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InGaAs *p-i-n* photodiodes for fibre-optic communication

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Abstract. High purity layers of $In_{1-x}Ga_xAs$ have been grown by liquid phase epitaxy using a novel impurity gettering technique with rare earth atoms. The electron concentration could thus be decreased from $3 \times 10^{18}\,cm^{-3}$ to $2{\cdot}4 \times 10^{15}\,cm^{-3}$ and the mobility increased from $7\,110\,cm^2/Vs$ to $18{,}981\,cm^2/Vs$ (100 K). The excellent quality of the layers has been evidenced by X-ray diffraction and photoluminescence measurements. The fabrication of *p-i-n* photodiodes using this technique is described and reliability aspects addressed.

Keywords. Liquid phase epitaxy; photodiodes; InGaAs; fibre-optic detector.

1. Introduction

$In_{0{\cdot}53}Ga_{0{\cdot}47}As/InP$ *p-i-n* photodiodes are widely used as detectors in fibre-optic communication systems at wavelengths of 1·3 and 1·55 μm. The choice of this system is based on (i) the band-gap of the ternary being 0·75 eV, corresponding to a cut-off wavelength of 1·6 μm, and (ii) the lattice-matching to InP substrates possible for this particular composition. Since InP itself has a higher band-gap of 1·35 eV it is transparent to the radiation and hence photodiode operation is possible with either top illumination or through the substrate. The ternary compound comprises a thin single crystal layer grown on InP by one of a number of growth techniques: liquid phase epitaxy (LPE), hydrite vapour phase epitaxy (VPE) or metal–organic vapour phase epitaxy (MOVPE). The latter processes have the advantage of providing lower carrier concentration i.e. higher purity, slower growth rate and better surface morphology over larger areas. However, as they are more complex and expensive, commercial production of these devices is still based to a large extent on LPE. This is a process of growth by slow cooling of a solvent in contact with a substrate, the solute being the desired component of the epi-layer. For *p-i-n* photodiodes the growth of the high purity layer is the prime concern.

This paper describes a novel gettering technique using the rare earth Dy for obtaining low carrier concentration and high mobility epitaxial InGaAs on InP. The characterisation of electrical and optical properties of these layers is described establishing their high quality.

2. Experimental

A graphite horizontal multi-bin boat is conventionally used for LPE of III–V compounds. The boat is contained in a transparent gold-coated furnace with a constant temperature zone of 10 cm controlled to $\pm 0{\cdot}1$°C and capable of being changed linearly at 0·1–10°C. Ultra high purity hydrogen flow maintains a reducing ambient. (100) Fe-doped InP substrates ($\rho > 10^7$ ohm-cm, 1·0 cm × 1·0 cm) are used with high purity In as solvent, the solute being InAs and GaAs in desired proportions as determined from the phase diagram.

The purity of the epitaxial layer is determined by the impurity of the solvent and the solute, and also the possible impurities in the graphite boat and the ambient. Great care is taken in cleaning and prolonged baking of the boat and the growth material. Nevertheless trace amounts of impurities are enough to cause unintentional doping. Such dopants, typically Si from the growth tube and chalcogens from the source compounds, form the principal contaminants. Prolonged baking up to 100 hours is often used to reduce background doping concentration from $10^{17}\,\mathrm{cm}^{-3}$ to $10^{15}\,\mathrm{cm}^{-3}$. Another technique is the introduction of controlled amounts of water vapour to oxidise and remove the residual Si.

A new technology evolved over the last 7–8 years involves the introduction of minute quantities of rare-earth elements such as Yb, Gd, Y, Ho or Dy which are found to reduce the background carrier concentration. These rare earths are known for their strong affinity towards oxygen. Gorelenok *et al* (1984) concluded that the addition of the rare-earth atoms reduces the concentration of background chalcogenide dopants S, Se and Te by forming rare-earth chalcogenides whereas the reduction of Si is only marginal. Kumar & Bose (1992), however, showed through SIMS studies on LPE-grown InP that the predominant donor impurity is Si and photoluminescence shows that adding Dy in the melt reduces the Si content.

