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Effects of repulsive and attractive ionized impurities on the resistivity of semiconductor heterostructures in the quantum Hall regime

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We have investigated experimentally and theoretically the effect of repulsive and attractive ionized impurities on the resistivity components (ρ_{xx} and ρ_{xy}) in the quantum Hall effect regime. GaAs/GaAlAs asymmetric modulation-doped quantum wells with additional delta doping (by Si donor atoms or Be acceptor atoms) in the GaAs channel or at the AlGaAs/GaAs interface has been grown using molecular beam epitaxy technique. Magnetotransport experiments, performed on samples doped with Si-attractive atoms, showed a plateau width increasing toward lower magnetic field at even filling factor. However, when samples were delta doped with Be repulsive atoms, the increase was observed in the opposite side. Part of the results was explained using a model based on the fifth Klauder's approximations where we demonstrate that the asymmetrical increase of the Hall plateaus with even filling factor (Landau gaps) is related to the asymmetry induced in the density of states by the additional impurities: the resulting disorder short range potential broadens and shifts the Landau levels but also creates impurity bands on the lower energy side of the Landau levels in the case of donors and on the upper energy side of the Landau levels in the case of acceptors. We notice that this asymmetrical behavior was not experimentally observed for odd filling factor plateaus (exchange gaps). We have also experimentally underscored the screening effect by free two-dimensional electrons of this disorder short range potential. Moreover, for delta-doped Be samples, the whole $\nu=1$ Hall plateau was shifted toward higher magnetic field with respect to the classical Hall effect. This shift, observed for all samples, cannot be explained by the asymmetry of the density of states but rather by a magnetic delocalization of electrons from the upper energy impurity band associated with the last Landau level ($n=0$) into the free $n=0$ Landau states when this impurity band overtakes the Fermi level at the end of the $\nu=2$ plateau. This magnetic delocalization effect is the opposite effect of the magnetic freeze out.

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I. INTRODUCTION

The role of impurities on the density of states (DOS) of a two-dimensional electron gas (2DEG), particularly in the presence of a perpendicular magnetic field, has been intensively studied. The first analytical calculation of the DOS was made by Ando *et al.*[1,2] using the self-consistent Born approximation and treating the disruptive potential as a delta function. Recently, in order to analyze far infrared (FIR) absorption experiments and magnetotransport experiments performed on particular structures with a controlled disorder, Bonifacie *et al.*[3] calculated the DOS of a 2DEG in the presence of a strong disorder created by two delta-doped layers. The first one located behind the spacer contains the parent donors of 2D electrons; the second one containing Si donor atoms or Be acceptor atoms is located in the 2D quantum well of conducting electrons. These new types of GaAlAs-GaAs heterostructures have been studied (both theoretically and experimentally) in the quantum Hall effect (QHE) regime by several groups.[4–13] Magnetotransport experiments were performed simultaneously with FIR magnetoabsorption experiments and show spectacular phenomena. The first one related to the so-called disorder mode[5] shows a second cyclotron line[6] and appears in the case of acceptors δ-doped structures. For those structures another remarkable phenomenon is the presence of a series of additional peaks in the cyclotron resonance spectrum attributed to localized acceptor states according to Bonifacie *et al.*[6] In magnetotransport experiments Haug *et al.*[4] observed that because of the presence of charged impurities, the plateaus of the Hall resistivity ρ_{xy} do not occur symmetrically with respect to the classical Hall effect $\rho^0_{xy}=B/eN_S$, where N_S is the surface density of the 2DEG and e is the elementary charge. They found that the additional doping of the GaAs channel with donor or acceptor atoms shifts the positions of QHE plateaus and of the corresponding ρ_{xx} minima to opposite directions. For donor-doped samples, the plateaus are shifted toward lower magnetic field values, i.e., larger values of the filling factor $\nu=hN_S/eB$, whereas for acceptor-doped samples the shift is toward smaller filling factors (higher magnetic field values). Haug *et al.*[4] made a microscopic transport calculation emphasizing non-Born scattering of electrons by individual impurities, which principally interpreted these results in terms of the asymmetry of the density of states. In a previous study made on Si metal-oxide-semiconductor field-effect transistors, Furneaux and Reinecke[14] investigated the effects of driftable Na$^+$ ions in the oxide on the width and the position of the Hall plateaus. They interpreted their results in terms of an asymmetric distribution of localized states in the band edges of overlapping Landau levels (LLs).

