by Wakefeld et al[9]. Using photoluminescence, Olego et al [10] and Nakajima et al
measured the band gap to be 1.47eV and 1.42eV respectively. Low temperature measurements gave a band gap of 1.508eV using cathodoluminescence[9,12] and 1.53eV and 1.56eV using photoluminescence[3,14] have been reported. In all these measurements, the main emission observed in the luminescence spectrum is assumed to be a band to band transition. Wakefield et al [9] made this assignment, because of the agreement within experimental error of the band gap measured by cathodoluminescence at room temperature and that measured by photovoltage spectroscopy[15]. This technique is complementary to cathodoluminescence in that it monitors the absorption of light by the specimen as a function of wavelength. The band gap is determined from the wavelength at which; there is a sudden increase in absorption. However, Praseuth et al[16] observed a pronounced energy shift (equal to or larger than 70meV) between the photoluminescence peak and the maximum in excitation spectroscopy and assigned the main luminescence emission to a band to deep level (possibly acceptor) transition. More recently, Oertel et al[17,24,29,31] used line shape analysis on the photoluminescence spectrum from MOCVD grown Al$_x$In$_{1-x}$As layers to identify the bound exciton emission energy and so obtained an energy gap 1.511eV for Al$_{0.48}$In$_{0.52}$As at 4K. The latter authors assigned the main luminescence emission to the (D$^0$,h) transition.

RESULTS AND DISCUSSION

Figure (3) shows typical low temperature photoluminescence spectra from the Al$_x$In$_{1-x}$As layers. The spectrum consists of a sharp line which varies form 1.52 to, 1.57eV depending on the particular sample (see table 2) and a broad emission. The broad emission could be due to the InP substrate [15,18,23,31] and donor-acceptor transitions in the AlInAs layer [12,17,28,31]. The ratio of the peak intensity of the sharp line and the broad emission is also sample dependent. The spread in the peak energy of the sharp feature could be due to the variation in the indium mole/fraction, although, this explanation is inconsistent with x-ray measurements, since there is significant variation in the peak energy for samples with the same mole fraction. The width of the photoluminescence peak of between 16 and 26meV is typical of MBE grown material[9,15,30,31] although significantly broader than the theoretical line widths limited by alloy broadening[19]. Welch et al [20] showed that for undoped MBE layers, the line width is broadened due to degraded crystalline structure. Temperature dependent photoluminescence measurements were performed and a thermal activation energy of the order of 31meV was obtained for the sharp.
A feature (see table 2) a thermal activation energy of 17meV was obtained by Ferguson et al[21]. The peak energy of this emission decreases up to 35K and then increases. This suggests that the peak is due to two emission bands, one dominates at low temperature. It has been shown that these two bands have different power dependences[21,22,32] and therefore this could account for the different activation energies.

The photoluminescence measurements using photon counting were made for two sampler and a weak emission feature at higher energy was observed (see figure 4) for both samples, tills features was about 40meV higher in energy than the main emission. Oertel et al[17] observed an energy difference of about 30meV between the main feature and a "much weaker feature at higher energy, which they assigned to (D^0,h) and (D^0,x) respectively.

In conclusion, it was noted that the photoluminescence measurements suggest that a band gap of 1.55eV for lattice matched AlInAs layers, at low temperatures.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Peak energy (eV)</th>
<th>FWHM(meV)</th>
<th>Activation energy (meV)</th>
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Fig-3: Photoluminescence spectrum for a MBE grown AlInAs layer (T = 4K)
Photoluminescence of Lattice Matched AlInAs Layers

Fig. 4: Photoluminescence spectrum for an MBE grown AlInAs layer using photon counting.

Wavelength (nm)

Luminescence Intensity (arb. units)

1.557 eV
1.515 eV
x200
REFERENCES
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