For the present study the high purity graphite boat was heated at 1200°C for 10 hours in vacuum to reduce residual impurities. The In melt was prebaked in ultra-pure hydrogen for three hours. The polycrystalline GaAs and InAs added to the melt were nominally undoped. Growth was carried out after 10–12 seconds etch back in pure In to remove any surface damage in the substrates which were either (100) semi-insulating or Sn-doped with $n = 10^{15}$–$10^{16}\,\mathrm{cm}^{-3}$. Growth was carried out between 638–631°C with a cooling rate of 0·4°C/min for 10 minutes with 3°C supercooling. The layer thickness measured was 5 μm, within 10% of the calculated value. The Dy content was varied in steps from 0 to 8×10^{-4} atomic fraction. Without Dy the donor concentration determined through resistivity and Hall effect was $1{\cdot}2 \times 10^{18}\,\mathrm{cm}^{-3}$ while the electron mobility was 3920 cm^2/Vs (300 K). As shown in table 1 the

Table 1. Electrical properties of InGaAs epilayers.

Sample no.	At. fraction Dy	ρ (Ω-cm)	$N_D - N_A$ (cm^{-3})	μ(300 K) (cm^2/Vs)	μ(83 K) (cm^2/Vs)
AD-1	0	$1{\cdot}28 \times 10^{-3}$	$1{\cdot}2 \times 10^{18}$	3920	7110
ADR-1	8×10^{-5}	$4{\cdot}18 \times 10^{-3}$	$3{\cdot}7 \times 10^{17}$	3970	7418
ADR-2	2×10^{-4}	$7{\cdot}25 \times 10^{-3}$	$1{\cdot}9 \times 10^{17}$	4384	8050
ADR-3	5×10^{-4}	$1{\cdot}65 \times 10^{-1}$	$6{\cdot}2 \times 10^{15}$	6069	12,500
ADR-4	6×10^{-4}	$3{\cdot}49 \times 10^{-1}$	$2{\cdot}4 \times 10^{15}$	7452	18,981
ADR-5*	8×10^{-4}	$4{\cdot}77 \times 10^{-1}$	$1{\cdot}2 \times 10^{15}$	106	150

**p*-type

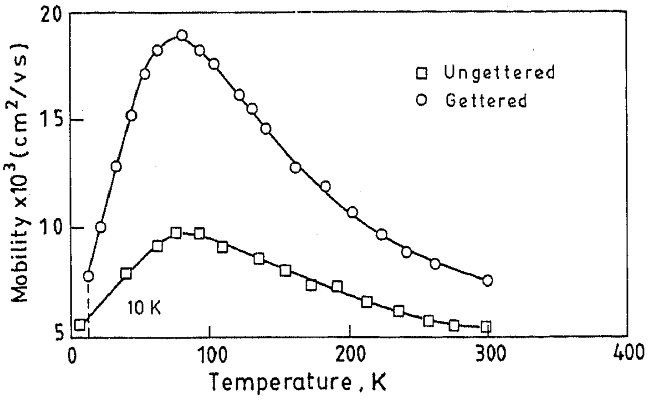

Figure 1. Temperature vs mobility for $In_{0\cdot53}Ga_{0\cdot47}As$ (AD-1 & ADR-4).

maximum mobility obtained was 7452 cm^2/Vs (300 K) and 18,981 cm^2/Vs (83 K) corresponding to a Dy concentration of 6×10^{-4} atomic fraction. The carrier concentration was $2\cdot4 \times 10^{15}$ cm^{-3}. For additional Dy the epilayer became p-type with hole mobility 106 cm^2/Vs (300 K).

The variation of mobility with temperature for the high purity (gettered) and ungettered layers is shown in figure 1. At $T < 80$ K the mobility $\mu \alpha\ T^{1\cdot33}$ is characteristic of impurity scattering whereas at $T > 100$ K $\mu \alpha\ T^{-2\cdot04}$ is due to polar optical phonon scattering. The mobility maximum is limited by alloy scattering which varies as $T^{-0\cdot48}$. A detailed analysis shows that for $In_{1-x}Ga_xAs$

$$\mu_{\text{alloy}} = \{182400/|\Delta U|\}\ T^{-0\cdot5}$$

where $|\Delta U|$ = alloy scattering potential, is $0\cdot95 \pm 0\cdot05$ eV.

