Transport and quantum electron mobility in the modulation Si δ-doped pseudomorphic GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ quantum well grown by metalorganic vapor phase epitaxy

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A study of transport and quantum mobility of electrons in two-dimensional electron gas (2DEG) in the modulation Si δ-doped pseudomorphic GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ quantum well (QW) grown by metalorganic vapor phase epitaxy is presented. Well-resolved Shubnikov–de Haas oscillations of the magnetoresistivity observed at $T=4.2\,\mathrm{K}$ suggest that the 2DEG with high electron mobility ($\mu_t \approx 46\,000\,\mathrm{cm^2/V\,s}$) formed in the QW with no significant parallel conduction. A persistent photoconductivity effect resulted in an increase in electron sheet density. An increase of transport and quantum mobilities up to the onset of the second subband occupancy was observed. Further illumination resulted in a decrease of both mobilities. Strong dependence of the quantum mobility on the thermal history of the investigated sample was attributed to the effect of actual distribution of ionized centers in the sample.
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Mobility of carries in quasitwo-dimensional electron gas (2DEG) formed at a semiconductor heterojunction is intrinsically limited by optical phonon scattering at room temperature. For high performance devices, an increase in electron density leads to enhanced channel conductivity. The existence of *DX* centers in $Al_xGa_{1-x}As(x>0.22)$ restricts the use of a high Al mole fraction in $Al_xGa_{1-x}As$/GaAs heterostructures. The small conduction band offset in such structures limits the electron density below $10^{12}\,\mathrm{cm^{-2}}$.[1] Owing to larger conduction band offset the pseudomorphic GaAs/$In_xGa_{1-x}As$/$Al_yGa_{1-y}As$ quantum wells (QWs) have attracted much interest in high-speed devices.[2] The best samples of those structures with very high 2DEG mobilities are usually grown by molecular beam epitaxy (MBE).[3–5] Recent progress in metalorganic vapor phase epitaxy (MOVPE) has led to growth of high quality heterostructures. Additionally, δ doping increases the electron density and mobility of 2DEG in the QW, and consequently improves device performance.[6–7] In previous letters we have reported on the effect of doping plane position[8] and the barrier composition[9] on the electrical properties of the Si δ-doped pseudomorphic GaAs/$In_xGa_{1-x}As$/$Al_yGa_{1-y}As$ QWs. In this letter we analyze the effect of electron sheet density on the transport and quantum mobilities in the optimized Si δ-doped pseudomorphic GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ QW grown by MOVPE.

The sample was grown at 630 °C and consisted nominally of 600 nm GaAs buffer layer, followed by 90 nm of (5 nm $Al_{0.2}Ga_{0.8}As$/5 nm GaAs) superlattice, 310 nm of $Al_{0.2}Ga_{0.8}As$ back barrier, 10 nm $In_{0.2}Ga_{0.8}As$ QW, and 205 nm GaAs top barrier. The Si δ doping ($n_D=2.3\times10^{12}\,\mathrm{cm^{-2}}$) was placed 10 nm from the QW in the back $Al_{0.2}Ga_{0.8}As$ barrier. Similar δ doping was applied 2 nm below the structure surface in order to saturate the surface states. Magnetotransport measurements were carried out on photolithographically defined Hall bars at $T=4.2\,\mathrm{K}$ in magnetic field up to 7 T. Photoluminescence (PL) measurements were carried out at $T=4.2\,\mathrm{K}$ using a cw laser $\lambda=780\,\mathrm{nm}$ beam, monochromator, and nitrogen cooled Ge *p-i-n* detector. The persistent photoconductivity (PPC) was obtained by illumination with an infrared light emitting diode ($\lambda=906\,\mathrm{nm}$).

The resistivity traces ρ_{xx} and ρ_{xy} measured just after cooling down the sample in the dark are presented in Fig. 1(a). Well resolved Shubnikov-de Haas (SdH) oscillations of the ρ_{xx} trace and the quantum Hall effect plateaus in the ρ_{xy} trace indicate the existence of the 2DEGs. After the illumination the sample resistivity first decreases [Fig. 1(b)], and then increases [Fig. 1(c)]. In the intermediate magnetic field, the magnetic field dependence of the ρ_{xx} resistivity can be written as[10]

$$\rho_{xx}=\rho_0\left[1-4\exp\left(-\frac{\pi}{\mu_q B}\right)\frac{X}{\sinh X}\cos\frac{2\pi^2\hbar n_0}{eB}\right], \tag{1}$$

where $X=2\pi^2k_BTm^*/\hbar eB$, n_0 is the electron sheet density, and μ_q is the quantum mobility. The electron sheet density n_0 can be therefore found from the fast Fourier transform (FFT) analysis of the ρ_{xx} resistivity. The FFT analysis of ρ_{xx} data showed a single peak suggesting occupancy of single electronic subband ($N=1$ electron subband in the QW) in our sample. It was observed however from ρ_{xx} resistivity traces, that after longer illumination a parallel conduction channel of much lower mobility has also been occupied [see

