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Quantum- and transport electron mobility in the individual subbands of a two-dimensional electron gas in Si-δ-doped GaAs

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In this paper we present measurements of both the quantum- and transport mobility in two populated subbands of a Si-δ-doped GaAs structure. In these structures it is expected that ionized impurity scattering is the main scattering mechanism at low temperature. We investigated this by measuring both the transport and quantum mobility. We observe that both mobilities are independent of temperature between 1.2 and 4.2 K and find a ratio of the transport to quantum mobility of typically 2–3 in both populated subbands. Both results confirm the dominant role of ionized impurity scattering in Si-δ-doped GaAs at low temperatures.

1. Introduction

During recent years the semiconductor materials and devices containing narrow doping profiles have gained strong interest. This so-called δ-doping technique is now used for electronic as well as optical applications [1], such as δFETs and n-i-p-i lasers. The possibility of obtaining high electron concentrations compared to GaAs–$Al_xGa_{1-x}As$ heterostructures is one of the advantages of δ-doping. This high electron density makes it possible to study multi-subband effects in the 2-dimensional electron gas (2DEG) formed at the doping layer. Zrenner et al. [2] have shown that the width of the doping layer can be obtained from a measurement of the distribution of the electrons over the various subbands. The electron mobility in each subband is a parameter which, contrary to the electron density in each subband, is not so easily accessible [3–5]. Furthermore, it is important to distinguish between a transport mobility μ_t, which is determined by the total scattering weighted by the scattering angle, and a quantum or single particle mobility μ_q, which is related to the total scattering [6]:

$$\frac{1}{\mu_t} = \frac{m^*}{e} \int W_{kk'}(\Theta)\,(1-\cos(\Theta))\,d\Theta\,, \tag{1}$$

$$\frac{1}{\mu_q} = \frac{m^*}{e} \int W_{kk'}(\Theta)\,d\Theta\,, \tag{2}$$

where $W_{kk'}(\Theta)$ is the scattering probability and Θ is the scattering angle. The ratio μ_t/μ_q is not the same for each scattering mechanism because the angular distribution of the scattering probability $W_{kk'}(\Theta)$ is different. Thus one can determine the main scattering mechanism by measuring both the transport and the quantum electron mobility [6].

In δ-doped structures, scattering on the ionized donors in the doping layer is expected to be the dominant scattering mechanism. We investigated this by measuring both the transport and quantum mobility in each populated subband. The transport mobility was determined from the classical magnetoresistance effect in low mag-

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netic fields and the quantum mobility was determined from the magnetic field dependence of the Shubnikov–de Haas (SdH) oscillations [4] in higher magnetic fields. We compared our measurements with the theoretical work on the mobility in δ-doped GaAs structures by Mezrin and Shik [7].

2. Experiments

The δ-doped sample was grown in a Varian modular MBE system. The sample was grown at 480°C with a background impurity concentration of the order of $10^{15}\,\mathrm{cm}^{-3}$. In order to obtain a planar doping layer on a smooth surface, the growth was interrupted by closing the Ga shutter for 10 s; then the Si furnace was opened for 7.5 s to deposit the Si-doping layer of about $3 \times 10^{12}\,\mathrm{cm}^{-2}$. The sample was grown with a buffer layer between the doping layer and the substrate of 2.5 μm and a top layer of 1 μm.

Magnetoresistance measurements at different temperatures and in a magnetic fields up to 20 T were performed on Hall bar-shaped samples in order to determine the electron density and mobility in each subband.

At low magnetic field we make use of the classical magnetoresistance effect to obtain the transport electron mobility in each subband. Beck and Anderson [8] proposed a method by which σ_{xx} and σ_{xy} can be transformed into a so-called mobility spectrum. In the magnetic field range where no Shubnikov–de Haas oscillations occur, they showed that

$$\sigma_{xx} = \int_{-\infty}^{\infty} \frac{en(\mu_t)\mu_t\,d\mu_t}{(1+(\mu_t B)^2)}, \quad (3)$$

$$\sigma_{xy} = \int_{-\infty}^{\infty} \frac{en(\mu_t)\mu_t^2 B\,d\mu_t}{(1+(\mu_t B)^2)}. \quad (4)$$

In these equations they adopt the convention that electrons have a negative mobility and holes have a positive mobility. Based on eqs. (3) and (4) they proposed a technique to obtain a mobility spectrum, $n^*(\mu)$, which gives the maximum carrier density as a function of mobility. This mobility spectrum is derived from $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ measured at a limited number of magnetic field positions. We used this analysis method of Beck and Anderson to determine the transport mobility in each subband.