The mismatch between the epitaxial $In_{1-x}Ga_xAs$ layer and the InP substrate can be measured very accurately using the double crystal X-ray diffraction technique. This was carried out for a series of layers. A typical result given in figure 2 shows two

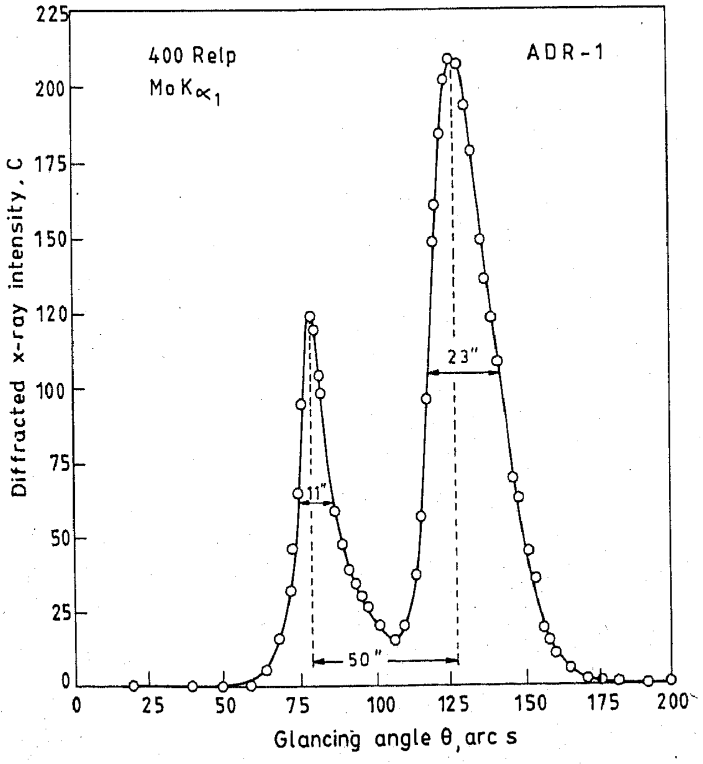

Figure 2. DXRD for InGaAs on InP substrate ($\Delta a/a = 8\cdot4 \times 10^{-4}$).

