# Electron mobility in $In_x Ga_{1-x}$ As alloys

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The conductivity and Hall coefficient of *n*-type alloys of  $In_xGa_{1-x}As$  ( $0 \le x \le 0.25$ ) have been measured at temperatures in the range 77-300 K. The crystals were grown from the vapor phase on insulating GaAs substrates and had electron concentrations of  $1-6 \times 10^{15}$  cm<sup>-3</sup>. At room temperature the mobilities show no strong variation with alloy concentration. The data have been analyzed to determine the effect on the mobility of the scattering due to disorder, which is found to be of the order estimated from a simple theory due originally to Brooks. Below 120 K the scattering due to disorder dominates the phonon scattering for samples having more than 10-at.% InAs.

## **I. INTRODUCTION**

Single-phase solid solutions of In<sub>x</sub>Ga<sub>1-x</sub>As alloys may be prepared over the complete compositional range<sup>1</sup>  $0 \le x \le 1$ . Optical-absorption measurements show that the band gap varies monotonically<sup>1-4</sup> from GaAs to InAs, and is believed to remain direct in the alloy system. Measurements reported of the transport properties in the alloys indicate the need for further study, since work with material of large impurity concentrations (of the order of  $10^{17}$  cm<sup>-3</sup>) suggests that the electron mobility is seriously degraded on alloying small amounts of InAs (several percent), <sup>5</sup> whereas recent measurements on purer material show fairly high mobilities<sup>6</sup> at 77 K in the alloys. Because of the strong interest in this alloy material for a number of applications (infrared detectors, lasers, <sup>7</sup> photocathode material<sup>4</sup>), a study was undertaken to measure the electron mobilities in fairly pure material and to draw conclusions regarding the scattering mechanisms in these alloys.

Alloy crystals have been prepared both by growth from the melt<sup>1,3,5</sup> and from the vapor.<sup>4,6,8</sup> It is difficult to prepare homogeneous alloys from the melt because of the large difference between the liquidus and the solidus in the phase diagram<sup>1</sup>; in addition, melt-grown alloys generally have unintentional donor concentrations greater than the  $\sim 10^{16}$ -cm<sup>-3</sup> range. In contrast, vapor-growth techniques result in quite homogeneous alloys of arbitrary composition. Because of the higherpurity reagents available and the lower growth temperatures which can be used, significantly lower donor concentrations can be achieved.

#### **II. EXPERIMENTAL PROCEDURE**

The In, Ga1-, As alloys were grown using procedures and equipment which have been described previously.<sup>4,9</sup> Separate metallic In and Ga metal sources were used to assure that a constant composition is maintained during the growth of the epitaxial layer; a single In-Ga metal alloy source is undesirable because preferential depletion of the Ga with time<sup>10</sup> changes the InCl-to-GaCl ratio and thus the alloy composition. High-purity HCl transports the In and Ga as the metal monochlorides<sup>10,11</sup> to the deposition zone, where they react with the thermal decomposition products of AsH<sub>3</sub>, principally As<sub>2</sub> and As<sub>4</sub>, to form a single-crystalline epitaxial layer of In, Ga1-, As on the surface of the single-crystalline substrate.

High-resistivity Cr-doped GaAs substrates were used, so that the electrical properties of the alloy layer could be measured accurately without removing the substrate. The growth rates observed for the alloys were about 20  $\mu$ m/h, and varied by less than 20% from that value for all the crystals grown. For most of the runs, the growth time was 1 h, so that layers of about 20- $\mu$ m thickness were produced. To check on the effect of strain on the measured electrical properties, an alloy layer of about 100  $\mu$ m (18-at. % InAs, sample 43) was prepared, and measured both on the substrate and after the substrate was removed.

The alloy composition was adjusted over the range 0-25-at. % InAs by varying the HCl flow rate in the In-metal source from 0 to  $25 \text{ cm}^3/\text{min}$ , while keeping the flow rate to the Ga set at 5  $cm^3/min$ . Flow rates of 18 and 2500  $\text{cm}^3/\text{min}$  were used for

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 $AsH_3$  and high-purity  $H_2$  carrier gas, respectively. Sufficiently large volumes of In and Ga provided the long reaction lengths necessary to insure complete reaction with the HCl, and the InCl and GaCl vapors were intimately mixed to promote alloy homogeneity. The growth temperature was 725 °C for all allovs.