Figure 1 shows $\rho_{xx}(B)$ and $\rho_{xy}(B)$ measured at 4.2 K. At low magnetic fields, $B < 0.3$ T, a small negative magnetoresistance effect is observed and SdH oscillations are visible only above 4 T. We used the values of ρ_{xx} and ρ_{xy} measured at 8 magnetic field positions (equidistant in $1/B$) between 0.5 and 4 T to transform ρ_{xx} and ρ_{xy} into a mobility spectrum as shown in fig. 2. The mobility spectrum clearly shows two peaks corresponding to two populated subbands. The structure that is observed below $300\,\mathrm{cm}^2/\mathrm{V\,s}$ is a spurious effect of the analysis technique of Beck and Anderson. In table 1 we present the transport mobilities in the subbands before and after illumination.

At high magnetic field we make use of the SdH effect to obtain the electron density and quantum electron mobility in each subband. The oscillating parts in ρ_{xx} and ρ_{xy} due to a single subband are given by [6]

$$\Delta\rho^i_{xx} \propto \Delta\rho^i_{xy} \propto \frac{X}{\sinh(X)} \times \exp\left(-\frac{\pi}{\mu^i_q B}\right)\cos\left(\frac{2\pi(E_F - E_i)}{\hbar\omega_c} + \pi\right), \quad (5)$$

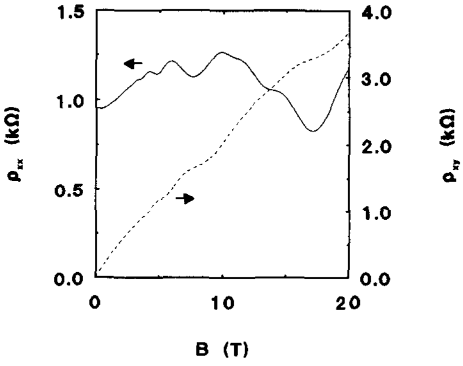

Fig. 1. The transversal magnetoresistivity ρ_{xx} and ρ_{xy} measured at 4.2 K.

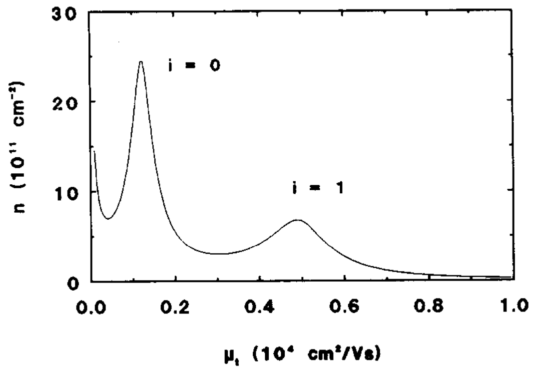

Fig. 2. The electron mobility spectrum obtained from ρ_{xx} and ρ_{xy} shown in fig. 1.

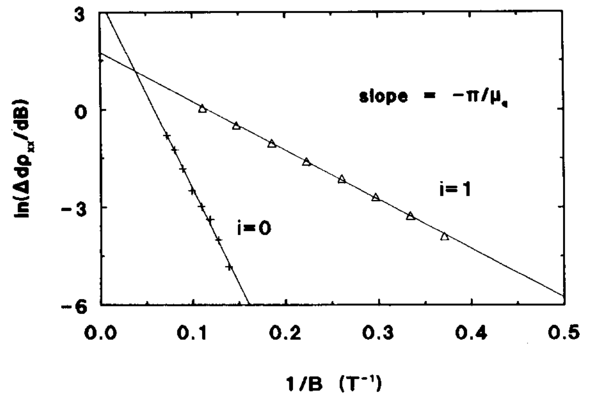

Fig. 3. Dingle plot of the $i = 0$ and $i = 1$ subband measured at 4.2 K before illumination.

where $E_F - E_i$ is the relative position of the Fermi energy to the subband energy, $X = 2\pi^2 k_B T/\hbar\omega_c$ and $\omega_c = eB/m^*$.

We measured ρ_{xx}, ρ_{xy}, $\partial\rho_{xx}/\partial B$ and $\partial\rho_{xy}/\partial B$ in fields up to 20 T. The two derivatives, $\partial\rho_{xx}/\partial B$ and $\partial\rho_{xy}/\partial B$, were measured directly by the use of a modulated magnetic field of 18 mT at 21 Hz superimposed on the main field. The population of each subband was then determined from the Fourier transform (FT) of either ρ_{xx}, ρ_{xy}, $\partial\rho_{xx}/\partial B$ or $\partial\rho_{xy}/\partial B$. Table 1 gives the results obtained from $\partial\rho_{xx}/\partial B$ and $\partial\rho_{xy}/\partial B$ between 1.2 and 4.2 K before and after illumination. We obtained similar results from ρ_{xx} and ρ_{xy}.

