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Electrical properties of low-compensation GaAs

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Recently we have reproducibly grown vapor-phase epitaxial GaAs, with less than 10% compensation, in an $AsCl_3$-Ga-H_2 reactor. The low-temperature electrical properties of such samples are quite interesting, with neutral-impurity scattering and screening being much more important than usual. The Hall mobility is typically above 10^5 $cm^2/V\,sec$ at 5 K and has two maxima as a function of temperature, the usual one near 50 K and another near 9 K. The latter phenomenon has not been observed before, to our knowledge. The mobility and carrier concentration temperature dependences for a low-compensation sample and a normal-compensation sample are theoretically fitted to determine the donor and acceptor concentrations. The low-compensation sample has $N_A/N_D = 0.06 \pm 0.03$.

I. INTRODUCTION

One of the most important factors in determining the usefulness of semiconducting materials is the ability to dope both n and p type without strong compensation effects. Thus, for example, strongly p-type CdS has never been produced, evidently because of a self-compensation mechanism, while nearly uncompensated Si and Ge of either type can be produced with ease. The situation with GaAs up to now is somewhat less clear, with the lowest reported compensation for n-type material being about 0.25.[1] However, in our laboratory, we have recently been able to grow reproducibly (211A) vapor-phase epitaxial (VPE) layers with compensation ratios $N_A/N_D < 0.1$ in an $AsCl_3$-Ga-H_2 reactor. The details will be discussed in a separate paper,[2] but here we will analyze the rather unusual, low-temperature electrical properties that result from such crystals. Two representative samples will be considered: RR-98, for which the Ga source was baked out prior to growth, and RR-126, for which it was not. This procedure evidently strongly affects the acceptor concentrations.

II. RESULTS

Temperature-dependent Hall effect and conductivity measurements were obtained for several VPE crystals over the range 5–380 K. An automated system, similar to that described in Ref. 3, was employed to gather and plot the data. Temperatures were measured by calibrated carbon-glass and platinum resistors, and could be precisely checked at 4, 77, and 296 K. In this way it was ascertained that temperatures were accurate to within 1% over the entire range. Electric-field effects were very important at $T \lesssim 10$ K, and it was found necessary to limit the field to about 50 mV/cm. The magnetic field was 4.5 kG.

Two methods were used to determine the donor and acceptor concentrations, N_D and N_A, respectively. [Here, N_D is the concentration of *shallow* (hydrogenic) donors, and N_A is the concentration of all acceptors more than a few kT below the conduction band. Deeper donors, which sometimes appear at higher temperatures, are ignored. Also, only neutral and singly charged species are considered in the analysis.] The first method involves the Hall mobility, $\mu_H \equiv R\sigma$, where R is the Hall coefficient and σ is the conductivity. The μ_H vs T data were theoretically fitted by solving the Boltzmann equation in the manner described by Nag[4] who used Rode's iterative method.[5] Nag's formulation includes the acoustic-mode deformation-potential, acoustic-mode piezoelectric-potential, optical-mode polar, and ionized-impurity (Brooks-Herring) scattering mechanisms, and incorporates free-carrier screening. To this we have added neutral-impurity (Erginsoy) scattering,[6] and neutral-impurity screening,[7] both of which are important for low-compensation samples. Overlap integrals, the nonparabolicity of the conduction band, and the effective-mass temperature dependence are also included in the calculation. The parameter N_A was allowed to float in order to obtain the best fit, while N_D was determined from $N_D \simeq N_A + n$ (80 K), since the shallow donors are nearly exhausted at 80 K. Note that it was necessary to include the n vs T data in the mobility analysis, because of the use of an effective screening concentration[7] n':

$$n' = n + (n + N_A)(1 - N_A/N_D - n/N_D) \quad . \tag{1}$$

To obtain a good fit for the low-temperature data it was found necessary to multiply the neutral-impurity (Erginsoy) scattering cross section by 0.3, whereas to fit the high-temperature data well, the usual polar-optical cross section had to be multiplied by 1.15. The other parameters chosen were $E_1 = 10$ eV (deformation-potential constant), and $P = 0.052$ (piezoelectric-potential constant), both in the range of commonly assumed values.[4,5] Although no claim of uniqueness is made for this set of parameters, it should be noted that many other combinations were attempted, without success. In support of these choices, it is known that the Erginsoy formula overestimates the neutral-impurity scattering at low energies[8,9] and a modification of the polar-optical scattering by only 15% also cannot be criticized on theoretical grounds. Recently, the impurity-scattering mechanisms have been considered in more detail,[9] without invoking the Born approximation, but it is beyond the scope of this paper to incorporate this more precise work, especially since other possibly important effects, such as multi-ion scattering, have been left out.