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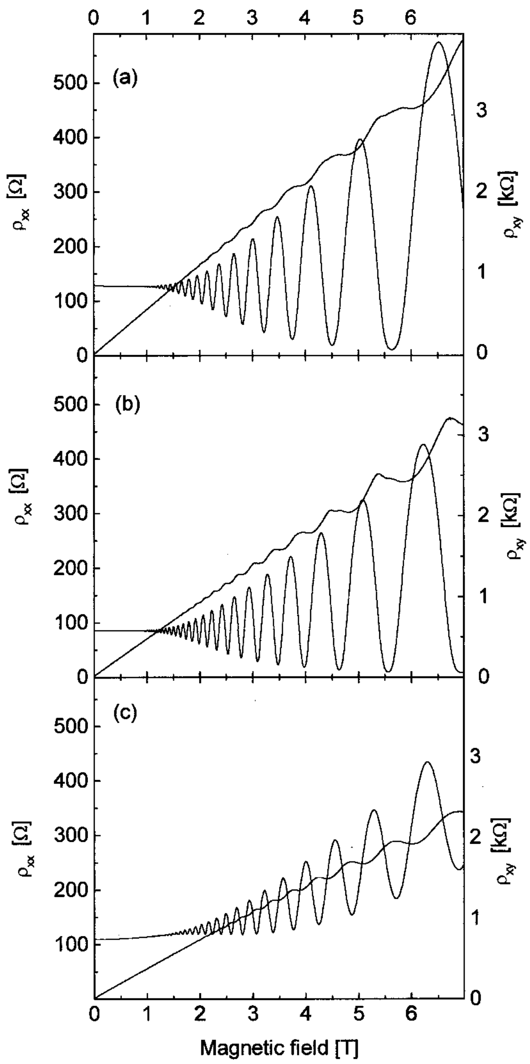

FIG. 1. The ρ_{xx} and ρ_{xy} resistivity of the modulation Si δ-doped pseudomorphic $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW grown by MOVPE measured at $T=4.2$ K in the dark just after cooling down the sample (a) and after short (b) and long (c) infrared illumination.

Fig. 1(c)]. In order to find the transport mobility μ_t in the $N=1$ subband of the QW we fit the diagonal component of conductivity tensor

$$\sigma_{xx}(B)=\frac{\rho_{xx}}{\rho_{xx}^2+\rho_{xy}^2} \tag{2}$$

with

$$\sigma_{xx}(B)=\sum_{i=1,2}\frac{\sigma_{xx}^i(0)}{1+(\mu_t^iB)^2}. \tag{3}$$

This method enables us to separate the conduction in the $N=1$ subband and in the parallel channel, which becomes apparent after longer illumination.

The quantum mobility μ_q was determined with electron effective mass $m^*=0.066m_0$, using the so called Dingle plot.[4] In the case of parallel conduction the high mobility channel conductivity was analyzed using the Dingle plot. The transport and quantum mobilities obtained using the above analysis are presented in Figs. 2(a) and 2(b), respectively.

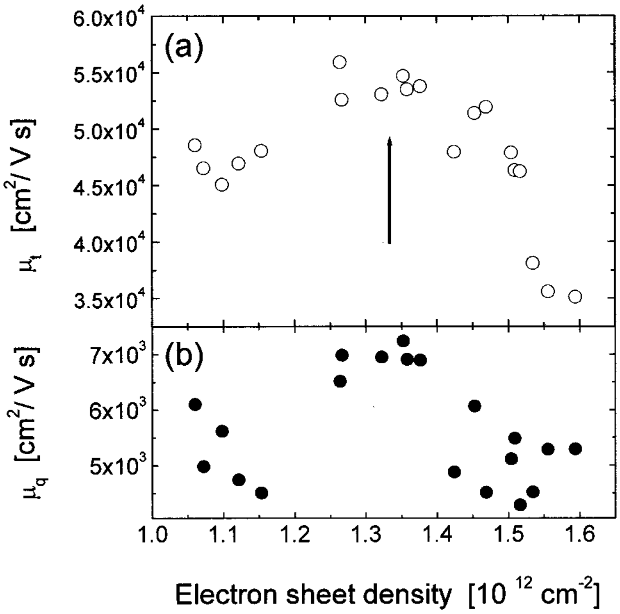

FIG. 2. The electron transport (a) and quantum (b) mobility in the $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW as a function of electron sheet density n_0. The onset of $N=2$ subband occupation deduced from the photoluminescence spectrum is denoted by an arrow.

