New Concept for the Reduction of Impurity Scattering in Remotely Doped GaAs Quantum Wells

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(Received 24 May 1996)

We present a new concept to reduce impurity scattering in remotely doped GaAs single quantum wells by using heavy-mass X electrons in barriers formed by short-period AlAs/GaAs superlattices to smooth the potential fluctuations of the ionized Si dopants. Electron mobilities as high as 120 $\mathrm{m}^2/\mathrm{V\,s}$ and electron densities up to $1.5 \times 10^{16}\ \mathrm{m}^{-2}$ are obtained in 10 nm GaAs single quantum wells in the one-subband conductivity mode without any parallel conductance. In addition to magnetotransport we present voltage dependent capacitance and photoluminescence measurements as well as self-consistent calculations to demonstrate the applicability of our concept. [S0031-9007(96)01724-3]

PACS numbers: 73.61.–r, 81.40.Rs, 85.40.Ux

Numerous attempts have been made to achieve ultrahigh conductivity in two-dimensional electron gas (2DEG) systems for both fundamental research and applications in low-noise, high-frequency devices. The most promising material systems are those which provide high potential barriers to confine the electron channel [1–6]. High barriers allow for large 2DEG concentrations n. At the same time, the devices can operate at higher temperatures. However, the possibilities to increase the conductivity by simply increasing the dopant density are limited for several reasons. First, high dopant densities can result in a parallel conductivity of the 2DEG with electrons in the doping channel. Second, large carrier densities can lead to the population of excited subbands which cause an additional scattering channel [7]. Third, and most important, a high dopant density increases the remote impurity scattering. All these mechanisms result in a lower electron mobility μ. However, a high mobility and a large carrier density are the prerequisite for a high conductivity $\sigma = qn\mu$, where q denotes the elementary charge. In the following we will use the product $n\mu$ as a measure for the two-dimensional conductivity. The remote impurity scattering can be suppressed by increasing the distance of the dopants from the conducting channel [8,9], but this reduces the carrier densities. In the well-known (Al,Ga)As system high electron mobilities of several hundred $\mathrm{m}^2/\mathrm{V\,s}$ at low temperatures have been reported. The systems consist of multiquantum wells with low carrier densities of $0.64 \times 10^{15}\ \mathrm{m}^{-2}$ per quantum well [4] or inversion layers at single heterointerfaces with carrier densities up to $3 \times 10^{15}\ \mathrm{m}^{-2}$ [5]. In such high mobility samples the mobility is limited by interface roughness scattering in (Al,Ga)As systems [10] or by alloy disorder scattering in ternary systems [11]. The pseudomorphic (AlGa)As/(InGa)As is another promising system to achieve high conductivities even at much higher temperatures. By optimizing the quantum well thickness and the dopant separation from the quantum well, conductivities approaching $n\mu = 9 \times 10^{16}\ (\mathrm{Vs})^{-1}$ up to temperatures as high as 77 K have been reported [6].

We propose a new concept for both the enhancement of the carrier concentration and the reduction of remote impurity scattering (RIS) in GaAs single quantum wells (SQW), thereby significantly increasing the conductivity. The barriers of the GaAs SQW are formed by AlAs/GaAs short-period superlattices (SPSL). In AlAs/GaAs SPSL the lowest conduction band state can be formed by the X-conduction band state of the AlAs layer [12] (X-electron). Self-consistent calculations show that with sufficiently high dopant densities the lowest-energy X-like conduction band state are occupied in the AlAs/GaAs superlattice with the X electrons located close to the doping layer. Because of their rather high effective mass, the X electrons effectively screen the ionized impurities. Furthermore, the heavy-mass X electrons exhibit a low mobility and, therefore, are expected to contribute less to the parallel conductance. We present magnetotransport experiments to confirm the applicability of this concept.