In this paper we present additional results obtained on structures with a controlled disorder: we reanalyze both ex-

TABLE I. Sample characteristics: N_i: density of additional impurities; z_0: distance of additional δ-layer impurities from the GaAs/GaAlAs interface; x: AlAs percentage; d: spacer thickness; w: width of the GaAs channel; N_S: density of 2D electrons; and μ: mobility of 2D electrons at low temperature.

Samples	Nature of impurity	N_i (10^{10} cm^{-2})	z_0 (Å)	x (%)	d (Å)	w (Å)	N_S (10^{11} cm^{-2})	μ (10^5 cm^2/V s)
S908	Reference			25	400	250	2.2	8.9
SA14	Si	2	+20	25	400	250	2.46	1.4
P810	Si	8	+30	33	100	250	6.13	0.79
B9B11 (dark)	Reference			33	250	250	2.05	4
B9B11 (light)	Reference			33	250	250	5.2	11
B9B18	Be	1	+20	33	250	250	2.18	0.8
35A52	Reference			26.8	400	250	2.7	5
35A53	Be	2	+25	26.8	400	250	2.5	0.88
		2	0					
35A54	Be			26.8	400	250	2.25	0.36
		2	+25					
35A55	Be	4	+25	26.8	400	250	1.36	0.53

perimentally and theoretically the role of ionized impurities located near the 2D conducting channel on magnetotransport phenomena in the QHE regime. Samples with different densities of Si or Be atoms in the delta layer located in the 2D quantum well have been investigated. We analyze the asymmetrical increase of the Hall plateaus and of the minima of ρ_{xx} as a function of the density of impurities, their nature, their location, the density of free electrons (screening effect), and the temperature. We then interpret our findings by a comparison between the experimental results and the results of the calculations[3] developed on the basis of the density of states obtained by using the multiple scattering approach proposed by Klauder[15] and the averaging procedure proposed by Ando.[1]

The paper is organized as follows. In Sec. II we characterize the investigated samples. Section III is dedicated to the theoretical investigations based on the previous study of the density of states for a disordered 2DEG;[3] in Sec. IV a comparison is made with experimental results, which shows a good agreement.

II. SAMPLE CHARACTERISTICS

Our samples are modulation-doped GaAs/Ga$_{1-x}$Al$_x$As asymmetric single quantum wells grown by molecular beam epitaxy (MBE). For all the investigated samples, the structure is delta doped (δ doped) in the GaAlAs barrier on one side by two planes of Si donors; the closer one from the interface contains parent donors which provide the conducting GaAs quantum well with 2D electrons. Moreover, excepted for reference structures, during the growth process either Si or Be additional impurities were introduced via a δ-doped layer located either at the interface or in the GaAs quantum well. The nature of the additional ionized impurities, the effective distance z_0 between this δ-doped layer and the interface, as well as the additional impurity density N_i, and the free-electron density N_S were the essential parameters of our systematic study. The experiments have been performed in a large temperature range (down to 50 mK for some samples) and under high magnetic field (up to 23 T for some samples). The characteristics of the investigated samples are reported in Table I.

III. THEORETICAL ANALYSIS

The simulations were performed using the model developed by Bonifacie *et al.*[3] where the density of states was calculated for a 2DEG located at the interface of a strongly disordered GaAs/GaAlAs heterojunction under a perpendicular magnetic field of arbitrary strength (fifth Klauder's approximation[15]). Hall resistance (R_{xy}) was calculated for GaAs/GaAlAs heterostructures with additional δ-doped layer (Si or Be) in the vicinity of the 2D conducting channel. We used the same parameters as in Ref. 3. The following approximations are made here: (i) the presence of residual acceptors in the GaAs channel was not taken into account; (ii) the spin splitting enhancement by the exchange interaction of electrons[16] was neglected. The disordered potential is created by two δ-doped layers. The first layer is located within the GaAlAs barrier at $z_0=-500$ Å from the interface. It contains the parent donors providing the quantum well with 2D electrons and creates a smooth disorder. The main effect of the corresponding long range potential of weak amplitude is the broadening of the Landau levels. The second layer doped with either donor or acceptor impurities is close to the GaAs/GaAlAs interface and consequently induces a strong disorder. The resulting short range potential of higher amplitude not only broadens and shifts the LLs but also creates impurity bands on the low energy side of LLs in the case of donors and on the upper energy side of LLs in the case of acceptors.[13,17] Furthermore, the consequence of the presence of disorder is the strong anharmonicity of the Landau ladder.[3]