High transport mobility ($\mu_t \approx 46\,000\ \mathrm{cm^2/V\,s}$) with a sheet density $n_0 \approx 1.08\times10^{12}\ \mathrm{cm^{-2}}$ was observed at $T=4.2$ K after cooling the sample in the dark. The PPC effect results in an increase of electron sheet density. An increase of the n_0 density due to illumination results first in an increase of transport mobility. Two processes limit transport mobility at low temperature. These are: the large-angle cluster scattering due to nonuniform In distribution in the QW and the remote ionized impurities Coulomb scattering.[3] In previous articles[3,4,11–13] an increase of transport mobility was attributed to the more effective screening of remote impurities by electron sheet density n_0. However for large In cluster size (>5 nm) the cluster scattering limited mobility should also increase with increasing n_0.[3] It is very likely that depending on the actual growth conditions both processes can contribute to the transport mobility. The MOVPE structures are usually grown at higher temperatures than their MBE grown counterparts, which should smooth out the In composition and result in larger characteristic sizes of In clusters. This could explain the observed mobility increase.

A maximum of transport mobility can be observed at electron density $n_0 \approx 1.35\times10^{12}\ \mathrm{cm^{-2}}$. Similar behavior reported recently[13] was attributed to the effect of resonant scattering from electronic states in the donor layer. In order to clarify the experimental situation in our sample we measured its PL spectrum (see Fig. 3). Two peaks are clearly observed at energies of 1.339 and 1.385 eV. The lower energy PL peak is interpreted as an emission from the $N=1$ electron subband to the $N=1$ heavy hole subband ($1e-1$hh), while the peak at higher energy results from the $N=2$ electron subband to the $N=1$ heavy hole subband ($2e-1$hh) transition.[14] Assuming that the onsets of electronic subbands occupancy in the QW can be identified from the maxima of PL intensity, it is possible to deduce the onset of the $N=2$

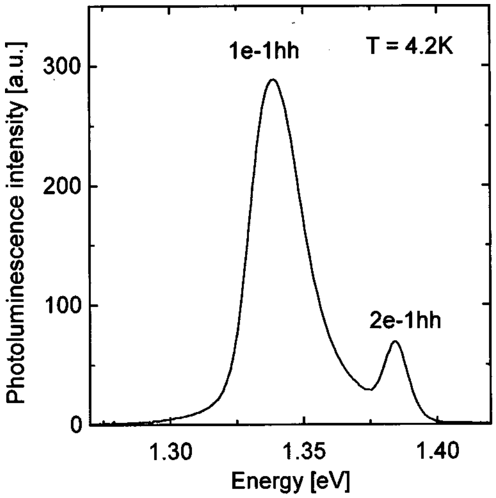

FIG. 3. The photoluminescence at $T=4.2$ K from the modulation Si δ-doped pseudomorphic $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW.

subband filling [see an arrow in Fig. 2(a)] with an accuracy of a few meV.[15]

The onset of the $N=2$ subband occupation in the QW coincides with the maximum of transport mobility (see Fig. 2). However no FFT peak due to high electron mobility channel expected from the $N=2$ subband can be seen. The resistivity data suggest rather the existence of a low-mobility parallel conduction channel, presumably due to electrons in the V-shaped potential well in the δ-doped layer. An increase of the Fermi energy in the QW above the $N=2$ subband energy must result in its electron occupancy. In our opinion the bottom of the $N=2$ subband is nearly degenerate with the electron level within the δ-doped layer potential well. In such a case no SdH oscillations due to the $N=2$ subband in the QW can be observed.[4] In the case of multisubband occupation in the QW both intersubband scattering and additional screening by the higher subband electrons are important.[16] The transport mobility is more sensitive to the large-angle scattering events like the intersubband scattering. The onset of the second subband occupancy should therefore result in a decrease of the transport mobility, which is the case in our structure.