The structures under investigation were grown by solid-source molecular beam epitaxy on semi-insulating GaAs (001) substrates. The barriers consist of a SPSL of 60 periods of 4 monolayer AlAs and 8 monolayer GaAs. The carriers in the 10 nm GaAs SQW are provided by remote δ doping with Si at a distance from the SQW interface of 14 nm (sample S1) and 10 nm (sample S2). The single Si δ-doping sheets with a dopant concentration of $N^{2\mathrm{D}} = 2.5 \times 10^{16}\ \mathrm{m}^{-2}$ were placed on both sides of the SQW into a GaAs layer of the SPSL. The growth temperature of the lower barrier and the SQW was 580 °C, whereas the temperature for the δ-doping sheet and its vicinity was 510 °C to suppress Si segregation into the well. The growth rate and the beam-equivalent As_4-to-Ga pressure ratio were 0.66 μm/h and 8, respectively. The observed (2×4) surface reconstruction during the SPSL and SQW deposition reflects the two-dimensional nucleation growth mode, which was monitored by additional experiments.

We studied the low-temperature magnetotransport properties of samples with a Hall-bar-geometry. Some of the samples were covered by a Ti/Au gate electrode. The gate was used to change the electron density and to investigate the electronic structure by voltage-dependent capacitance (CV) measurements. In all measurements the magnetic field was applied perpendicular to the surface.

TABLE I. Peak mobilities μ_H, electron densities n, and τ_t/τ_s for two distances d_δ of the δ-doping layer from the SQW interface in ungated samples at $T = 0.33$ K.

Sample	d_δ (nm)	μ_H ($\mathrm{m^2/V\,s}$)	n_H ($10^{16}\ \mathrm{m^{-2}}$)	n_{SdH} ($10^{16}\ \mathrm{m^{-2}}$)	τ_t/τ_s
S1	14	120	1.14	1.15	35
S2	10	84.5	1.46	1.45	47

The main result of our investigations is the simultaneous observation of a very high mobility and very high electron densities. Figure 1 shows the dependence of the parallel ρ_{xx} and transverse ρ_{xy} components of the resistivity tensor on the magnetic field. The electrons occupy only one subband which is manifested by Shubnikov-de-Haas (SdH) oscillations with only one frequency of the corresponding σ_{xx} component of the conductivity tensor up to the highest gate voltages. We used the procedure described in Ref. [13] to derive the electron densities n_{SdH} from the SdH frequency according to $\sigma_{xx} \sim \sigma_{\mathrm{osc}} \cos(2\pi E_f/\hbar\omega_c)$. Here E_f denotes the Fermi energy and ω_c is the cyclotron frequency. The prefactor σ_{osc} contains information about the single particle relaxation time τ_s. In Table I the highest electron densities n_{SdH} are listed for the samples without any gate electrode. These values are in excellent agreement with the carrier densities n_H calculated from the low field Hall effect $\rho_{xy} = \gamma/qn_H$ using the Hall factor $\gamma = 1$. Together with the exact value $\rho_{xy}^{\nu} = h/q^2\nu$ and $\rho_{xx}^{\nu} = 0$ in the quantum Hall regime for the integer filling factor ν, these results demonstrate the absence of any parallel conductance in the doping region. Therefore, we can determine the Hall mobilities of the 2DEG as $\mu_H = \rho_{xy}/\rho_{xx}$ at low magnetic fields. Now we discuss the dependence of μ_H on the electron density n_H, Fig. 2, which appears to be very unusual. While we observe a powerlike dependence $\mu_H \sim (n_H)^k$ with $1.5 < k < 2$ at lower densities (for example, $n_H < 0.95 \times 10^{16}\ \mathrm{m^{-2}}$ in sample S1), the mobility increases much more strongly up to $120\ \mathrm{m^2/V\,s}$ for $n_H > 0.95 \times 10^{16}\ \mathrm{m^{-2}}$ within a very narrow electron density region. In this range, the exponent k reaches values exceeding 8. The power $1.5 < k < 2$ at lower densities is usually related to the remote impurity scattering (RIS) by randomly distributed impurities in the doping plane [11,14]. The much larger value in the high mobility region is difficult to model by scattering theories based on random potentials. To speculate about the scattering mechanism in this region we investigate the value of the scattering time ratio τ_t/τ_s (STR). The transport scattering time τ_t is calculated according to $\tau_t = (m_{\mathrm{eff}}/e)\mu_H$. The STR for the highest mobilities is listed in Table I. We did not observe a significant change of STR with electron density. This behavior as well as the value of STR is characteristic for RIS. The lower value of the STR for sample S1 (cf. Table I) can be explained by the increasing weight of interface roughness scattering in SQW's with larger distances. We also deduce the dominance of the RIS from the slight increase of the conductivity with in-