For the calculations of the Hall resistance R_{xy} we took the simple assumption that all the states are localized except one state whose energy E_n is given by the maximum of the nth Landau level.[18,19] Furthermore, we assumed that the contribution of each of this level to the Hall conductivity is e^2/h. Then the Hall resistance is given by

$$R_{xy}^{-1} = \frac{e^2}{h}\sum_n [1 - f(E_n)], \tag{1}$$

where $f(E)$ is the Fermi distribution.

In order to calculate the density of states more efficiently we replaced in our theoretical model the random potential by a Gaussian one defined by $v(r)=(V_0/\pi d^2)\exp(-r^2/d^2)$, where V_0 is the strength of the potential and d is its spatial extent. V_0 and d are the fitting parameters to adjust the single electron energies with the ones obtained by the complete calculations. For a typical reference sample with only one δ-doped layer of Si donors of density $N_D=4\times10^{11}$ cm^{-2} in the GaAlAs barrier at $d_0=-500$ Å from the interface, we took for those parameters: $d=500$ Å and $V_0/\pi d^2$ $=0.17$ meV.[3] Figure 1(a) shows the calculated Hall resistance vs magnetic field at different temperatures (0.1–10 K) and the surface density is $N_s=2\times10^{11}$ cm^{-2}. Except for the lower temperature ($T=0.1$ K), all the plateaus are not symmetrical with respect to the crossing point of the ρ_{xy} curves (integer value of the filling factor ν). This is related to the asymmetrical doping with Si donors (in the GaAlAs barrier) and the fact that the residual acceptors of the GaAs channel were neglected.

Figure 1(b) depicts the case of sample with additional Si donor impurities at the interface ($z_0=0$) with density $N_i=2$ $\times10^{10}$ cm^{-2}. The fitting parameters are $d=90$ Å, $V_0/\pi d^2$ $=+8.5$ meV (short range Gaussian potential) and all others parameters are the same as in the previous case [Fig. 1(a)]. Figure 1(b) shows clearly a strong asymmetry of the Hall plateaus with respect to the crossing point even for the lower temperature: the width of the plateaus increases toward the lower magnetic field values when the temperature is decreased.

In the case of samples with additional doping of Be repulsive acceptors at the interface ($N_i=2\times10^{10}$ cm^{-2}) we used a short range potential where $d=90$ Å and $V_0/\pi d^2$ $=-8.5$ meV. The surface density of 2D electrons is the same as for the reference sample and for the Si δ-doped sample ($N_S=2\times10^{11}$ cm^{-2}). The asymmetry of the Hall plateaus is much stronger and increases rapidly when the temperature decreases [Fig. 1(c)]. The width of the plateaus increases now toward the higher magnetic field values. We will see in the following that this behavior is experimentally verified.

In Fig. 2, we report a summary of the different observations. It shows the Hall resistance vs magnetic field at 0.1 K for the three cases: the reference structure, the δ-doped structure with attractive donors at the interface, and the δ-doped structure with repulsive acceptors at the interface. The much stronger effect obtained for the acceptor case is clearly shown.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Effect of impurity's nature and density

Figure 3 shows the resistivity components ρ_{xx} and ρ_{xy} vs magnetic field at different temperatures (1.5–10 K) for a reference sample S908. Shubnikov–de Haas oscillations show a strong asymmetric behavior in the vicinity of the plateaus with even filling factor. This was early reported by Haug *et al.*[20] Nevertheless the Hall plateaus with exact quantization in h/ie^2 are symmetric with respect to classical free-electron line $\rho_{xy}^0=B/eN_S$. We can notice that the symmetry is also perfectly respected for ρ_{xy} and for the domain of zero values of ρ_{xx} around filling factor $\nu=1$.

