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A study on the temperature dependence of the quasi-two-dimensional electron concentration and mobility in $Al_xGa_{1-x}As$/GaAs selectively doped heterostructures

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Abstract. We present a quantitative analysis of the temperature dependence of the quasi-two-dimensional electron concentration in $Al_xGa_{1-x}As$/GaAs heterostructures taking into account the fact that in the bulk Si-doped $Al_xGa_{1-x}As$ two types of donor coexist, i.e. deep and shallow, which independently, and by different mechanisms, provide electrons to the bulk $Al_xGa_{1-x}As$ different conduction band minima and to the quasi-two-dimensional electron gas (Q2DEG). We calculate the electronic states, the ionized-donor concentrations, the Q2DEG and the bulk-electron concentrations and the corresponding mobilities as a function of temperature. Our numerical results are in very good agreement with the experimental data.

1. Introduction

From the early eighties, experiments based on the Hall effect, in various $Al_xGa_{1-x}As$/GaAs selectively doped heterostructures [1–7], showed that up to a certain temperature the sheet electron concentration remains almost constant and then continuously increases up to room temperature. Conventional Hall experiments cannot separate the contribution of the bulk electrons from that of the quasi-two-dimensional electron gas (Q2DEG), not only as far as the Hall sheet electron concentration, n_H, is concerned but also the Hall mobility, μ_H. However, the determination of the Q2DEG concentration and mobility is an essential parameter for all these high-speed devices. Although experimental results on the mobility of the Si-doped bulk $Al_xGa_{1-x}As$ have been reported [8-10], there is a lack of such reports for the mobility of the Q2DEG. Only recently Schacham *et al* [11] presented an experimental technique to separate the Q2DEG from the bulk contribution at room temperature.

In a previous work [12], we systematically investigated the electronic states in $Al_xGa_{1-x}As$/GaAs/$Al_xGa_{1-x}As$ selectively doped heterostructures, at $T = 0$ K. In the present work, we present a quantitative analysis to interpret the temperature dependence of the Q2DEG sheet electron concentration, n_1, versus the bulk sheet electron concentration, n_2. The values of n_1 and n_2, theoretically evaluated, together with experimental values for n_H and μ_H allow us to obtain the Q2DEG and the bulk mobilities, μ_1 and μ_2, respectively, at any temperature. We find that in the low-temperature range there are no bulk electrons close to the GaAs well. However, as we raise the temperature, bulk electrons move towards the well. At low temperatures the Q2DEG concentration dominates over the bulk-electron concentration, while at high temperatures this picture is overturned. We also show that the ionized-donor concentration is not homogeneous and we investigate the relative contribution

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of the deep and the shallow donors to the total ionized-donor concentration. In section 2 we introduce the problem together with the necessary equations. In section 3 we discuss our results and we compare them with experimental data.

2. Formulation of the problem

To start with it is necessary to make some remarks concerning the inclusion of temperature in the study of the electron concentration in $Al_xGa_{1-x}As/GaAs$ modulated doped heterostructures.

First of all, one cannot use the abrupt depletion approximation because the ionized-donor concentration depends on the temperature and on the potential energy and is not spatially homogeneous.

It is also inappropriate to use a 'one-equivalent-donor' approximation, applied by Lee *et al* [13] and by Svensson and Swanson [7], given that in the Si-doped $Al_xGa_{1-x}As$ layer(s) both deep and shallow donors exist. The deep-to-shallow-donors relative percentage is a function of the Al mole fraction [14–16]. These two types of donor provide electrons by different mechanisms. The shallow donors, for the usual doping, and for an Al mole fraction near 0.3 that is commonly used, are all ionized even at liquid helium temperature, due to the formation of an impurity band which merges with the Γ conduction band [14]. The deep donors become ionized by a temperature-dependent law, although their status is under investigation [14, 17–18].

These two types of donor provide electrons not only to the Γ conduction band minimum, but also to the L and X conduction band minima of the bulk $Al_xGa_{1-x}As$ [10, 14, 16], as well as to the Q2DEG. One should also take into account that due to the fact that $Al_xGa_{1-x}As$ has a zincblende lattice, there are four equivalent L conduction band minima and three equivalent X conduction band minima [19].

