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Impurity reduction in $In_{0.53}Ga_{0.47}As$ layers grown by liquid phase epitaxy using Er-treated melts

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Hall mobility and carrier concentration measurements are done on $In_{0.53}Ga_{0.47}As$ layers grown by liquid phase epitaxy from melts containing 0.1–0.18 wt % Er. The carrier concentration in the layer decreased to $2\times10^{14}\,cm^{-3}$ upon the addition of 0.16 wt % Er to the growth melt but the corresponding mobility of the layer increased only marginally. A detailed analysis of the temperature-dependent Hall mobility data for the samples using a theoretical curve fitting technique revealed that the donor impurities in the material are reduced to a greater extent compared to the acceptors, making the layers compensated. The experimental mobilities are further compared with the published values of theoretically calculated mobilities for InGaAs with similar compensations. It is shown that the space charge scattering effects are to be considered in order to get a good agreement between the experimental and the theoretical values. © *2000 American Institute of Physics.* [S0003-6951(00)03212-5]

Er is getting increased attention in semiconductor optoelectronics because of its ability to produce stable optical emission at 1.55 μm when used as a dopant in III–V compound semiconductors.[1–3] Er and other rare earth metal dopants can also greatly reduce the residual impurities in III–V epitaxial layers grown by liquid phase epitaxy (LPE) when added in minute quantities to the growth melt. This is a great advantage as it reduces the otherwise long-time high temperature melt baking schemes required for getting high purity layers by LPE. Impurity reduction by Er has been observed in many LPE-grown III–V compounds such as GaAs,[4] InP,[5] InGaAsP,[6] and InGaAs.[7] In all these reports, however, the general reduction of impurities has been emphasized but no study has been made so far to clarify the gettering action of Er on donor and acceptor type impurities separately. In some of the earlier studies,[8] it was noted that the as-grown *n*-type material became *p* type after the addition of Er to the growth melt indicating that Er gettering is probably more effective for reducing the donors. Gao *et al.*[7] observed an extremely low *n*-type carrier concentration in $In_{0.53}Ga_{0.47}As$ layers grown by LPE from Gd-treated melts but the mobility did not show the expected enhancement for apparently such high purity materials. The authors suggested that the layers were compensated due to a greater reduction of the donors compared to the acceptors. From photoluminescence studies, we have shown earlier[9] that Er reduces both types of impurities in LPE-grown InGaAs layers but a quantitative assessment of such reduction could not be made. In this study, we have used a temperature-dependent Hall effect measurement technique and a theoretical curve fitting procedure to determine the residual donor and acceptor concentrations in InGaAs layers grown by LPE from melts containing Er. The resultant compensation in the layers has been calculated and attempts have been made to use the data for explaining the observed low mobilities in such layers.

The details of our LPE technique for the growth of InGaAs layers from Er containing melts have been reported earlier.[9] In this work, we have used layers grown from melts containing 0.1–0.18 wt % Er. Er is added to a melt which has already been baked at 700 °C for 20–25 h and an additional 5 h baking at 750 °C is used to assist the Er gettering of the impurities. For Er content above 0.17 wt % in the growth melt, the grown layers showed scattered microparticles on the surface which were earlier attributed to precipitated ErAs.[10]

Rutherford backscattering (RBS) technique was used to check the composition and also to identify the presence of any Er in the material. Figure 1 shows the RBS spectrum for a layer grown from a melt containing 0.18 wt % Er. The Er

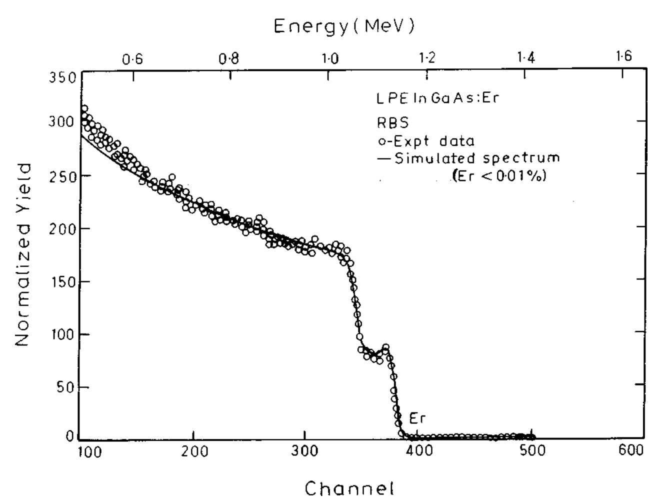

FIG. 1. RBS spectrum for an InGaAs layer grown from a melt containing 0.18 wt % Er. The open circles are experimental data whereas the solid line is a theoretical fit.

