Investigation of molecular beam epitaxial $In_{0.53}Ga_{0.47}As$ regrown on liquid phase epitaxial $In_{0.53}Ga_{0.47}As/InP$

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Molecular beam epitaxial $In_{0.53}Ga_{0.47}As$ regrown on high-purity liquid phase epitaxial $In_{0.53}Ga_{0.47}As$ has been investigated. The regrown layers have been characterized by Hall measurements, low-temperature photoluminescence, and deep level transient spectroscopy. The regrown layers have properties comparable to material directly grown on InP substrates.

I. INTRODUCTION

Single $In_{0.53}Ga_{0.47}As$ layers lattice matched to InP substrates and $In_{0.53}Ga_{0.47}As$–$In_{0.52}Al_{0.48}As$ heterostructures are currently being grown by molecular beam epitaxy (MBE) for electronic and optoelectronic device applications.[1–4] For integrated optics it is sometimes necessary to regrow MBE semiconductor layers, after some intermediate processing steps, on the original epitaxial layers. For monolithic integration, it is useful to fabricate avalanche or photoconductive detectors with high-purity liquid phase epitaxial (LPE) layers and make the electronic device on MBE-grown heterostructures. However, such regrowth can result in a large density of interface defects.[5,6] In this paper we report the successful regrowth of MBE $In_{0.53}Ga_{0.47}As$ on the same ternary grown by LPE.

II. MOLECULAR BEAM EPITAXIAL REGROWTH

Fe- and Sn-doped (100) InP substrates were used for LPE and MBE growth. 5–10 μm thick ternary layers were grown by liquid phase epitaxy using standard step-cooling techniques.[7] The undoped layers are characterized by $n_{300\ K} = (1\text{–}2)\times 10^{15}$ cm^{-3}, $\mu_{300\ K} = 10\,000\text{–}11\,000$ $cm^2/V\ s$, and $\mu_{77\ K} = 40\,000\ cm^2/V\ s$.

Molecular beam epitaxial growth of the ternary layers were accomplished in a three-chamber Riber 2300 epitaxy system. System and source preparation have been described by us in detail in an earlier publication.[8] 6 N purity In from Johnson–Matthey and Mitsubishi were used for MBE and LPE growth.

The LPE InGaAs layers were mounted on Mo sample holders with In. Native surface oxides were desorbed under As_4 flux at 580–600 °C until a clear streaked RHEED pattern was observed. Single InGaAs layers, InGaAs–InAlAs modulation-doped heterostructures and InGaAs p^+–n diode structures were regrown on the LPE-grown ternary layers. Similar layers were also directly grown by MBE on InP substrates for comparison. InGaAs and InAlAs layers were grown at a rate of 1.5 $\mu m/h$ with $T_{sub} = 450\text{–}470$ °C. The V/III beam equivalent pressure ratio during growth was typically 30. After initiation of growth a c(2×4) surface reconstruction pattern was observed on the RHEED screen. Be and Si are used as *p*- and *n*-type dopants, respectively. Schematics of directly grown and regrown modulation-doped heterostructures are shown in Fig. 1.

III. RESULTS AND DISCUSSION

Carrier concentrations and mobilities for various types of samples are listed in Table I. Nearly equivalent mobilities are obtained at room temperature with and without AlInAs (0.5 μm) and with LPE InGaAs buffers. On the other hand, the electron concentration in sample UM232 at room temperature is slightly higher. We believe this is due to a reduction of compensating acceptors diffusing from the substrate. This was confirmed from several growth runs. The parameters in the regrown layers were computed by taking into account parallel conduction in the LPE ternary layer. It may be noted that the first two samples listed in Table I were grown with Johnson–Matthey In, while the other two were grown with Mitsubishi In. The electron concentration in all the samples falls almost an order in value on lowering the temperature to 77 K. The effect is independent of the In source. From the $n_H - 1/T$ plots, a level with activation energy of 28–30 meV is detected. We believe this is a donor level which is characteristic of MBE-grown InGaAs and is related to growth conditions.