Epitaxial-layer thicknesses were measured on a microscope, and the alloy composition determined from x-ray-diffraction measurements of the lattice constants. All of the alloys are singlephase solid solutions with sharp diffraction lines, indicating good crystallinity and no appreciable variation in composition for each layer.

Six holes were drilled in the samples, filled with indium, and alloyed to provide Ohmic contacts. In separate experiments it was confirmed that the use of this geometry (Fig. 1) gave the same results as conventional edge contacts.

Hall measurements made for magnetic fields in the range 1000-3000 G, varied less than 5% with magnetic field in this range. The difference between the Hall coefficients measured at the two sets of side contacts was generally about 5%, indicating a variation in net donor concentration of this order in most of the samples.

#### III. EXPERIMENTAL RESULTS AND ANALYSIS

Table I provides a summary of the measurements on the samples of alloys, as well as on two samples of pure GaAs which were grown in the same way. In Fig. 2 we plot the electron mobility values at 300 K as a function of alloy composition, together with values published by other investiga-



Fig. 1. Typical sample dimensions, all given in mm. Holes are approximately 0.23 mm in diameter, and filled with In, which is alloyed into the material surrounding the hole.

Sample	Composition	Thickness	Electron density $(R_H e)^{-1}$	Electron Hall mobility (cm <sup>2</sup> /V sec)	
No.	(at. % InAs)	$(\mu m)$	$(10^{15} \mathrm{cm}^{-3})$	(300 K)	(80 K)
51	0	30	0.6	6300	72 000
8	0	28	0.7	5500	39 400
9	2.1	22	3.0	5570	36 700
10	5.7	20	1.8	5650	24800
83	8.4	25	2.4	5520	29700
93	11.1	24	1.25	5870	28400
17	15.7	25	5.0	6050	$23\ 500$
16	16.0	20	2.6	5790	33200
43	18.3	96,5	2.35	6450	23500
18	25.3	19	6.0	5950	17700

TABLE I. Properties of indium-gallium-arsenide alloy crystals.

tors. <sup>1,3,5,8</sup> Since the doping concentrations are different for the different samples, it is necessary to correct properly for the contribution of ionized-impurity scattering. Impurity scattering affects the mobility at room temperature, and for heavily doped material like that used by Burdukov *et al.*, <sup>5</sup> may even be dominant at room temperature.

We analyzed our data using a relaxation-time approximation<sup>12</sup>; i.e., we assumed that the scattering probability in collisions per second per electron could be written as  $1/\tau(\mathcal{E})$ , where  $\tau$  is the collision relaxation time and  $\mathcal{E}$  is the electron energy. The conductivity mobility is then given by an average of the relaxation time:



Fig. 2. Measured electron mobilities of GaAs-InAs alloys at 300 K : •, this work (electron density  $n \sim 10^{15}$  to  $6 \times 10^{15}$  cm<sup>-3</sup>); □, Ref. 1  $(n \sim 6 \times 10^{16}$  to  $15 \times 10^{16}$  cm<sup>-3</sup>); +, Ref. 5  $(n \sim 2 \times 10^{17}$  cm<sup>-3</sup>); ○, Ref. 3; ×, Ref. 3.

$$\mu = \frac{e}{m^*} \frac{\int_0^\infty \tau \mathcal{S}^{3/2} e^{-\mathcal{S}/kT} d\mathcal{S}}{\int_0^\infty \mathcal{S}^{3/2} e^{-\mathcal{S}/kT} d\mathcal{S}} .$$
(1)

Here  $m^*$  is the electron effective mass. When several mechanisms contribute to the scattering, the *i*th mechanism giving a relaxation time  $\tau_i$ , their scattering probabilities are added,  $(1/\tau) = \sum_i (1/\tau_i)$ , and the resulting  $\tau$  is used in Eq. (1).

Since scattering by polar optical phonons is strongly inelastic, the use of a relaxation time for such scattering at temperatures below the opticalphonon temperature is generally not a good approximation. However, the relaxation-time approximation was used in this study because it made the calculations simple and could be adjusted (through choice of the power law of the energy dependence) to give calculated mobilities within 5-10% of the measured values over the temperature range studied here.