The fitted values of N_A are given in Table I for samples RR-98 and RR-126, and the fits to the data are shown in Fig. 1. Both samples had measured Hall mobility values

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

	μ_{Hn} vs T	n vs T			Best value	
Sample	N_A (cm^{-3})	N_A (cm^{-3})	N_D (cm^{-3})	E_{D0} (meV)	N_A (cm^{-3})	N_A/N_D
RR-98	1.5×10^{13}	2.5×10^{13}	3.1×10^{14}	4.7	$(2\pm1)\times10^{13}$	0.06 ± 0.03
RR-126	7.8×10^{13}	1.1×10^{14}	3.2×10^{14}	4.3	$(9\pm3)\times10^{13}$	0.28 ± 0.09

within 10% of 8000 cm^2/V sec at 300 K, and since impurity scattering cannot possibly influence μ_n at 300 K for these pure samples, the mobilities were normalized to give this value at 300 K. By using this normalization, the least-squares fitting with parameter N_A was not influenced by the high-temperature data. The polar-optical multiplier of 1.15, and the deformation-potential constant of 10 eV, were chosen to fit the high-temperature data as well as possible. As can be seen, the fit to RR-98 is excellent and the fit to RR-126 is also certainly acceptable.

The second method of determining N_D and N_A involves an n vs T fit to the following charge-balance equation,[10] appropriate for neutral and singly charged species:

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

where

$$\phi=\frac{2(2\pi m_n^* k)^{3/2}}{h^3}\frac{g_0}{g_1}e^{\alpha/k}T^{3/2}e^{-E_{D0}/kT} \quad . \tag{3}$$

Here the shallow donor state has an energy defined by $E_D=E_{D0}-\alpha T$, and degeneracies g_1 and g_0 when occupied, and unoccupied, respectively. All other symbols have their usual meanings. The temperature dependence of m_n^* was also included.[11] The electron concentration was determined from the Hall coefficient by $n=r/eR$, where the Hall scattering factor r was deduced from the mobility fit. The four parameters resulting from the n vs T fit are N_D, N_A, E_{D0}, and $C\equiv(g_0/g_1)\exp(\alpha/k)$. In reality, since $r=r(N_D,N_A)$, a self-consistent procedure involving both the mobility and carrier concentration data should be employed. However, we will find that the results from the separate fits are consistent anyway. It should be noted that the common assumption $r=1$, for all T, can sometimes result in significant errors in N_A/N_D and C, unless r happens not to be very temperature dependent. Another common practice is to let $g_0/g_1=\frac{1}{2}$, and $\alpha=0$, both reasonable assumptions for s-like hydrogenic donors. Then $C=0.5$. However, we find significantly poorer fits with $C=0.5$ than with C in the range 0.9–1.5. The reason for this difference is unknown but may involve a temperature-dependent screening factor[12] in which α simply represents a linearized screening coefficient.

The data and theoretical fits are shown in Fig. 2, and the fitted parameters are given in Table I. For sample RR-126, the best value of C was 1.2, and the acceptable range was 0.9–1.5. For sample RR-98, the acceptable range for C was much larger, about 0.9 to 4 , because of data scatter. Thus, we used the RR-126 data to determine the value of C,

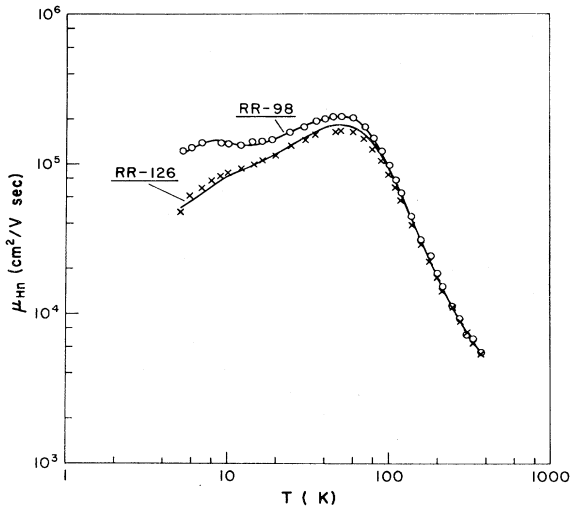

FIG. 1. Hall mobility vs temperature data and theoretical fits for the two samples of this study.