Figure 2 shows the measured temperature dependence of mobility in modulation-doped heterostructures. The two samples were grown with different sources of In. While the mobilities in the directly grown structure are among the best that have been reported, the mobilities in the regrown structure are lower. It is thought that the reason is partly due to

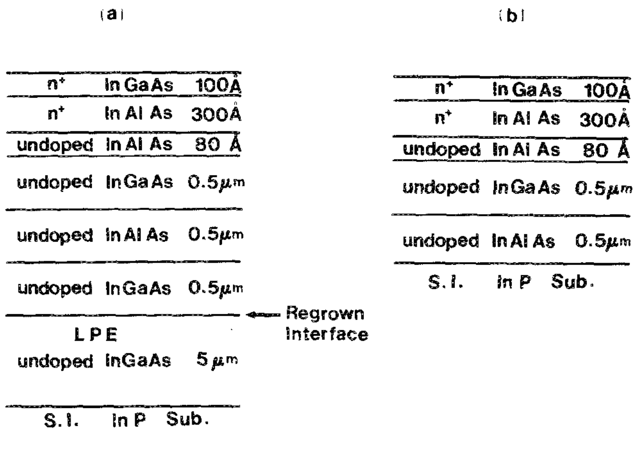

FIG. 1. Schematic diagrams of (a) regrown MBE InGaAs–InAlAs modulation-doped heterostructures on undoped LPE InGaAs, and (b) directly grown modulation doped heterostructure on InP substrates.

TABLE I. Electrical properties of MBE InGaAs.

Sample	Buffer layer	μ_H at 300 K (cm^2/V s)	n_H at 300 K (cm^{-3})
UM160	···	10 000	3.9×10^{15}
UM190	InAlAs	8000	5.5×10^{15}
UM241	InAlAs	9100	5.7×10^{15}
UM232	LPE InGaAs	8100	9.6×10^{15}

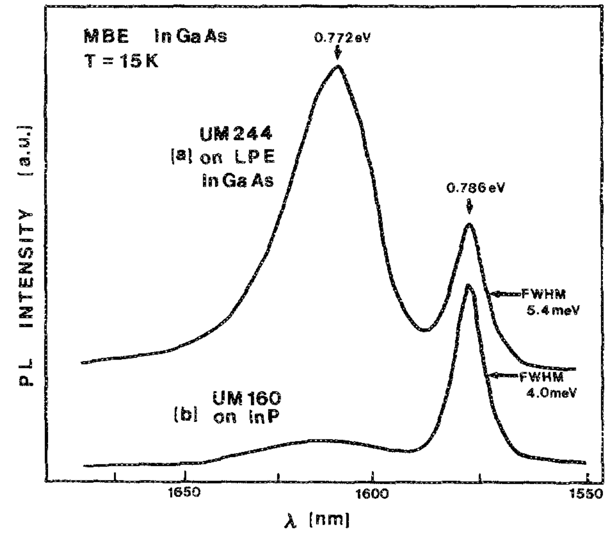

FIG. 3. Low-temperature photoluminescence spectra of (a) regrown and (b) directly grown In$_{0.53}$Ga$_{0.47}$As.

different sources of In. Our results demonstrate that high-mobility modulation-doped structures can be regrown on LPE buffers.

Photoluminescence spectra measured at 15 K on regrown and directly grown InGaAs are shown in Fig. 3. The spectrum of the directly grown layer is characterized by a bound exciton transition with FWHM = 4.0 meV. This is the smallest value obtained, even in comparison with previously reported data recorded at lower temperatures.[1] The large peak in the spectrum of the regrown layer, separated by $\simeq 14$ meV from the bound exciton peak, may be partially vacancy related,[1] but is probably more due to Zn and Si impurities originating from the In used.

Deep level transient spectroscopy (DLTS) measurements were performed on the regrown InGaAs layers to ascertain the nature of deep level traps present in the MBE layers and at the regrowth interface. For the purpose of this study a 5–10 μm thick LPE In$_{0.53}$Ga$_{0.47}$As layer was grown over a Sn-doped n^+ InP substrate, followed by a 0.7 μm unintentionally doped n-type In$_{0.53}$Ga$_{0.47}$As layer grown by MBE. Finally, a 1.0 μm thick Be-doped ($p \sim 2\times10^{18}$ cm^{-3}) InGaAs layer was grown by MBE for the fabrication of $p^+ - n$ diodes. Devices with 150–250 μm diameter were delineated by standard photolithography. The electron concentration profile through the regrown interface was measured in a number of devices by capacitance–voltage measurement. As expected, the electron concentration falls in going from the MBE side to the LPE side. In addition, a small depletion of carriers is observed at the interface. A similar effect has been previously reported.[5,6]

Typical DLTS data for a diode with applied reverse bias values of − 1.0 V and − 6.0 V are shown in Fig. 4. At − 1.0 V bias the depletion region is within the MBE layer, and the peaks B and C correspond to traps in MBE In$_{0.57}$Ga$_{0.47}$As with activation energies of 0.18 and 0.30 eV, respectively. However, with increased reverse bias, these two peaks shift