We first tested this approach by analyzing the electron mobility in GaAs samples 51 and 8. Rode and Knight<sup>13</sup> have calculated the drift mobility for GaAs as a function of electron concentration and total ionized-impurity concentration (ionized donors and acceptors). We found that their calculations required different densities of compensating charged acceptors at 300 and at 77 K for the same sample, in order to give agreement with our measured Hall mobilities at those temperatures. Be cause of the weak variation of electron density with temperature in our samples, it is clear that the density of compensating impurity centers (ionized acceptors) should not be a function of temperature. We have compared measured Hall mobilities with calculated<sup>13</sup> drift mobilities. Although there is a decrease in the Hall coefficient of about 15-20%as the temperature is increased from 80 to 300 K, it appears difficult to apportion this change so as to find a set of compensation ratios and calculated mobilities that fit the data for the moderately doped GaAs, as proposed by Rode and Knight<sup>13</sup> to explain the discrepancies when they tried to fit other experimental data with their theory. However, this question needs an appropriate calculation of the Hall coefficient scattering factor for its resolution.

## A. Phonon scattering

In our analysis using the relaxation-time approximation, we needed to make some assumption about a relaxation time for the scattering of the electrons by the optical and acoustical phonons in GaAs. We decided to make the simplest assumption which would give a reasonable fit to our data, i.e., we assumed a power-law dependence of the scattering time on the electron energy, and varied the exponent moderately to improve the fit to the mobility of our GaAs samples:

$$\tau_{\rm ph} = \tau_{\rm p0} T^{-2.4} (\mathcal{E}/kT)^{-p}.$$
 (2)

The exponent p which gave the best fit had the value 1;  $\tau_{b0}$  had the value 3.524×10<sup>-7</sup> sec K<sup>2.4</sup>.

# B. Ionized-impurity scattering

For the scattering by ionized impurities, we used the Brooks-Herring expression<sup>14</sup>

$$\tau_{I} = \frac{16\sqrt{2\pi}\epsilon^{2}(m^{*})^{1/2}\mathcal{S}^{3/2}}{e^{4}N_{I}} \left\{ \ln(1+b) - \frac{b}{1+b} \right\},$$
(3)  
$$b = \frac{32\pi^{2}\epsilon m^{*}kT}{ne^{2}h^{2}} \mathcal{S}.$$

In this expression  $\epsilon$  is the dielectric permittivity,  $N_I$  is the total density of ionized impurities (donors plus acceptors), and *n* is the density of free electrons. All quantities are in mks units. When we combined these two expressions and used Eq. (1), we obtained an excellent fit to sample 51 (see Fig. 3) with the assumption of a negligible acceptor density, and a reasonable fit (not as good as for 51) for sample 8, assuming a moderately large acceptor density of  $9 \times 10^{14}$  cm<sup>-3</sup>. The deviations of the experimental points from the calculations were towards lower values than theory for 150 < T < 250 K. This is in the direction expected, since the mobility<sup>13,15</sup> in very pure material deviates in this direction from a power law by about the same amounts –



Fig. 3. Mobility of GaAs epitaxial layer (sample 51) as a function of temperature. The curve is calculated for an uncompensated density of donors of  $6 \times 10^{14}$  cm<sup>-3</sup>, using the technique described in the text.

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up to 10%-in this temperature range.

For the alloys, we used the measured effective masses, <sup>6</sup> extrapolated for concentrations above 15-at. % InAs, and an assumed linear variation of the dielectric constant between pure GaAs and InAs, in calculating the ionized-impurity scattering. We assumed that the phonon scattering relaxation time varied as  $(m^*)^{-1/2}$ , which is appropriate for polar optical-phonon scattering.<sup>16</sup> What was not known in our analysis was the amount of impurity compensation (ionized acceptor density) in the alloys. We first analyzed all of the alloy data, assuming that scattering was by phonons and ionized impurities and that the compensation level should be assumed large enough to give a fit to the data. In all cases, but most critically for the alloys containing 16-25-at. % InAs, the resulting curves were poorer fits to the data than were the calculated curves for our GaAs samples. In addition, the fits required very high levels of compensation, as can be seen in Table II, where the required total ionized-impurity concentrations are listed in the column labeled "Case A." We noted that there was some correlation between the variation in electron density along the length of the sample and the level of acceptor density. Sample 51 of GaAs had a small variation of electron density (3%) and is believed to have a small density of compensating acceptors; sample 8 of GaAs had a moderately large variation in electron density (11%) and is believed to have a moderately large compensating density of acceptors, larger than the electron concentration. There is a similar behavior among the alloy samples. However, the variation in electron density for samples 16 and 17 of the alloys is small (3-4%), but this analysis would require moderately large compensating acceptor densities to be present. The poor quality of the best fit using this approach can be seen in comparing the dashed curve with the

TABLE II. Estimated compensation levels.