As our calculations show, especially at low temperatures and due to the strong influence of the shallow donors, the temperature-dependent chemical potential does not lie far below the $Al_xGa_{1-x}As$ Γ conduction band minimum. Therefore, the Boltzmann statistics used by Svensson and Swanson [7] for the occupation of the Γ conduction band minimum of the Si-doped $Al_xGa_{1-x}As$, is not an appropriate approximation for the whole temperature range.

Table 1. Electron concentrations of the Γ, L and X conduction band minima (N_Γ, N_L, N_X, respectively) and the total electron concentration (N_{total}) of Si-doped bulk $Al_xGa_{1-x}As$ at four characteristic temperatures. $E_{C\Gamma}$ is the Γ conduction band minimum and $\mu(T)$ is the chemical potential.

T (K)	N_Γ (cm^{-3})	N_L (cm^{-3})	N_X (cm^{-3})	N_{total} (cm^{-3})	$E_{C\Gamma} - \mu(T)$ (meV)
50	0.2595×10^{18}	0.9264×10^{9}	0.1067×10^{5}	0.2595×10^{18}	−15.53
150	0.2537×10^{18}	0.5645×10^{16}	0.1489×10^{15}	0.2595×10^{18}	−7.25
250	0.1628×10^{18}	0.8746×10^{17}	0.1084×10^{17}	0.2611×10^{18}	18.70
300	0.1110×10^{18}	0.1335×10^{18}	0.2437×10^{17}	0.2689×10^{18}	40.57

Before any calculation concerning heterostructures we investigated the Si-doped bulk $Al_xGa_{1-x}As$ behaviour. Table 1 shows the electron concentrations of the Γ, L and X conduction band minima, and the total electron concentration at four characteristic temperatures. We use the nominal density of states, Al mole fraction $x = 0.3$, shallow-donor percentage 26%, deep-donor activation energy 135 meV, total donor concentration

1×10^{18} cm^{-3}, acceptor concentration 5×10^{14} cm^{-3} and energy distances of the L and X conduction band minima from the Γ conduction band minimum 110 meV and 160 meV, respectively. The energy distance of the Γ conduction band minimum from the chemical potential is also shown. These results have driven us to the inclusion of the L and X conduction band minima in the present treatment. However, it is obvious that the calculated increase of the total electron concentration with temperature is negligible. On the other hand, it is an experimental fact that after 150 K the electron concentration increases significantly up to room temperature [10, 14]. As our calculations show, using the nominal density of states, this problem cannot be overcome by varying the shallow-donor percentage, the deep-donor activation energy, the deep-donor degeneracy factor, the total donor concentration or the energy distances of the L and X conduction band minima from the Γ conduction band minimum, within acceptable limits. Specifically, the shallow-donor percentage is more or less strictly defined by the low-temperature-range (0 K–100 K) electron concentration. On the other hand, decrease of the deep-donor activation energy certainly provides more electrons; however, the increase of the electron concentration starts at temperatures lower than the value of approximately 150 K that is observed in the experiments [10, 14]. The variation of the deep-donor degeneracy factor has a minor effect. This has also been pointed out in the past by Watanabe and Maeda [16]. The variation of the energy distances of the L and X conduction band minima from the Γ conduction band minimum has to be unacceptably large in order to be effective. Thus, the nominal densities of states do not give a satisfactory agreement with the experiment. According to our calculations, the only way to achieve this agreement is the use of much larger values for the densities of states (two orders of magnitude). This fact, probably surprising at first glance, has also been extensively pointed out by Schubert and Ploog in their systematic study of the Si-doped bulk $Al_xGa_{1-x}As$ [14]. There, they considered both deep and shallow donors and also the Γ, L and X conduction band minima. Our results verify Schubert and Ploog's calculations. Svensson and Swanson [7] studied the temperature dependence of the electron concentration in $Al_{0.28}Ga_{0.72}As/GaAs$ heterostructures, considering only deep donors lying approximately 60 meV below the Γ conduction band minimum. They applied Boltzmann statistics for its occupation, and they did not take into account the higher-lying L and X conduction band minima. Even with these hypotheses, at high temperatures, to interpret the electron concentration behaviour, they were obliged to use a ten times larger density of states. They also reported that variation of the donor concentration or of the donor activation energy, within acceptable limits, is not sufficient to solve the above-mentioned discrepancy. Specifically, they notice that the donor activation energy would have to be less than 10 meV which would classify it as a shallow donor. Thus, this great distortion of the density of states, mainly a physical consequence of the very high doping concentrations [20, 21], seems to be a fact. Even the formation of the impurity band modifies significantly the situation from that of the undoped $Al_xGa_{1-x}As$. We think that the preceding discussion imposes the necessity for a thorough investigation of the influence of doping on the density of states (both theoretical and experimental). However, this is far beyond the scope of the present paper. Here, we will make a phenomenological use of a much larger density of states than the nominal one, to simulate the electron concentration of the bulk Si-doped $Al_xGa_{1-x}As$ as a function of temperature. This makes the inclusion of the non-parabolicity of the Γ band of minor significance. Therefore, we ignore it.