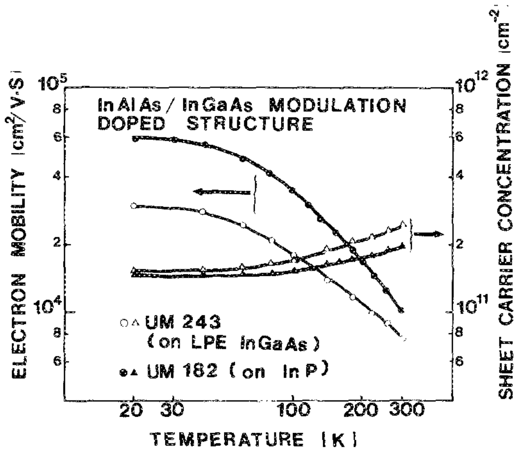

FIG. 2. Temperature dependence of Hall mobility and sheet electron concentration in directly grown and regrown InGaAs–InAlAs modulation doped structures.

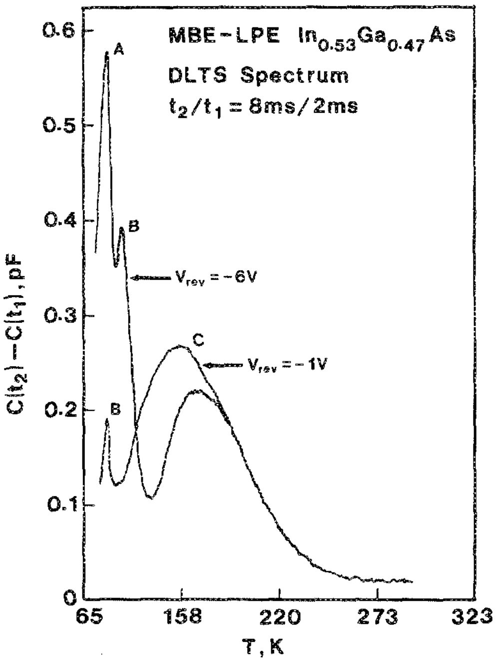

FIG. 4. DLTS data showing electron traps in LPE- and MBE-grown regions of hybrid layers. The interface region is penetrated by increased reverse bias applied to the diode.

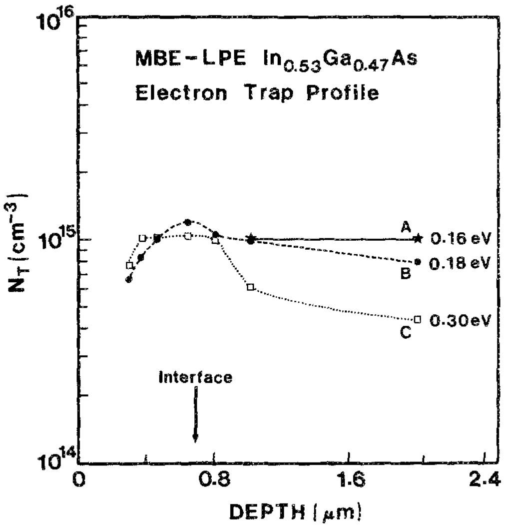

FIG. 5. Concentration profiles of traps observed in MBE- and LPE-grown regions of hybrid layers.

slightly towards higher temperatures and a third peak, A, corresponding to a trap with activation energy 0.16 eV, appears. Since we could not lower the sample temperature below 77 K, it was not possible to ascertain the presence of trap A in the MBE layers using smaller reverse bias. The concentration profiles of the three traps are depicted in Fig. 5. It is apparent that traps B and C are characteristic of both LPE and MBE $In_{0.53}Ga_{0.47}As$. This cannot be said of trap A at present. The apparent increase of the concentrations of traps B and C at the regrowth interface is probably due to carrier-depletion effects at the interface.[5] Trap A (0.16 eV) is similar to the 0.16 eV electron trap in LPE material reported by Forrest and Kim.[9] Traps B and C are being observed for the first time and they were also detected by us in MBE material grown directly on InP substrates. Origins of these two traps are uncertain at the present time and are being investigated.

In conclusion, we have successfully demonstrated regrowth of high-quality $In_{0.53}Ga_{0.47}As$ by MBE on the same ternary grown by LPE. The transport properties in regrown single layers and modulation-doped heterostructures are comparable to directly grown samples. No additional deep level traps are created at the regrowth interface.

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