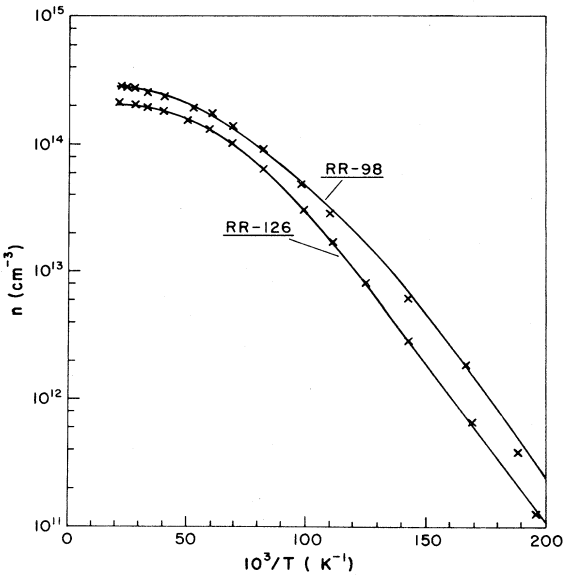

FIG. 2. Electron concentration (corrected for Hall scattering factor) vs temperature data and theoretical fits for the two samples of this study.

which should of course be the same for both samples. The difference in the activation energies, 4.7 meV for RR-98 and 4.3 meV for RR-126, may be due to the different acceptor concentrations, but more likely simply results from the RR-98 data scatter.

III. DISCUSSION

Sample RR-126 exhibits a temperature-dependent mobility curve typical of those reported in the literature for high-quality VPE layers.[13] The mobility peaks at about 50 K and contains a shoulder in the 10–25-K region. This shoulder results from changes in the ionized-impurity concentration due to carrier freezeout; that is, at low temperatures, $N_I \simeq 2N_A$, while at higher temperatures, say 30 K, the shallow donors are nearly exhausted, and $N_I \simeq N_A + N_D$. For very high compensation, $N_A \simeq N_D$, and thus N_I varies little as a function of temperature, and there is no shoulder. Therefore, the predominance of the shoulder gives a rough indication of the amount of compensation, which is about 28% in RR-126.

Sample RR-98, on the other hand, has such a pronounced shoulder that a second maximum actually appears, at about 9 K. This phenomenon has never been reported before, to our knowledge, and denotes extremely low compensation. Two factors contribute to the high low-temperature mobility: (1) the relatively low scattering due to ionized impurities, and (2) the relatively high screening due to neutral impurities. An acceptor concentration of about $(2 \pm 1) \times 10^{13}$ cm^{-3} is consistent with both the n vs T and μ_{Hn} vs T data, giving a compensation ratio of $N_A/N_D \simeq 0.06 \pm 0.03$. This result is supported by the appearance of sharp photothermal conductivity lines observed in another laboratory.[14]

There appears to be a strong correlation between the Ga bakeout before growth and the acceptor concentration in the resulting crystals. Note from Table I that the donor concentration is relatively unaffected by the bakeout. These pheonomea have been observed in many other VPE layers, grown similarly. The identities of the acceptors are of course unknown from the Hall measurements, but photoluminescence data, to be published elsewhere, will help to clarify this issue.

Samples such as RR-98 should be useful in the study of low-temperature scattering theories, since neutral-impurity screening and scattering are much more important than usual. The curve fittings shown in Fig. 1 involve only the standard Brooks-Herring ionized-impurity scattering theory, and a somewhat modified (weakened) Erginsoy theory for the neutral-impurity scattering. Improvements to these treatments have been discussed in the literature,[9] and perhaps can be tested on such samples.

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