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Low Compensation Vapor-Phase Epitaxial Gallium-Arsenide

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dimensional electron gas is formed at the heterojunction interface.

Figure 3 shows the reciprocal magnetic field corresponding to the resonance plotted as a function of the Landau number N . The two-dimensional electron gas density in the channel n_{ch} is found to be $2 \times 10^{11} \text{ cm}^{-2}$ from the oscillation period $\Delta(1/B)$, by using the equation $n_{ch} = q/\pi\hbar\Delta(1/B)$. The Fermi level is determined to be located 10 meV above the lowest energy level E_1 in the potential well by using the equation $E_F = g\hbar/m^*\Delta(1/B)$, where m^* of $0.047m_0$ determined by the cyclotron resonance data⁵ is employed.

Figure 4 shows the observed electron mobility and the sheet electron concentration as a function of temperature. Mobility increases monotonically as the temperature is decreased down to 50 K. At low temperatures below 50 K, mobility is fairly constant. The mobilities at 4.2, 77, and 300 K are 106 000, 71 200, and 9 400 cm^2/Vs , respectively. These values are the highest values ever reported in the heterostructures which used $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ as the electron accumulation layer.

In conclusion, we have reported the existence of the high mobility, two-dimensional electron gas at the interface of the selectively doped $\text{InP}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ grown by chloride transport vapor phase epitaxy. Enhanced electron mobilities were as high as 106 000, 71 200, and 9 400 cm^2/Vs at 4.2, 77, and 300 K, respectively. The existence of the high mobility, two-dimensional electron gas at the heterojunction indicates the excellent interface properties of the selectively doped $\text{InP}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ heterostructure grown by chloride transport vapor phase epitaxy.

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Low compensation vapor phase epitaxial gallium arsenide

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Vapor phase epitaxial gallium arsenide (GaAs) layers, with lower compensation ratios than any reported heretofore, have been reproducibly grown by the $\text{Ga}/\text{H}_2/\text{AsCl}_3$ method. One of these samples has been studied extensively by electrical measurements and shows an acceptor concentration of $(2.0 \pm 0.7) \times 10^{13} \text{ cm}^{-3}$, and a compensation rate of $N_A/N_D = 0.06 \pm 0.02$. These numbers are supported by magnetophotothermal spectroscopy and photoluminescence measurements. The preparation involves growth on [211A] substrates, and a pregrowth bakeout of the Ga source, which results in a significantly lower Zn acceptor concentration in the layer. These results have important implications for various compensation mechanisms which have been proposed for GaAs.

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One of the most important factors determining the usefulness of semiconductor materials for a variety of device applications is the tendency toward self-compensation. For example, low-band-gap, well-controlled materials such as Si show very little self-compensation, and can be made n type or p type as desired, while some of the high-band-gap materials such as CdS cannot be usefully type changed. Thus, there has been a continuing interest in the origin of the compensation which has been observed in GaAs ($N_A/N_D \simeq 0.2$ – 0.6) in the course of several studies.^{1–4} The lowest compensation, consistently grown GaAs previously reported is the vapor phase epitaxial (VPE) material of Wolfe and Stillman.¹ They

found an 0.25 compensation ratio to hold over a wide range of dopant species and concentrations. Other studies have reported higher compensation over a wide range of growth conditions for lightly doped material.^{2–4} The common features of these studies have been the insensitivity of the compensation ratios to the growth parameters that were varied and the absence of any relatively uncompensated samples ($N_A/N_D < 0.1$). Some studies have proposed compensation mechanisms involving defect complexes to account for these results.^{1–3}

In view of this background, we believe that the low-compensation, high-purity VPE material that can be consis-

TABLE I. Hall mobility values at various temperatures for several VPE GaAs samples. The mobility unit is $10^5 \text{ cm}^2/\text{V s}$.

Sample ^a	$\mu(45 \text{ K})$	$\mu(10 \text{ K})$	$\frac{\mu(10 \text{ K})}{\mu(45 \text{ K})}$	$\mu(5 \text{ K})$	$\frac{\mu(5 \text{ K})}{\mu(45 \text{ K})}$
RR98B	2.15	1.41	0.66	1.26	0.59
RR126B	1.76	0.89	0.51	0.54	0.31
RR130B	2.69	1.67	0.62	1.07	0.40
RR133B	2.79	1.70	0.61	1.41	0.50
RR135B	3.00	1.81	0.60	1.23	0.41
Stillman and Wolfe ^b	2.00	1.10	0.55	0.80	0.40

^a B suffix on RR series dropped in text.

^b G. E. Stillman and C. M. Wolfe, Thin Solid Films **31**, 69 (1976) (least compensated sample).

tently grown in our Ga/AsCl₃/H₂ reactor by bakeout of the Ga source before growth, is of significant interest. In this letter we will summarize the measurements which reliably establish the low compensation of this material and then discuss their implications. A detailed discussion of the electrical properties, which show some rather unusual but predictable phenomena, will be published elsewhere.⁵

The samples that had low compensation were grown at about 700 °C on [211A] substrates, with a Ga source which had been baked out at operating temperature (about 820 °C), in the reactor, for about 16 h before saturation and a series of growth runs was begun. The previous study of Zn evaporation in liquid phase epitaxy (LPE) bakeouts has indicated that more than an order of magnitude reduction of Zn content might be expected for a 16-h bake at 820 °C of a gallium solution.⁶ We have used Alusuisse special high-purity Ga throughout this work but note that impurities in Ga might be picked up from the laboratory environment during handling; for example, it has been observed that relative concentrations of donor species in LPE GaAs grown at the Max-Planck Institute changed when they moved from city to countryside.⁷

The mobilities at 45, 10, and 5 K and their ratios are listed in Table I for a number of samples of a series grown with a baked Ga source. While the data are subject to scatter, they indicate that the samples are typically substantially less compensated than those previously reported. The compensation varies from approximately equal to the least compensated previously reported sample to the record low of RR98. Two samples will be considered for detailed analysis: RR98, for which the Ga source was baked out prior to growth and RR126, for which it was not.