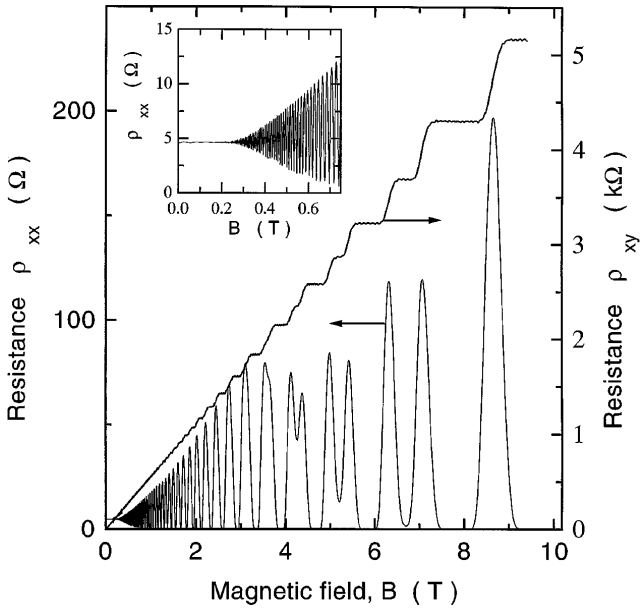

FIG. 1. Magnetic field dependence of ρ_{xx} and ρ_{xy} at $T = 0.33$ K for sample S1. The inset shows ρ_{xx} at low fields.

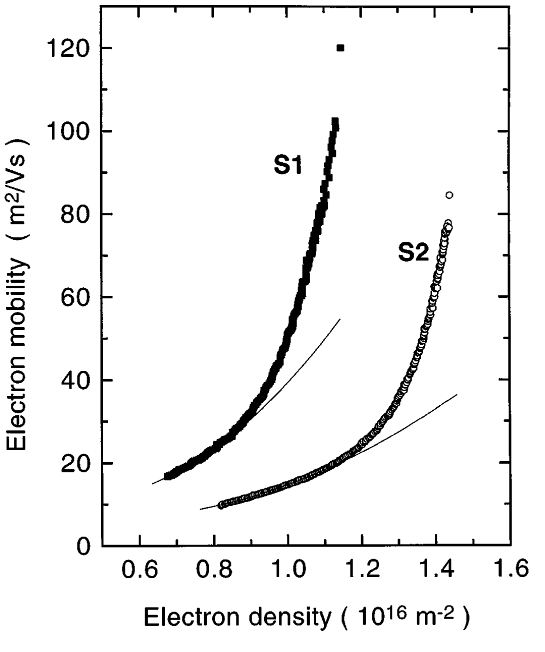

FIG. 2. Dependence of the electron mobility μ_H on the electron density n_H obtained at $T = 0.33$ K and $B = 0.1$ T for both samples using a gate. The single points of maximum mobility in both curves were measured on ungated samples. The thin lines represent a fit with the power $k = 2$.

creasing temperature. We found the maximum conductivity $n\mu = 1.35 \times 10^{18}$ (V s)$^{-1}$ and 4.20×10^{17} (V s)$^{-1}$ at temperatures 0.3 and 77 K, respectively. These values are comparable to the highest conductivities reported in SQW's at low temperatures, $T < 1$ K [4,5]. Our conductivity at 77 K is even several times higher than any value so far reported in 2DEG's [6]. To explain the enhanced mobility in our system we adopt a RIS model with a scattering potential with reduced fluctuations taking into account additional carriers with low mobility in the SPSL very close to the doping layers. To prove the existence of these carriers we show the dependence of the ac capacitance C determined with a 100 kHz excitation and $C^{2D} = q\Delta n_H/\Delta U_g$ on the gate voltage U_g in Fig. 3. While C is sensitive to all the rechargeable carriers in the system, C^{2D} carries information only from carriers in the high mobility 2DEG. The relatively flat region of C at lower gate voltages $U_g < -1.5$ V corresponds to the depletion of the electrons in the SQW. The higher capacitance at $U_g > -1.5$ V and the vanishing of C^{2D} in the same gate voltage region indicate the presence of additional carriers outside the SQW nearby the doping layer. The strong increase of the electron mobility takes place in the same gate voltage region and is, therefore, related to the existence of these carriers.