The quantum mobility can be obtained from the magnetic field dependence of the amplitude of the SdH oscillations. In our case of multi-subband population we determined the contribution of a single subband to ρ_{xx} and ρ_{xy} in the following way. First we take the Fourier transform of a measured ρ_{xx} and ρ_{xy} curve and next we take the inverse Fourier transform of the FT peak corresponding to a single subband. The quantum mobility of this single subband was then obtained from the Dingle plot, i.e. ln($\Delta\rho_{xx}$) or ln($\Delta\rho_{xy}$) versus $1/B$. This method can also be used for the measurements of $\partial\rho_{xx}/\partial B$ and $\partial\rho_{xy}/\partial B$ provided that a magnetic field dependent scaling factor due to the magnetic field modulation is taken into account. In fig. 3 we show the

Table 1
Population of the subbands and transport and quantum mobility in the subbands before and after illumination as determined from the mobility spectra and from the SdH oscillations in $\partial\rho_{xx}/\partial B$ and $\partial\rho_{xy}/\partial B$. The ratio of μ_t/μ_q is also given in this table. The values presented in this table are the averaged values of 6 measurements between 1.2 and 4.2 K.

i	Electron density (10^{11} cm^{-2})			Mobility (cm^2/V s)		μ_t/μ_q
	Mobility spectra	FT	Calculated	Transport	Quantum	
Dark						
0	24.8 ± 1.0	25.3 ± 0.1	25.2	1250 ± 100	507 ± 54	2.5 ± 0.3
1	7.2 ± 1.0	6.6 ± 0.1	6.7	4800 ± 200	2040 ± 11	2.4 ± 0.1
Total	32.0 ± 1.4	31.9 ± 0.1	31.9			
Illuminated						
0	22.7 ± 1.0	24.7 ± 0.2	24.5	1300 ± 100	510 ± 33	2.5 ± 0.3
1	9.1 ± 1.0	7.7 ± 0.1	9.2	7200 ± 300	2692 ± 55	2.4 ± 0.1
2		2.5 ± 0.1	1.2	–	2841 ± 106	–
Total	31.8 ± 1.4	34.9 ± 0.2	34.9			

Dingle plot of the two populated subbands, obtained from $\partial\rho_{xx}/\partial B$ measured in the dark at 4.2 K. In table 1 we present the quantum mobilities in the subbands before and after illumination. We obtained similar result from the analysis of the SdH oscillations in both ρ_{xx} and ρ_{xy}.

3. Discussion

In table 1 we have gathered the results obtained from both the mobility spectra and the FT analysis. We could not find a temperature dependence between 1.2 and 4.2 K in any of the quantities measured.

First we compare the electron densities obtained from the mobility spectra with the electron densities obtained from the SdH oscillations. We observe that the electron densities obtained from the two peaks in the mobility spectra are in nice agreement with the FT values for the $i = 0$ and $i = 1$ subband (see table 1). However, a third subband ($i = 2$) which was observed in the FT spectrum of $\partial\rho_{xx}/\partial B$ and $\partial\rho_{xy}/\partial B$ obtained after illumination was not found in the mobility spectrum obtained after illumination. It is possible that the transport mobility in the $i = 1$ and $i = 2$ subbands is equal. This seems reasonable because the quantum mobility in the $i = 1$ and $i = 2$ subbands is equal. In case that the transport mobility in the $i = 1$ and $i = 2$ subband are equal, the electron density obtained from the peak at 7200 $cm^2/V\,s$ in the mobility spectrum is the sum of the electron densities in both subbands. The total number of electrons we find from both analysis methods is close to the intended doping concentration of $3 \times 10^{12}\ cm^{-2}$.

Comparison of the measured subband population in the dark with the subband population obtained from self-consistent calculations gives a width of the donor distribution less than 20 Å when an acceptor concentration of $8 \times 10^{14}\ cm^{-3}$ is assumed. The total electron density increases after illumination because the charged acceptors in both depletion regions next to the doping layer are neutralized during illumination. With illumination, electron–hole pairs are created; the electrons flow towards the 2DEG and the holes recombine with the charged acceptors. For an acceptor concentration of $8 \times 10^{14}\ cm^{-3}$ the total concentration of depletion charges on both sides of the δ-layer is $2.6 \times 10^{11}\ cm^{-2}$. Thus the total electron density has to increase by the same number when all charged acceptors in the depletion region are neutralized during illumination. This is in good agreement with the observed increase of the total electron density of $3 \times 10^{11}\ cm^{-2}$ after illumination (see table 1). In case all charged acceptors are neutralized the conduction band outside the 2DEG region will become flat and thus the confining potential will become different. We calculated the subband population in this situation and find that just as in the experiment, three subbands are populated after illumination. The population of each subband is also in reasonable agreement with the experiments (see table 1).