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TABLE I. 77 K Hall mobilities and corrected carrier concentrations of InGaAs layers grown from Er-treated melts.

Sample No.	Er (wt %) in growth melt	Melt bake after Er addition (h)	77 K Hall mobility (cm^2/V s)	Carrier concentration (n) (cm^{-3})
230	0.1	5	29 281	4.4×10^{15}
231	0.16	5	37 230	2×10^{14}
234	0.16	9	41 760	3×10^{14}

detection limit of the RBS system was 0.01% and we could not find any Er-related peak in the spectrum indicating that the resultant Er content in the material must be below this limit. From the usual curve fitting procedure, the In content in the layer was obtained as 53%.

Hall measurements in the range 77–300 K were done on 3–4 mm^2 Van der Pauw samples with alloyed In–Sn contacts applied at the four corners. In all measurements, a magnetic field of 2800 G was used. Three InGaAs samples, labeled 230, 231, and 234 were used in the study. Sample 230 was grown from a melt containing 0.1 wt % Er. Samples 231 and 234 were grown from the same melt containing 0.16 wt % Er. However, after the growth of sample 231, the melt was subjected to an additional 4 h bake at 750 °C and then used for the growth of sample 234. Samples 231 and 234 exhibited very low carrier concentrations near $10^{14}\,cm^{-3}$ and, for them, corrections due to surface depletion and effective thinning of the conducting channel were necessary.[11] The surface depletion width at different temperatures were calculated from the corresponding InGaAs band bending potentials which were, in turn, calculated from the surface Fermi level pinning potential of about 0.2 V for InGaAs.[12] Further, the measured carrier concentrations were corrected for the temperature dependence of the Hall factor.[13] The corrected carrier concentrations for each sample were almost independent of temperature as is expected for the full ionization of the donors.

Table I lists the 300 and 77 K Hall mobilities of the samples alongwith their corrected carrier concentrations. Free carrier concentrations in both 231 and 234 are reduced by one order of magnitude compared to that in sample 230. This reflects the very effective impurity gettering action of Er. However, the corresponding increase of mobility in samples 231 and 234 is much less than what one would expect for such ultrapure materials. This observation is similar to that of Gao *et al.*[7] and can be supported only by assuming a high compensation for the layers. In order to get a more clear picture of the situation, we did a detailed analysis of our measured temperature-dependent Hall mobility data considering the important scattering mechanisms in the material, *viz.* ionized impurity scattering, polar-optic phonon scattering, alloy scattering, and space charge scattering. We have used the expressions derived by Brookes,[14] Petritz and Scanlon,[15] Tietzenand and Weisberg,[16] and Conwell and Vassel[17] for calculating the mobilities limited by the earlier four kinds of scattering mechanisms, respectively.

Figure 2 shows the temperature dependence of the Hall mobility and carrier concentration for sample 231. The other two samples showed similar behavior. The solid circles in the figure are the experimental data whereas the continuous

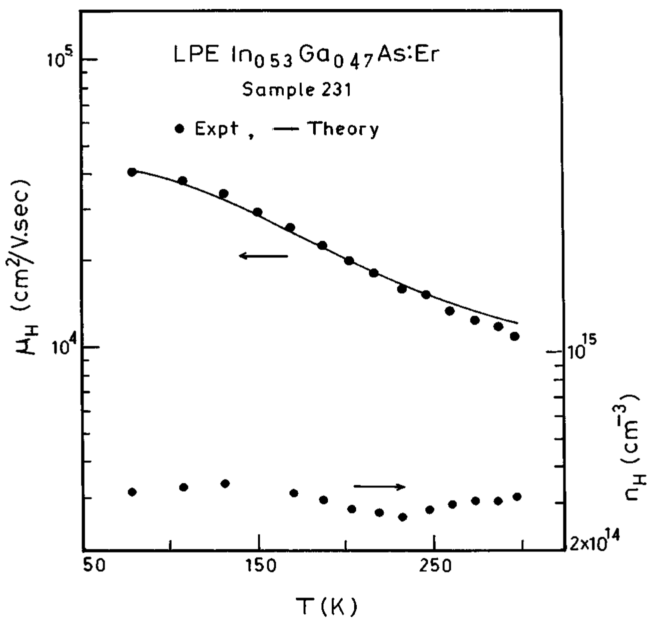

FIG. 2. Temperature dependence of the Hall mobility (μ_H) and the carrier concentration (n) for InGaAs sample 231 grown from a melt containing 0.16 wt % Er. The solid circles in the figure represent experimental data whereas the continuous line is a theoretical fit.