Sample No.	Composition (at.% InAs)	Electron density (10 <sup>15</sup> cm <sup>-3</sup> )	Total ionized- impurity density Case A <sup>a</sup> (10 <sup>15</sup> cm <sup>-3</sup> )	Total ionized- impurity density Case B <sup>b</sup> (10 <sup>15</sup> cm <sup>-3</sup> )
51	0	0.6	0.6	
8	0	0.7	2.5	
9	2.1	3.0	4.0	3.0
10	5.7	1.8	7.0	4.6
83	8.4	2.4	6.0	2.7
93	11.1	1.25	6.0	2.0
17	15.7	5.0	11.0	5.0
16	16.0	2.6	6.0	2.6
43	18.3	2.35	10.0	3.2
18	25.3	6.0	20.0	9.0

<sup>a</sup>Case A: No scattering due to disorder included. <sup>b</sup>Case B: Disorder scattering included, as calculated by Makowski and Glicksman (Ref. 18).



Fig. 4. Mobility of the 25.3at.-% InAs alloy as a function of temperature. The curves are calculated. The unlabeled solid curve is for combined phonon, impurity, and disorder scattering. Labeled solid curves are for ionized-impurity scattering only  $(\mu_I)$ , phonon scattering only  $(\mu_{ph})$ , and disorder scattering only  $(\mu_D)$ . In the solid curves, the electron density was taken to be  $6 \times 10^{15}$  cm<sup>-3</sup> and the total ionized-impurity density was  $9 \times 10^{15}$  cm<sup>-3</sup>. The dashed curve is calculated for combined phonon and impurity scattering only, and for an electron concentration of  $6 \times 10^{15}$  cm<sup>-3</sup> and a total ionized-impurity concentration of  $2.0 \times 10^{16}$  cm<sup>-3</sup>. Curves calculated for "combined" scattering are transport averages of the total scattering rate, as noted in the text following Eq. (1).

experimental data for the 25-at.% alloy, shown in Fig. 4.

## C. Disorder scattering

We then analyzed the data for disorder scattering, using two approaches. The simpler one was to assume that the compensation level was small and to subtract the calculated mobility from the measured values, leaving a scattering contribution which could be attributed to alloy disorder. The other approach was to assume that the scattering relaxation time due to disorder was of the form discussed by Brooks<sup>17</sup> and applied recently to this system<sup>18</sup>:

$$\tau_{D} = \frac{\pi}{2\sqrt{2}} \frac{\hbar^{4} N_{0} \mathcal{E}^{-1/2}}{(m^{*})^{3/2} |\Delta E|^{2} \alpha (1-\alpha)}.$$
 (4)

In this expression  $N_0$  is the density of atoms in the crystal,  $\alpha$  is the alloy mole fraction, and  $|\Delta E|$  is the difference in energy between the band edges in GaAs and InAs, which has been taken as the difference in the energy band gaps.<sup>18</sup> This scattering time was then combined with the phonon and impurity scattering times in calculating a mobility to be compared with experiment, with the density of ionized acceptors allowed to be varied to obtain a best fit to the data. Better agreement with experiment was obtained this way than was found when no disorder scattering was included. An example of the quality of the fit can be seen in Fig. 4, which is a plot of the calculated mobilities for the 25-at. %-InAs alloy sample, compared with the data, and with the previous theory ignoring disorder scattering (dashed curve). Also plotted are the mobilities calculated for the various mechanisms which contribute to the scattering in the alloy, so that their relative strength may be compared.

Table II lists the impurity densities required for this fit, which are labeled in the last column as "Case B." We see that the extent of compensation required is now quite reasonable, with the alloys having the most uniform electron concentrations now requiring negligible compensation (16 and 17). In Table III we list the mobilities calculated for phonon scattering alone  $(\mu_{ph})$ , and for disorder scattering alone  $(\mu_D)$ , at 80 and at 300 K. It should be noted that the disorder scattering dominates the electron transport at 80 K for alloys containing more than 10-at. % InAs, while it provides a moderate correction (30% at 25-at. % InAs) to the electron mobility at room temperature.