Although our treatment is quite general, applicable to various types of $Al_xGa_{1-x}As/GaAs$ selectively doped heterostructure, we will apply it to the case of a double heterostructure used in the experimental work presented by Inoue and Sakaki [2]. It consists of a 500 Å Si-doped (1×10^{18} cm^{-3}) $Al_{0.3}Ga_{0.7}As$ layer, a 100 Å undoped $Al_{0.3}Ga_{0.7}As$

spacer, a 300 Å undoped GaAs well, a 100 Å undoped $Al_{0.3}Ga_{0.7}As$ spacer, and a 500 Å Si-doped (1×10^{18} cm^{-3}) $Al_{0.3}Ga_{0.7}As$ layer.

We denote by $N_1(z)$ the concentration of the Q2DEG and by $N_2(z) = N_\Gamma(z) + N_L(z) + N_X(z)$ the concentration of the electrons in the parallel $Al_xGa_{1-x}As$ paths. $N_\Gamma(z)$, $N_L(z)$ and $N_X(z)$ are the electron concentrations at the Γ, L, and X minima, respectively. For the electron effective masses at the Γ, L and X minima, respectively, we use the values [16] $m^*_\Gamma = 0.092m_e$, $m^*_L = 0.588m_e$ and $m^*_X = 0.831m_e$. m_e is the electron mass. The band offset between the $Al_{0.3}Ga_{0.7}As$ Γ conduction band minimum and the GaAs Γ conduction band minimum is taken to be 300 meV [12]. The GaAs L and X conduction band minima were not considered, due to their large energy distance from the GaAs Γ conduction band minimum (approximately 270 meV and 460 meV respectively [14, 17]).

$$N_1(z) = \sum_i \frac{m^* k_B T}{\pi \hbar^2} \ln\left(1 + \exp\left(\frac{\mu(T) - E_i}{k_B T}\right)\right) |\zeta_i(z)|^2 \tag{1}$$

where $\zeta_i(z)$ is the z axis envelope function with corresponding eigenvalues E_i. For simplicity, for the electron effective mass, we use $m^* = 0.067m_e$. This value is only slightly smaller than the one that should be used taking into account the small penetration of the envelope functions into the $Al_{0.3}Ga_{0.7}As$ layers [22, 23]. $\mu(T)$ is the temperature-dependent chemical potential. Using the nominal densities of states we should write:

$$N_\Gamma(z) = M_\Gamma 4\pi \left(\frac{2m^*_\Gamma}{h^2}\right)^{3/2} \int_{U(z)}^{\infty} \frac{(E - U(z))^{1/2}\,\mathrm{d}E}{\exp([E - \mu(T)]/k_B T) + 1} \tag{2}$$

$$N_\Xi(z) = M_\Xi 2 (k_B T)^{3/2} \left(\frac{m^*_\Xi}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{\mu(T) - E_{C\Xi}(z)}{k_B T}\right). \tag{3}$$

Here, $\Xi = \mathrm{L}, \mathrm{X}$, while $M_\Gamma = 1$, $M_L = 4$, and $M_X = 3$ are the numbers of the equivalent conduction band minima. $E_{CL}(z)$, $E_{CX}(z)$ are the L, X conduction band minima, lying 110 meV and 160 meV above the Γ conduction band minimum, respectively [14]. $U(z)$ is the Γ conduction band minimum. However, as we have already mentioned, the nominal densities of states used to obtain equations (2) and (3) do not give a satisfactory simulation of the electron concentration in the Si-doped bulk $Al_{0.3}Ga_{0.7}As$ as a function of temperature. In order to have such an agreement, we have to multiply the r.h.s. of equations (2) and (3) by a factor of 100.