curve represents the theoretically expected variation of the mobility limited by the earlier scattering mechanisms. Fitting of the theoretical curve with the experimental points was done by assuming the values of the donor concentration N_D, acceptor concentration N_A and the space-charge-density-scattering-cross-section product N_SQ for each sample. Table II gives the assumed values the earlier three parameters for obtaining best fit of the theoretical data with the experimental ones, along with the calculated compensation ratio for each sample. Two important observations can be made from the data of Table II. First, Er reduces both the donor and the acceptor type impurities in the material. However, the donors are reduced by a much larger ratio compared to the acceptors so that the net compensation in the material increased from 1.7 in sample 230 to 9 in sample 231. Additional bake of the growth melt reduced the acceptors further and the compensation in sample 234 is lowered to 5. In Table III, we compare our measured 300 and 77 K mobility data with that calculated by Takeda[18] for similar free carrier concentrations and compensation ratios. 300 K values show reasonable agreement within experimental errors. However, the 77 K mobilities calculated by Takeda are much higher than our experimental values even after considering the compensation in the materials. One plausible argument is that Takeda did not take into account mobility reduction by space charge scattering in his calculations. Space charge scattering was

TABLE II. Values of N_D, N_A, N_SQ, and compensation ratio for InGaAs layers grown from Er-treated melts, obtained from the theoretical curve fitting of the experimental data.

Sample No.	N_D (cm^{-3})	N_A (cm^{-3})	N_SQ ($10^4\,cm^{-1}$)	Compensation Ratio $(N_D+N_A)/n$
230	6×10^{15}	1.4×10^{15}	2	1.7
231	1×10^{15}	8×10^{14}	2	9.0
234	9×10^{14}	6×10^{14}	2	5.0

TABLE III. Experimental values of the mobilities of InGaAs layers grown from Er-treated melts, compared with the theoretically calculated values of Takeda (see Ref. 18).

Sample No.	Compensation ratio	Experimental Hall mobility		Calculated Hall mobility	
		300 K	77 K	300 K	77 K
230	1.7	10 950	29 281	12 000	40 000
231	9.0	12 000	37 230	14 000	60 000
234	5.0	11 500	41 760	14 000	70 000

recognized as an important ''mobility killer'' in GaAs[17] and was attributed to impurity fluctuations in the material. Kotada *et al.*[19] have shown that inclusion of the space charge scattering term is essential to get a proper fit of the theoretically calculated mobilities in $In_{0.53}Ga_{0.47}As$ with the experimental values. The authors suggested that this particular kind of scattering, with the same kind of temperature dependence as the alloy scattering, is associated with space charge regions surrounding structural defects or local composition fluctuations in the material. In InGaAs layers, grown from Er containing melts, the space charge scattering is likely to be more dominant due to enhanced surface defects associated with precipitated Er, for larger Er contents. In our calculations, a value of $N_s Q = 2\times 10^4\ \text{cm}^{-1}$ had to be assumed to fit the theory with the experiment. Further, we can note that for an assumed value of $N_s Q = 1.5\times 10^4\ \text{cm}^{-1}$, Takeda's 77 K, mobilities corresponding to our samples 230, 231, and 234 in Table III, modified by the inclusion of space charge scattering give the values of 28 480, 37 342, and 40 986 $\text{cm}^2/\text{V s}$ which are very close to our experimental data.

In conclusion, we have done a detailed Hall analysis of InGaAs layers grown by LPE from Er-treated melts and obtained the values of the residual donor and acceptor concentrations in the same. We have shown that the donors are reduced more drastically compared to the acceptors as a result of Er addition to the growth melt and the compensation in the grown layers is increased. The increased compensation accounts for the observed low mobilities in these materials. Er or rare-earth-treated III–V compounds, in general, may not therefore be very attractive for applications where very high purity as well as high mobility materials are required.

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