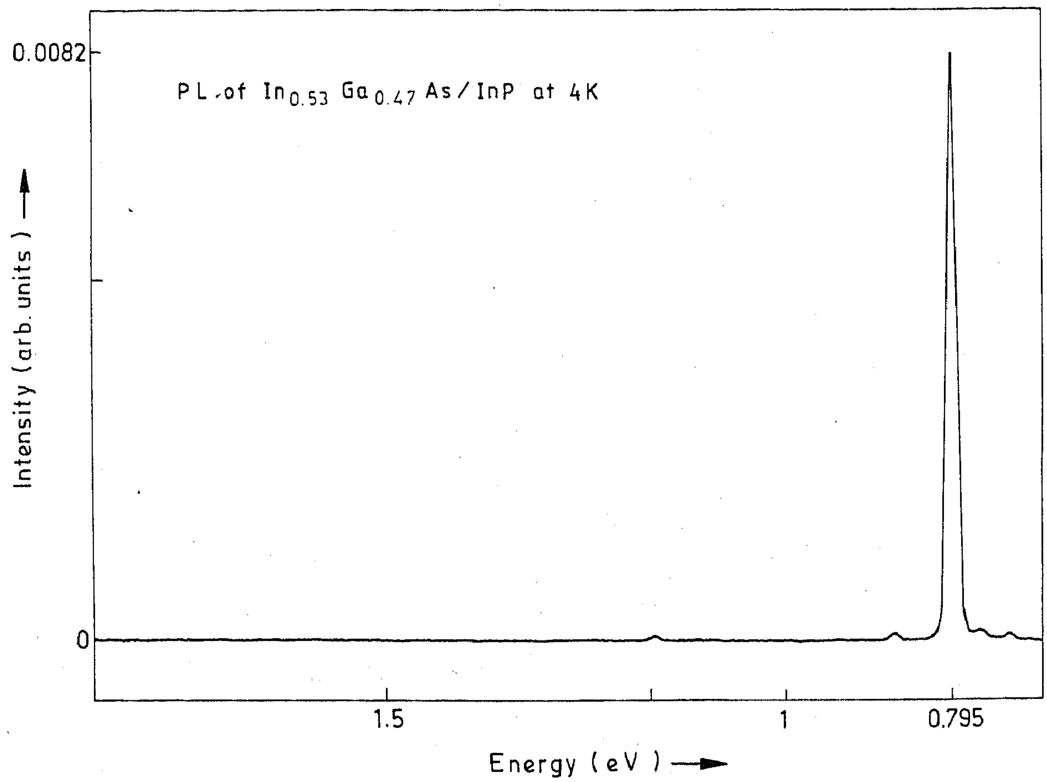

Figure 3. A typical photoluminescence spectra of $In_{0.53}Ga_{0.47}As/InP$ at 4 K.

diffraction peaks with half width at full maximum (FWHM) of 11 arc s for the substrate and 23 arcs for the epilayer, the difference of 50 arcs corresponding to a lattice mismatch of $9{\cdot}73 \times 10^{-4}$. Another index of the quality of the epilayer is obtained from the half-width of the photoluminescence peak at 4 K (figure 3) which is very low, decreasing systematically with carrier concentration from 33 meV to 11 meV for n decreasing from $3 \times 10^{18}\,cm^{-3}$ to $2{\cdot}4 \times 10^{15}\,cm^{-3}$.

3. Discussion

The reduction of carrier concentration in the epitaxial layer is due to gettering of impurities by Dy. In this case since the principal impurity is Si, silicides such as Dy_3Si_5 and $DySi_2$ are considered to form and remain in the melt. The atomic size of Dy is not conducive to its incorporation in the epitaxial layer and has not been reported. Another remarkable finding is the reduction in the etch pit density in InP due to Dy gettering which may be due to gettering of O.

The above technique was used to grow high purity InGaAs with only 3 hours baking of the melt followed by growth of a Zn-doped p^+ InGaAs layer of thickness of $1{\cdot}0\,\mu m$. This is the structure required for a *p-i-n* photodiode. For this device the top ohmic contact was made by evaporating Au–Zn alloy and the bottom contact by using In–Sn. Si_3N_4 antireflection film (~ 1000 Å) by plasma enhanced CVD (PECVD) was used to increase the quantum efficiency. The I–V characteristics of such a device showed low reverse saturation current density of $2\,\mu A$. The gettered InGaAs showed a large photoconductive response which has been studied as a function of temperature.

4. Passivation and reliability

Two types of device structures have been widely used for the fabrication of *p-i-n* photodiodes: mesa and planar. The former are easier to fabricate and provide low capacitance due to their smaller areas rendering them suitable for high frequency applications. The exposed *p-n* junction of these devices however requires careful passivation to provide low leakage current and good long-term stability. The planar structure has the advantage of a protected junction with a capping layer leading to lower leakage current and better long term stability.

Recently a two-step SiN_x passivation of mesa photodiodes has been shown to give very low leakage current. This is realised by simultaneous hydrogenation and nitridisation of the mesa surface.

A detailed study of mesa and planar diodes has been reported recently by Skrimshire *et al* (1990). The epilayers were grown by LPE, hydride VPE and MOVPE. While the initial dark current of mesa photodiodes was low (4 nA), life testing at 70° and 125°C under 5 V bias caused rapid fluctuations and deterioration in a few hours. The planar *p-i-n* diode on the other hand withstood $2{\cdot}5 \times 10^6$ hours under similar conditions and 10^4 hours at 200°C. Polyimide passivation of the mesa diodes resulted in some improvement i.e. stability of upto 10^3 hours at 150°C but these diodes remained inferior to the planar photodiodes. This study has shown clearly the desirability of planar structures with proper passivation for obtaining highly reliable diodes.

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