We assume that all layers have a small unintentional acceptor doping (5×10^{14} cm^{-3}). The total donor concentration is equal to the sum of the shallow-donor concentration, N_{sd}, which for Al mole fraction 0.3 is about 25% of the total donor concentration [14–15], and the deep-donor concentration, N_{dd}. We assume that the shallow donors are all ionized. $N^+_{dd}(z)$ is the ionized-deep-donor concentration, given by

$$N^+_{dd}(z) = \frac{N_{dd}}{1 + g_{DD} \exp([\mu(T) - U(z) + \Delta E_{dd}]/k_B T)}. \tag{4}$$

We use the value $\frac{1}{2}$ [16] for the deep-donor degeneracy factor, g_{DD}. The deep-donor activation energy, ΔE_{dd}, is given by $\Delta E_{dd} = E_{C\Gamma} - E_{DD}$ where $E_{C\Gamma}$ is the nominal bulk $Al_{0.3}Ga_{0.7}As$ Γ conduction band minimum and E_{DD} is the energy of the deep-donor level. ΔE_{dd} is taken to be 135 meV [14].

We solve numerically and self-consistently Schrödinger and Poisson equations. The charge neutrality condition, i.e. the requirement that the integral of the charge density throughout the structure is zero, allows us together with the equations above, to

determine $\mu(T)$. $\mu(T)$ should always be identified with the chemical potential calculated independently for the bulk Si-doped $Al_{0.3}Ga_{0.7}As$ layers. The determination of $\mu(T)$ and $U(z)$ allows us to calculate $N_1(z)$, $N_2(z)$ and $N_{dd}^+(z)$. Integrating $N_1(z)$ or $N_2(z)$ throughout the structure, we obtain n_1 or n_2, respectively. We use the values 12.244 and 13.18 for the dielectric constants of $Al_{0.3}Ga_{0.7}As$ and GaAs, respectively. We obtained these values by interpolating AlAs and GaAs dielectric constants [24].

We can analyse the Hall data resulting from the contribution of the two parallel layers, 1 and 2, using the following equations [25]:

$$n_H = (\mu_1 n_1 + \mu_2 n_2)^2/(\mu_1^2 n_1 + \mu_2^2 n_2) \tag{5}$$

$$\mu_H n_H = \mu_1 n_1 + \mu_2 n_2. \tag{6}$$

In equations (5) and (6), n_1 and n_2 are taken from our theoretical analysis, while n_H and μ_H are known from the experiment [2]. This enables us to obtain μ_1 and μ_2 at any temperature.

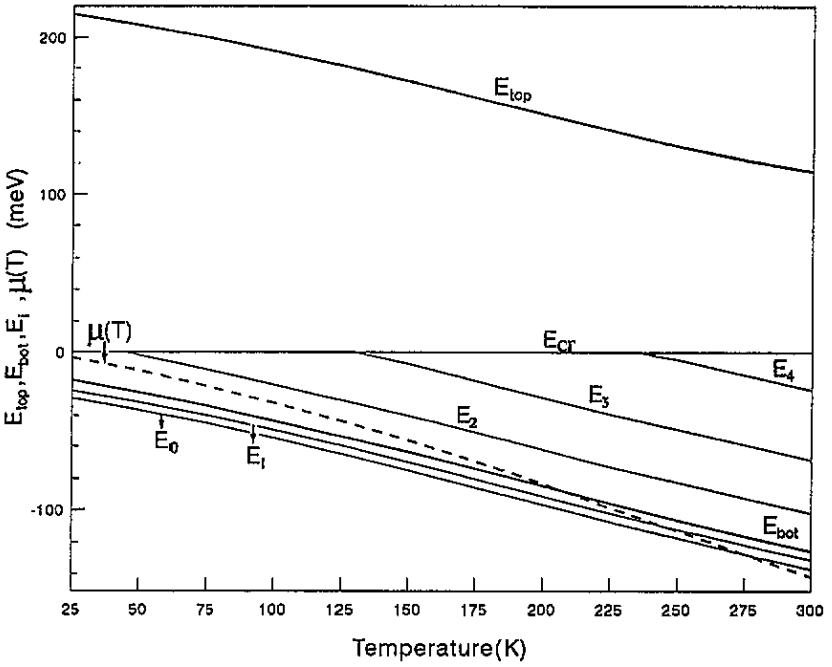

Figure 1. The variation with temperature of (a) the energy of the top of the well, E_{top}, and the energy of the centre of the bottom of the well, E_{bot} (bold full lines), (b) the subband energies, E_i (full lines) and (c) the chemical potential, $\mu(T)$ (bold dashed line). All the energies have been evaluated with respect to E_{CT}.