As it can be seen in Fig. 2(b), which summarizes results of several cooling down procedures, the quantum mobility is more sensitive to the sample thermal history than the transport mobility. The quantum mobility reflects every scattering process including low-angle Coulomb scattering from remote ionized centers. Therefore it must be sensitive to the actual potential landscape of the QW, which can be affected by the distribution of ionized centers in the structure. The existence of charge correlations in the Si δ-doped layer has been proven by high pressure freeze-out experiments.[12] In our opinion such correlations can be responsible for the observed strong dependence of the quantum mobility on the cooling procedure. Despite that dependence, the same trend as in the transport mobility can be clearly observed with the maximum around the onset of parallel conduction channel occupancy. An increase of the quantum mobility with an increase in electron sheet density can be due to more effective screening of the remote impurities. Another mechanism was recently proposed to explain similar behavior in the GaAs/InGaAs/GaAs QW with the δ doping in the back barrier.[17] An apparent increase of the quantum mobility was explained by the ionization of deep centers in the top barrier which changed the QW from asymmetric to the more square-like. The resulting shift of the electron charge distribution away from the δ layer leads to an increase of electron transport mobility in the QW. An explanation of the quantum mobility decrease after the upper subband occupation is less straightforward. The intersubband scattering presumably present in this density region has the opposite effect on the quantum mobility than the more effective remote charge screening. Moreover a light-induced destruction of charge correlations may be important.

In conclusion we presented the study of transport and quantum mobility of electrons in the Si δ-doped pseudomorphic $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW grown by MOVPE. The high electron mobility 2DEG was formed in the investigated structure with no significant parallel conduction. Nonmonotonic dependence of both transport and quantum mobilities on electron sheet density was observed with the maximum related to the onset of the upper subband occupancy.

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[1] L. Pfeiffer, K. W. West, H. L. Störmer, and K. W. Baldwin, Appl. Phys. Lett. **55**, 1888 (1989).
[2] L. D. Nguyen, D. C. Radulescu, M. C. Foisy, P. J. Tasker, and L. F. Eastman, IEEE Trans. Electron Devices **ED-36**, 833 (1989).
[3] J-K Luo, H. Ohno, K. Matsuzaki, and H. Hasegawa, Jpn. J. Appl. Phys., Part 1 **27**, 1831 (1988).
[4] M. van der Burgt, V. C. Karavolas, F. M. Peeters, J. Singleton, R. J. Nicholas, F. Herlach, J. J. Harris, M. Van Hove, and G. Borgs, Phys. Rev. B **52**, 12218 (1995).
[5] M.-I. Ke, X. Chen, M. Zervos, R. Nawaz, M. Elliott, D. I. Westwood, P. Blood, M. J. Godfrey, and R. H. Williams, J. Appl. Phys. **79**, 2627 (1996).
[6] J. E. Cunningham, W. T. Tsang, G. Timp, E. F. Schubert, A. M. Chang, and K. Uwususekyere, Phys. Rev. B **37**, 4317 (1988).
[7] E. F. Schubert, J. E. Cunningham, W. T. Tsang, and G. L. Timp, Appl. Phys. Lett. **51**, 1170 (1987).
[8] G. Li, A. Babinski, and C. Jagadish, Appl. Phys. Lett. **70**, 3582 (1997).
[9] G. Li, A. Babinski, S. J. Chua, and C. Jagadish, Appl. Phys. Lett. **72**, 2322 (1998).
[10] P. T. Coleridge, R. Stoner, and R. Fletcher, Phys. Rev. B **39**, 1120 (1989).
[11] W. Knap, A. Zduniak, L. H. Dmochowski, S. Contreras, and M. I. Dyakonov, Phys. Status Solidi B **198**, 267 (1996).
[12] L. H. Dmowski, A. Zduniak, E. Litwin-Staszewska, S. Contreras, W. Knap, and L. J. Robert, Phys. Status Solidi B **198**, 283 (1996).
[13] J. L. Pearson, M. C. Holland, C. R. Stanley, A. R. Long, E. Skuras, A. Asenov, and J. H. Davies, J. Cryst. Growth **201/202**, 757 (1999).
[14] M. S. Skolnick, D. M. Whittaker, P. E. Simmonds, T. A. Fisher, M. K. Saker, J. M. Rorison, R. S. Smith, P. B. Kirby, and C. R. H. White, Phys. Rev. B **43**, 7354 (1991).
[15] H. Brugger, H. Mussig, C. Wolk, K. Kern, and D. Heitmann, Appl. Phys. Lett. **59**, 2739 (1991).
[16] R. Fletcher, E. Zaremba, M. D'Iorio, C. T. Foxon, and J. J. Harris, Phys. Rev. B **41**, 10649 (1990).
[17] M. Zervos, M. Elliot, and D. I. Westwood, Appl. Phys. Lett. **74**, 2026 (1999).