Low-temperature, high-resolution photoluminescence was used to observe radiation associated with excitons bound to shallow acceptors and donors in these samples. The principal difference seen in the photoluminescence spectra of samples RR98 and RR126, shown in Fig. 1, is a drastic reduction of the luminescence associated with Zn acceptors (relative to that associated with donors) in the low-compensation sample compared to the luminescence in the more compensated sample.

Temperature-dependent Hall-effect (TDH) and conductivity measurements were obtained over the range 5–380 K. Temperatures were accurate to within 1% over this range. The magnetic field employed was 4.5 kG and the electric field about 50 mV/cm. Data were analyzed with the following equations:

$$n = r/eR \quad (1)$$

$$n + N_A = \frac{N_D}{1 + n/\phi}, \quad (2)$$

where

$$\phi = \frac{2(2\pi m_n^* k)^{3/2}}{h^3} \frac{g_0}{g_1} e^{\alpha/kT} T^{3/2} e^{-E_{DO}/kT}. \quad (3)$$

Here R and r are the Hall coefficient and scattering factor, respectively, g_0 and g_1 are the degeneracies of the unoccupied and occupied donor states, respectively, and E_{DO} and α are

FIG. 1. Photoluminescence spectra in the bound exciton region for samples RR126 (dashed), RR98 (solid): acceptor lines $(A^0, X)_{n=1}$ are those of Zn. The lines labeled $(D^0, X)_{n=1}$, $(D^0, X)_{n=2}$, are the transitions of excitons bound to neutral donors and their electron replicas.

FIG. 2. Hall mobility vs temperature data and theoretical fits for the two samples studied in detail.

TABLE II. Fitted parameters from n vs T and μ_{Hn} vs T data.

Sample	μ_{Hn} vs T	n vs T		E_{DO} (meV)	Best value N_A (cm ⁻³)	N_A/N_D
	N_A (cm ⁻³)	N_A (cm ⁻³)	N_D (cm ⁻³)			
RR-98B	1.5×10^{13}	2.5×10^{13}	3.1×10^{14}	4.7	$(2 \pm 0.7) \times 10^{13}$	0.06 ± 0.02
RR-126B	7.8×10^{13}	1.1×10^{14}	3.2×10^{14}	4.3	$(9 \pm 2) \times 10^{13}$	0.28 ± 0.08

defined by the donor energy $E_D = E_{DO} - \alpha T$. All other symbols have their usual meanings.

The temperature dependence of r was determined by fitting the Hall mobility curves according to a solution of the Boltzmann equation as described by Nag⁹ and Rode.¹⁰ The scattering mechanisms considered here included acoustic-mode deformation potential, acoustic-mode piezoelectric potential, optical-mode polar, ionized-impurity (Brooks-Herring), and neutral-impurity (Erginsoy). Overlap integrals, nonparabolicity, effective mass temperature dependence, free-carrier screening, and neutral-impurity screening, were all included in the formalism. The best fits to the mobility data for samples RR98 and RR126 are shown in Fig. 2. The deduced parameters are N_A , and r vs T , for each sample. It may be noted that the low-temperature mobility of sample RR98 is much higher than that normally observed.

With the values of r vs T determined from the mobility analyses, it was possible to fit Eqs. (1)–(3) to the carrier-freezeout (n vs T) data. These results, to be discussed in detail in a separate publication,⁵ yielded N_D , E_{DO} , $C \equiv (g_0/g_1)\exp(\alpha/k)$, as well as another value of N_A , to be compared with that obtained from the mobility analysis. All results are given in Table II.

Sample RR126 is quite typical of good-quality VPE GaAs, with a maximum Hall mobility of about 1.7×10^5 cm²/Vs at 50 K, and a 5-K mobility of about 5×10^4 cm²/Vs. These results are consistent with the measured compensation ratio of 0.28. In sample RR98 the mobility shoulder, due to carrier freezeout, is much more pronounced, in fact producing a second maximum at about 9 K. The 5-K mobility (1.2×10^5 cm²/Vs) is as high as any ever reported, to our knowledge (excluding some quantum well structures, of course). This is consistent with the low acceptor concentration determined from the carrier freezeout measurements, and from the very narrow lines observed in the photothermal ionization measurements on this same sample.⁷ The measured compensation ratio of 0.06 thus may be considered reliable. In fact the consistency of all of these measurements supports the reliability of compensation ratios calculated from low-temperature mobility data which was called into question by Poth *et al.*² The growth of VPE material with such a low compensation ratio calls into question the applicability of any universal (i.e., defect) model for compensation in GaAs. We note that our growth temperatures are lower

than those of Wolfe and Stillman,¹ and that if the model of Hurle³ applied to both studies, our films would be more compensated, rather than less, as observed.

Photoluminescence measurements indicate the presence of a much higher Zn concentration in the more compensated sample grown, i.e., that with the unbaked Ga source. This fact supports the observations of Ozeki *et al.*⁴ that shallow acceptors are an important part of the compensation observed in much of the VPE material studied. The present work does not provide an explanation for the relatively constant compensation seen in previous studies but it does suggest that the increased compensation seen in the highest purity layers is simply due to incidental residual acceptors. We note that the preparation of the In source has been observed to strongly affect residual Zn levels in PCl₃/InP (Ref. 11) but we are not aware of any comparably detailed study of the acceptors present in layers grown from differently prepared Ga sources.

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