3. Results and discussion

The material parameters we use (26% shallow-donor percentage, $\Delta E_{dd} = 135$ meV, $E_{CL}(z) = 110$ meV, $E_{CX}(z) = 160$ meV, two orders of magnitude greater than the nominal density of states) were calibrated, with the help of the experimental data of Schubert and Ploog [14], to simulate the electron concentration in Si-doped bulk $Al_{0.3}Ga_{0.7}As$. Specifically, we interpolated the experimental data concerning two samples with Al mole

fraction $x = 0.25$ and $x = 0.32$ to obtain the situation for $x = 0.3$. We summarize our results in figures 1–4.

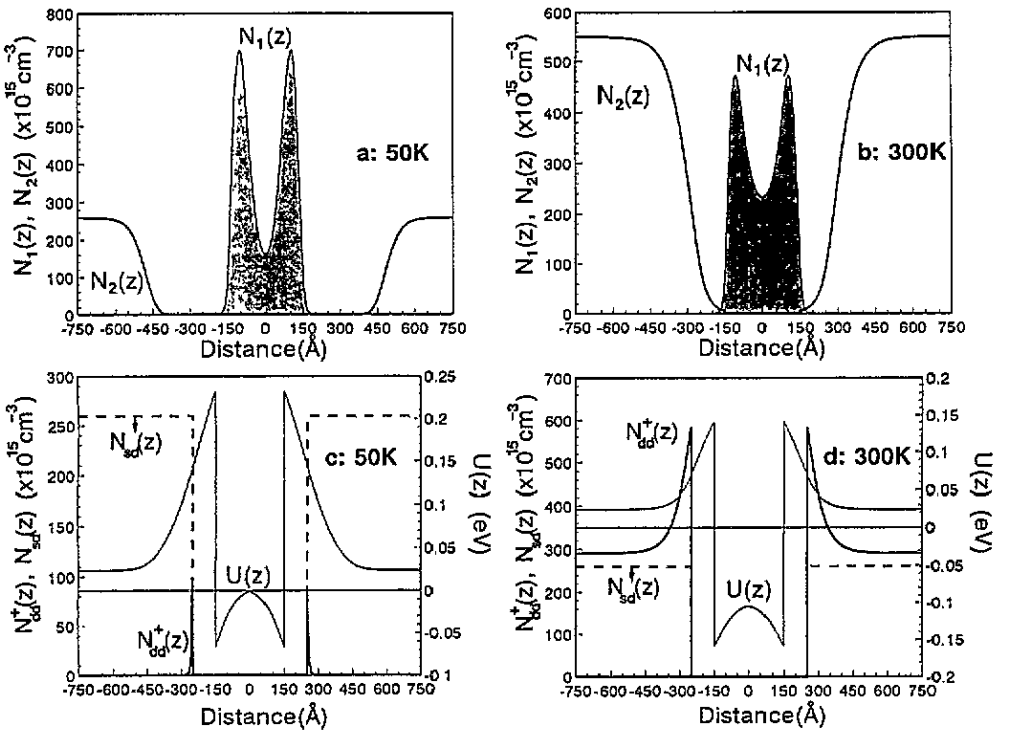

Figure 2. (a) $N_1(z)$ (shaded area) and $N_2(z)$ (open area), at $T = 50$ K. (b) $N_1(z)$ (shaded area) and $N_2(z)$ (open area), at $T = 300$ K. (c) $N_{dd}^{+}(z)$ (bold full line), N_{sd} (bold dashed line) and $U(z)$ (full line), at $T = 50$ K. (d) $N_{dd}^{+}(z)$ (bold full line), N_{sd} (bold dashed line) and $U(z)$ (full line), at $T = 300$ K. The structure includes a 300 Å undoped GaAs well, 100 Å undoped $Al_{0.3}Ga_{0.7}As$ spacers and 500 Å Si-doped (1×10^{18} cm^{-3}) $Al_{0.3}Ga_{0.7}As$ layers.