The use of a disorder scattering relaxation time provided the best fits to the data. Although it is possible to provide theoretical curves which approximate the experimental values at low alloy concentrations by assuming increased impurity scattering (due to compensation) rather than alloy (disorder) scattering, this approach yields a much poorer fit (Fig. 4) at the higher alloy concentrations. The disorder scattering used in the theoretical fits<sup>17,18</sup> yields a mobility which varies as  $T^{-0.5}$ ; in the case of the two 16 at. % alloys, we found (using the method of subtraction of mobilities) that the data were fitted better if a stronger dependence on temperature were used—of the order of  $T^{-0.8}$ . The analysis should not be considered sufficiently precise to make a distinction between dependences of this kind. The values for the phonon scattering mobilities listed in Table III are a little lower than those measured<sup>15</sup> in purer GaAs at the higher temperatures, since they have been adjusted to fit our samples (with their moderate concentration of impurities). They agree with the values<sup>19,20</sup> in pure InAs to better than 10%, and should thus be fair approximations to what is expected in the alloys if there were no disorder present. They should also be relevant for comparison with the magnitude of the disorder scattering mobilities we found necessary to fit the data.

#### **IV. DISCUSSION**

We have measured the mobilities in *n*-type alloys of GaAs and InAs, and find that our values at 300 K are considerably higher than those previously reported. <sup>1,5</sup> Further, mobility values for our samples with the higher alloy concentrations are larger than those reported at 77 K for samples of comparable purity. <sup>6</sup>

In assessing these results, we should consider possible effects on the measurements resulting from inhomogeneity and strain in the materials. As mentioned above, precautions were taken to

Composition	"Phonon" scattering mobility (10 <sup>3</sup> cm <sup>2</sup> /V sec)		Disorder scattering mobility $(10^3 \text{ cm}^2/\text{V sec})$	
(at.% InAs)	(300 K)	(80 K)	(300 K)	(80 K)
0	7.0	165		•••
2.1	7.1	169	218	422
5.7	7.35	175	73	142
8.4	7.55	180	53.5	104
11.1	7.75	185	42.1	81.5
15.7	8.17	195	34	~ 80
16.0	8.17	195	34	$\sim 100$
18.3	8.38	200	33	64
25.3	9.06	216	29.7	57.5
100	34	830	• • •	• • •

TABLE III. Calculated scattering contributions.

grow alloys as homogeneous as possible, and the sharpness of the x-ray-diffraction lines confirms that homogeneous alloys were grown. When sample 43 was removed from the substrate its mobility increased by 13% at 300 K and 19% at 80 K. However, the electron mobility in this  $100-\mu$ m-thick layer, when on the substrate, was lower than for thinner samples (on substrates) of about the same composition and doping. Measurements were repeated on all samples at two different laboratories; in general, the reproducibility was within 5%, the largest deviation (two points) being 10%. These results suggests that strain is not a problem for the 20- $\mu$ m-thick samples used in this work.

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The electron mobilities measured in the alloys show a temperature dependence that becomes weaker as the amount of alloying becomes larger. It is thus clear that the alloying is having an effect on the type of scattering in the crystals, since the normal phonon scattering in pure GaAs and in InAs provides a strong dependence of mobility on temperature.<sup>20</sup> Our simple analysis indicates that this decreased temperature dependence can be ascribed to the increasing "disorder" scattering in the alloys, with the strength of scattering described fairly well by the Brooks expression.<sup>17</sup> The extremely strong scattering proposed by Burdukov

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and co-workers<sup>5</sup> is not present, their low mobilities may be due to an increasing impurity scattering in their alloys, which they do not analyze.

An analysis of the kind performed by Rode and Knight<sup>13</sup> on pure GaAs would be appropriate for the treatment of the mixed scattering, but there appear to be problems in fitting the data when moderate compensation may be present. Such an analysis would be of value when samples having negligible compensation become available.

Our measurements and analysis show that the electron mobilities in the alloys are reasonably high, so that there should be no problems in using alloys in this system in the various applications of interest. There is no indication of the minimum in mobilities near the GaAs end reported by earlier workers, <sup>1,3</sup> and thus no need for speculation<sup>18</sup> regarding additional scattering to explain it. The mobility "minimum" observed by earlier workers may be related to high impurity concentrations which increased as the InAs concentration in their samples was increased.

It is also of interest that in this system (like the germanium-silicon alloy system<sup>21</sup> and the InP-InAs alloy system<sup>18</sup>), disorder scattering does influence the carrier mobility, particularly at low temperatures.

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