To clarify the nature of the additional carriers we show in Fig. 4 the results of model calculations of the potential and charge distribution in our structure [15]. These calculations account for two different kinds of electrons. First, we consider the usual Γ electrons with the isotropic effective mass $m_\Gamma/m_e = 0.07$, which form the 2DEG ground subband. These electrons with high mobility are located in the SQW. The edge of the higher Γ-electron subbands in the SQW as well as in the SPSL are more than 170 meV above the Fermi energy. Therefore, they cannot be occupied at low temperatures. The possible maximum density for the conductivity with a single subband occupation is not yet known. Our model calculations show that this value can be much higher than 2×10^{16} m^{-2}. Second, we have to include the higher conduction band minima of the AlAs/GaAs-SPSL system into the calculation. It is known from experiments with AlGaAs/AlAs multiple quantum wells [16] that at AlAs-thicknesses $d_{\mathrm{AlAs}} < 3-4$ nm the so-called X_z electrons govern the transport properties. These are electrons with an in-plane effective mass of about $m_{\mathrm{eff}}/m_0 = 0.25$, while the heavy mass component $m_{Xl}/m_e = 1.1$ in AlAs accounts for the subband quantization. Our calculations show that the X_z states are occupied first. The perpendicular states, the so-called X_{xy} states are well above the Fermi energy and cannot be occupied by electrons at low temperatures. Because of the high quantization energy we can neglect the influence of biaxial compressive stresses and intermixing effects, which may be important for much wider AlAs quantum wells [17]. Our simple calculations do not account for any spatial lateral fluctuations in the SPSL, but show quantitatively that in the system the X electrons appear in the AlAs layer closest to the δ-doped GaAs layer. Their quantity and spatial distribution,

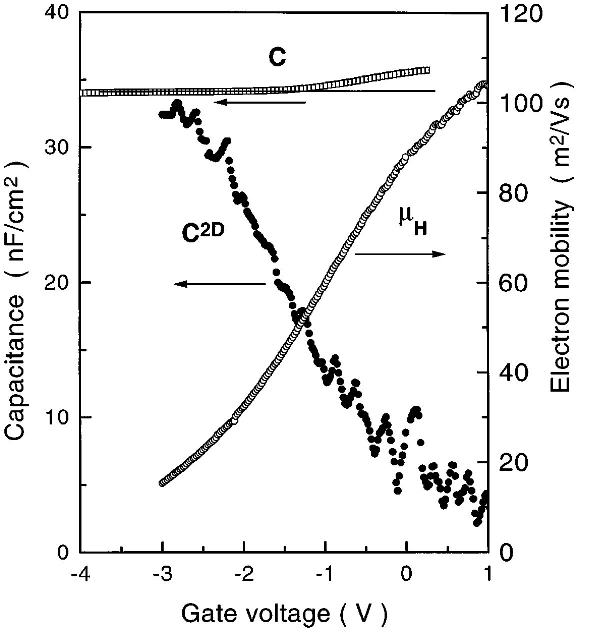

FIG. 3. Dependence of capacitances C, C^{2D}, and mobility μ_H on the gate voltage. The line, which extrapolates the flat region of C, is a guide to the eye. It corresponds to the CV characteristic without the X electrons.