Figure 1 shows the variation with temperature of (a) the energy of the top of the well, E_{top}, and the energy of the centre of the bottom of the well, E_{bot}, (b) the subband energies and (c) the chemical potential. All the energies appearing in figure 1 have been evaluated with respect to $E_{C\Gamma}$. We observe that on raising the temperature that E_{top} and E_{bot} decrease with respect to $E_{C\Gamma}$. This results in the appearance of an increasing number of bound energy states. The relative distances of the subband energies with respect to E_{bot} remain constant, as expected for a quantum well of constant width [12].

Figures 2(a) and 2(b) show $N_1(z)$ and $N_2(z)$ at $T = 50$ K and $T = 300$ K, respectively. We observe that at low temperatures (figure 2(a)) the Q2DEG concentration dominates over the bulk-electron concentration. $N_1(z)$ and $N_2(z)$ are clearly spatially separated. Note that the shape of $N_1(z)$ is due to the form of $|\zeta_0(z)|^2$ and $|\zeta_1(z)|^2$ which have relative and absolute minimum at the centre of the well, respectively. At room temperature (figure 2(b)) the situation is totally overturned. Not only does $N_2(z)$ dominate, but also the spatial separation of the two concentrations is not clear any more. Comparing figures 2(a) and 2(b), we observe that the contribution of the higher-lying excited states to the Q2DEG concentration, as the temperature is raised, increases. The filling, at room temperature, of the 'valley' between the two 'mountains' of the Q2DEG concentration is mainly due to the shape of the envelope function ($|\zeta_2(z)|^2$ has absolute maximum at the centre of the well)

and the significant occupation of the second excited subband.

Figures 2(c) and 2(d) show $N_{dd}^{+}(z)$ and N_{sd} at $T = 50$ K and $T = 300$ K, respectively. We observe that at low temperatures (figure 2(c)) $N_{dd}^{+}(z)$ vanishes, except from a small region just before the spacers, due to the abrupt band bending. N_{sd} dominates and the total ionized-donor concentration is almost homogeneous. However, in contrast to the usually used depletion approximation, the total ionized-donor concentration is only a small fraction of the total donor concentration. In contrast, at room temperature (figure 2(d)) due to thermally induced ionization, $N_{dd}^{+}(z)$ rather dominates. On the other hand, due to the band bending, $N_{dd}^{+}(z)$ is not constant. This results in an inhomogeneous total ionized-donor concentration.