The results obtained from the mobility spectra show that the transport mobility increases with the subband number (see table 1). It is clear that the quantum mobility also rises with the subband number. After illumination both the quantum and the transport mobility in the $i = 0$ subband remain constant. The quantum mobility and the transport mobility in the $i = 1$ subband increases strongly after illumination. Using the transport mobility data and a simple two or three subband model we are able to calculate the Hall electron density and Hall mobility as observed from a simple Van der Pauw measurement at 0.5 T (see table 2). The nice agreement we get validates once more the use of the mobility spectra in order to obtain the transport mobilities. Note

Table 2
The measured Hall electron density and Hall mobility at 4.2 K before and after illumination. The Hall electron density and Hall mobility were also calculated using the transport mobility and electron density obtained from the mobility spectra.

	n_H ($10^{11}\ cm^{-2}$)		μ_H ($cm^2/V\,s$)	
	Measured	Calculated	Measured	Calculated
Dark	22.0	21.5	2830	3020
Illuminated	21.2	19.7	5043	5250

that the Hall electron density is much lower than the total electron density as determined from SdH measurements and thus gives only limited information [3, 5]. Also note that the increase of the Hall mobility after illumination is solely due to the change of electron density and mobility in the $i = 1$ subband.

Skuras et al. [3] determined the subband mobility both from the width and the peak height of the FT peaks. They also determined the subband mobilities from a fit with a two carrier model to the magnetic field dependence of ρ_{xx} and ρ_{xy} in low fields. They do not state whether they measure transport or quantum mobility. In fact they assume that there is no difference between the transport mobility obtained from low field Van der Pauw data and the quantum mobility obtained from SdH oscillations in high magnetic fields. The mobility they obtained from the SdH measurements, which should be the quantum mobility, increases with subband number just as in our experiments. Yamada et al. [4] determined the quantum mobility in each subband from a Dingle plot. Their results also show a higher quantum mobility in a higher subband. When they compare the quantum mobility averaged over all the subbands with the Hall mobility they incorrectly assume, just as Skuras et al., that transport and quantum mobility are equal.

Theoretical work on the mobility in a δ-doped structure is still in its initial stage. Mezrin and Shik [7] have calculated the electron transport mobility in the 2DEG of GaAs δ-doped structure where the doping layer has a zero width and depletion charges are absent. The absolute values of the transport mobilities they find for $n_{tot} = 3.5 \times 10^{12}\ cm^{-2}$ are $1960\ cm^2/V\,s$ for the $i = 0$ subband, $4300\ cm^2/V\,s$ for the $i = 1$ subband and $6860\ cm^2/V\,s$ for the $i = 2$ subband. These results also show an increase of the transport mobility with subband number. The absolute values compare relatively well with our measurements.

From table 1 it is clear that in dark as well as after illumination the ratio μ_t/μ_q in both subbands is typically 2–3. These results can be compared with measurements performed on $GaAs/Al_xGa_{1-x}As$ heterostructures with a small spacer. In these structures, where ionized impurity scattering is the main scattering mechanism, the ratio μ_t/μ_q is typically 5–10 [6, 9]. This is a higher ratio than in the case of Si-δ-doped GaAs structures. Theoretical work of Das Sarma and Stern [10] has shown that for ionized impurity scattering in heterostructures the ratio μ_t/μ_q decreases when the separation between the scattering centers and the 2DEG decreases. They calculated that the ratio μ_t/μ_q is close to 2.5 in a $GaAs/Al_xGa_{1-x}As$ heterostructure without a spacer and an electron density of $3.5 \times 10^{12}\ cm^{-2}$. Although this result is only valid for $GaAs/Al_xGa_{1-x}As$ heterostructures containing a single subband, the ratio is very close to the value we obtained. In the work of Mezrin and Shik, the quantum mobility in only the lowest subband is calculated. They find that the quantum mobility is about a factor of 3 lower than the transport mobility which is in good agreement with our results. The absence of a temperature dependence between 1.2 and 4.2 K in the quantum and transport mobility and the ratio μ_t/μ_q confirm that at low temperatures ionized impurity scattering is the main scattering mechanism in Si-δ-doped GaAs structures.

4. Conclusions

We have measured the transport and quantum mobility in two populated subbands of a Si-δ-doped GaAs structure for the first time. We did observe that both the transport and quantum mobility are independent of the temperature between 1.2 and 4.2 K. The ratio of the transport and quantum mobility in the sample we have studied, is typically 2–3 for every subband. These findings are in agreement with ionized impurity scattering which is the main scattering mechanism below 4.2 K in Si-δ-doped GaAs structures.

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