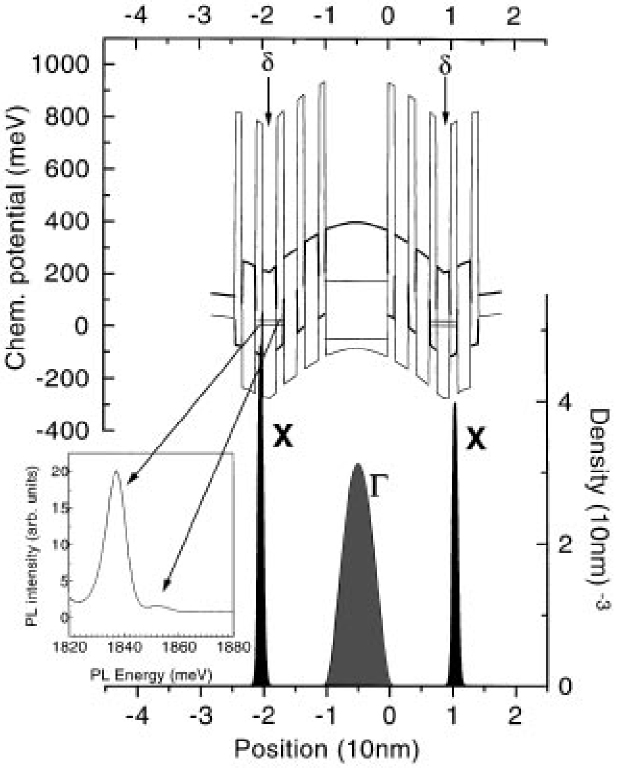

FIG. 4. Calculated potential (upper part) and distribution (lower part) of the X and Γ carriers, thick line V_X, thin line V_Γ. Thin horizontal lines represent the subband edge energies. Note the level splitting of the X-band electrons. The inset shows a typical PL spectrum for the type-II recombination.

however, depend sensitively on the interface structure and the lateral potential fluctuations. We assume that the additional carriers detected in the CV measurements of Fig. 3 are X electrons near the δ-doping layer, which, however, do not contribute to the conductivity. From CV measurements we estimate the concentration of these carriers, which strongly depends on the gate voltage, to have a maximum value of a few 10^{15} m^{-2}.

Our results show conclusively that with X electrons in the SPSL the mobility of the electrons in the GaAs SQW is considerably increased. The explanation follows directly from our calculations, which show that the X electrons are located in the AlAs layer on one side of the doped GaAs layer in the SPSL (cf. Fig. 4). Their expected Bohr radius $a_B^X \approx 2-3$ nm, as well as their nominal distance from the doping layer $d \approx 1.7$ nm, is considerably smaller than the average distance between the Si-dopant atoms $d_D = 1/\sqrt{N_D} \approx 8-9$ nm. Therefore, the X electrons can be very easily localized at the minima of the fluctuating potential caused by the randomly distributed dopants. This localization explains the absence of any measurable parallel conductivity originating from the X electrons in the magnetotransport experiments. Moreover, it is known that additional localization effects take place in systems with disorder at high magnetic fields [18]. The high effective mass of the X electrons result in a screening parameter, which is several times higher than that of the Γ electrons. Therefore, the X electrons screen the fluctuating potential of the ionized Si impurities more effectively and selectively, leading to an increase of the mobility of the Γ electrons in the GaAs SQW. We expect this effect to be similar to the mobility enhancement by an increasing correlation in the spatial distribution of the impurities [19].

To study the energy spectrum of the X electrons, we have carried out photoluminescence (PL) measurements. In all our samples the PL spectra for the type-II recombination region show a double-peaked band (see inset of Fig. 4). This structure follows directly from the subband splitting of the X electrons in the SPSL, which is caused by the electric field of the separated X and Γ electrons. The indirect recombination is possible from the AlAs layer on both sides of the GaAs layer with a small energy difference. According to calculations this subband splitting with an energy separation of nearly 20 meV depends weakly on the position and the doping density (cf. Fig. 4). This splitting is close to the observed peak separation in the PL. The higher density of X electrons at the lower energy sublevel explains the higher intensity of the low-energy side peak in the PL spectra.

In conclusion, we have shown that impurity scattering in remotely doped GaAs single quantum wells (SQW) can be effectively reduced by the presence of heavy-mass X electrons within the AlAs/GaAs SPSL in the direct vicinity of the dopant atoms in the barrier. These X electrons exhibit an extremely high screening capability and are able to smooth the potential fluctuations caused by the random distribution of the dopants. They are strongly localized and do not contribute to the conductivity. Investigations of the voltage dependent capacitance and of the photoluminescence as well as self-consistent calculations confirm the existence of X electrons in the AlAs/GaAs SPSL barriers.

The authors wish to thank M. Hoericke for MBE growth and A. Riedel for assistance with the sample preparation. We thank H. Grahn for a careful reading of the manuscript.

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