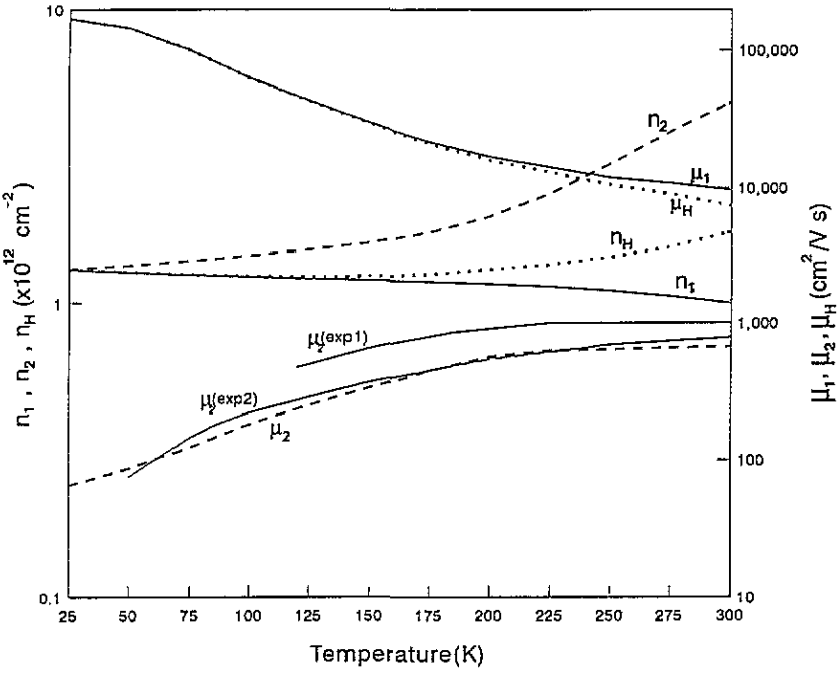

Figure 3. The variation with temperature (based on our hypotheses) of (a) n_1 and μ_1 (full lines), and (b) n_2 and μ_2 (dashed lines) and (c) n_H and μ_H (dotted lines) μ_2(exp1) is the experimental mobility of Si-doped bulk $Al_{0.3}Ga_{0.7}As$ with $N_d = 3 \times 10^{17}$ cm^{-3} [9]. μ_2(exp2) is the experimental mobility of Si-doped bulk $Al_{0.29}Ga_{0.71}As$ with $N_d = 2.5 \times 10^{18}$ cm^{-3} [10].

Figure 3 shows n_1, n_2, n_H and μ_1, μ_2, μ_H as a function of temperature. We observe the following.

(i) Due to the variation of the position of $\mu(T)$ with respect to the subband energies (figure 1), n_1 decreases with increasing temperature.

(ii) On raising the temperature, n_2 increases, in accordance with the experimental results of Ishikawa *et al* [9] (their experiment was performed only at high temperatures), Chand *et al* [10] and Schubert and Ploog [14]. n_2 does not vanish at low temperatures, in agreement with Chand *et al* [10] and Schubert and Ploog [14]. This is a direct consequence of the fact that in the present treatment we have included shallow donors.

(iii) The value of n_1 calculated at very low temperatures (1.28×10^{12} cm^{-2}) coincides with the experimental n_H, in the same temperature range [2]. This justifies the use of the value 26% for the shallow-donors percentage.

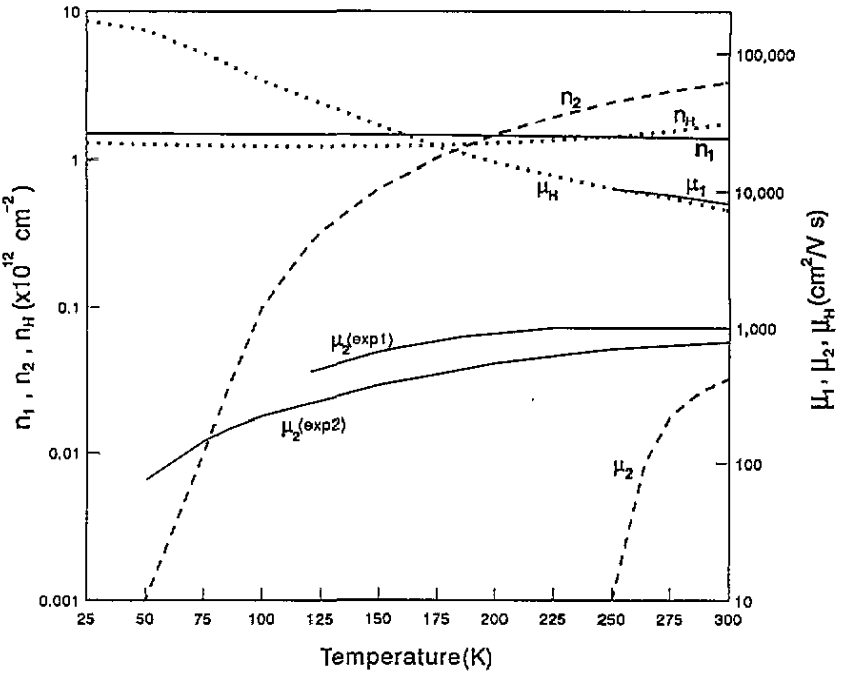

Figure 4. The variation with temperature of (a) n_1 and μ_1 (full lines), (b) n_2 and μ_2 (dashed lines) and (c) n_H and μ_H (dotted lines). μ_2(exp1) and μ_2(exp2) are also shown. Here we include only deep donors with $\Delta E_{dd} = 60$ meV and only the Γ conduction band minimum of the bulk $Al_{0.3}Ga_{0.7}As$. Boltzmann statistics is applied and a density of states ten times larger than the nominal is used.

(iv) In figure 3 we compare the behaviour of μ_2 obtained from our analysis, for $Al_{0.3}Ga_{0.7}As$ ($N_d = 1 \times 10^{18}$ cm^{-3}) with experimental results. μ_2(exp1) is the experimental mobility of Si-doped bulk $Al_{0.3}Ga_{0.7}As$ with $N_d = 3 \times 10^{17}$ cm^{-3}, measured by Ishikawa *et al* [9]. μ_2(exp2) is the experimental mobility of Si-doped bulk $Al_{0.29}Ga_{0.71}As$ with $N_d = 2.5 \times 10^{18}$ cm^{-3}, measured by Chand *et al* [10]. We observe that the experimental data of the heavily doped sample are very close to our calculated values. The less doped sample has higher mobility, for the whole temperature range measured.

(v) At low temperatures μ_1 and μ_H almost coincide because of the large difference (three orders of magnitude) between μ_1 and μ_2. n_2 increases with temperature, while n_1 decreases. This, but mainly the fact that simultaneously μ_2 increases while μ_1 decreases with temperature, results in the splitting of μ_1 from μ_H, for $T > 150$ K. At 300 K, $n_1 = 0.996 \times 10^{12}$ cm^{-2}, $n_2 = 4.859 \times 10^{12}$ cm^{-2}, $\mu_1 = 9500$ cm^2 V^{-1} s^{-1} and $\mu_2 = 670$ cm^2 V^{-1} s^{-1}, while μ_H(300 K) $= 7300$ cm^2 V^{-1} s^{-1}. Due to the fact that n_1 decreases with temperature, and as long as the bulk-electron contribution to the measured n_H is negligibly small, a slight decrease of n_H is observed. This decrease of n_H was pointed out by Mendez *et al* [3]. Raising temperature, the bulk-electron contribution becomes important. Therefore, this previous descending tendency drastically changes, resulting in an increasing n_H.

To illustrate the significance of our hypotheses, we give figure 4. We present n_1, n_2, n_H and μ_1, μ_2, μ_H as a function of temperature, using only deep donors lying 60 meV below the Γ conduction band minimum of the bulk $Al_{0.3}Ga_{0.7}As$. We include only the Γ

conduction band minimum of the bulk $Al_{0.3}Ga_{0.7}As$, we apply Boltzmann statistics for its occupation, and we use a density of states ten times larger than the nominal, according to [7]. We observe the following.

(i) Due to the exclusion of shallow donors, n_2 vanishes for $T < 50$ K, in disagreement with the experiments of Chand *et al* [10] and Schubert and Ploog [14].

(ii) Equations (5) and (6) give physically acceptable values for μ_1 and μ_2 only for $T > 250$ K. Even in the region where the solutions are acceptable, μ_2 obtained is not comparable with the experimental values reported by Ishikawa *et al* [9] and Chand *et al* [10].

(iii) At low temperatures $n_1 > n_H$. To identify n_1 with n_H, at these temperatures, we had to use a deep donor lying 110 meV below the Γ conduction band minimum. However, in this case, n_2 vanishes for $T < 150$ K, while μ_2 obtains unacceptably large values.

Recently Schacham *et al* [11] reported that they succeeded in distinguishing experimentally, for the first time, the contribution of the Q2DEG from that of the bulk electrons. Their homogeneously doped sample is an $Al_{0.3}Ga_{0.7}As/GaAs$ heterojunction. The $Al_{0.3}Ga_{0.7}As$ layer is Si doped with $N_d = 1 \times 10^{18}$ cm^{-3}. Unfortunately, they do not report the width of the spacer. Therefore, a simulation of their structure is impossible. We agree with their general ascertainment that the difference between n_1 and the room temperature n_H is very significant due to the contribution of the electrons in the $Al_{0.3}Ga_{0.7}As$ layer. Nevertheless, they attribute to n_1 lower mobility and to n_2 higher mobility compared with our calculated values. Specifically they report $\mu_1(300\ \text{K}) = 8080$ cm^2 V^{-1} s^{-1} and $\mu_2(300\ \text{K}) = 1810$ cm^2 V^{-1} s^{-1}, a value which is two or three times larger than the corresponding value for the bulk Si-doped $Al_{0.3}Ga_{0.7}As$ found in the literature [9, 10]. We believe that if their experimental discrimination of the Q2DEG from the bulk electrons is not complete, but some bulk electrons are attributed to the Q2DEG, inevitably μ_2 is overestimated while μ_1 is underestimated.

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