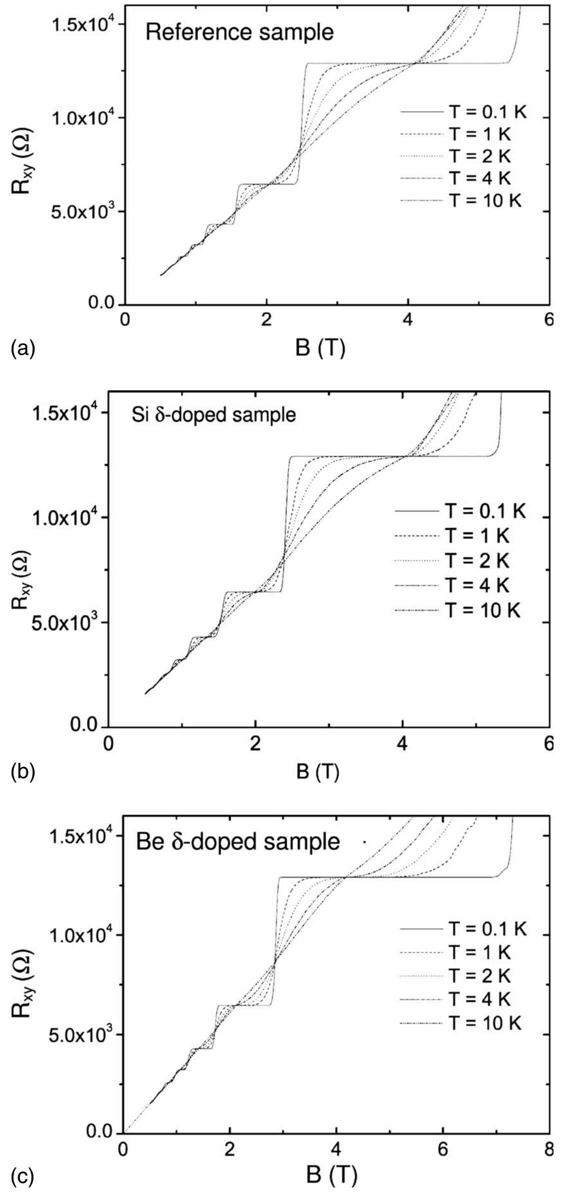

FIG. 1. Theoretical Hall resistance at different temperatures for three different samples with a surface density $N_S=2\times10^{11}$ cm^{-2}. Figure 1(a): reference sample. Figure 1(b): sample with additional Si donor impurities at the interface ($N_i=2\times10^{10}$ cm^{-2}). Figure 1(c): sample with additional Be acceptor impurities at the interface ($N_i=2\times10^{10}$ cm^{-2}).

The transport experimental results for sample SA14 with additional δ-doped layer of 2×10^{10} cm^{-2} Si atoms in the GaAs channel at $z_0=+20$ Å from the interface are presented in Fig. 4. An increase of the Hall plateaus width toward lower magnetic fields is observed for the even filling factor

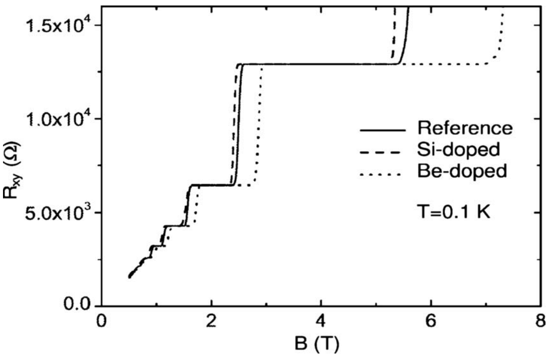

FIG. 2. Theoretical Hall resistance at 0.1 K for the three cases, reference sample, and samples with additional donor or additional acceptors at the interface.

($\nu=2$ for example). As shown by the calculations this asymmetry is larger when the temperature is decreased. We notice that the $\nu=1$ plateau as well as the corresponding domain where $\rho_{xx}=0$ are still symmetric with respect to the crossing point in the whole temperature range.

Figure 5 shows the case of sample B9B18 where the δ doping in the quantum well was made by Be acceptor atoms (1×10^{10} cm^{-2}). The surface density is close to that of other two samples SA14 and S908 (reference; Table I). In Fig. 5(a) the transport measurements under dark conditions and for $T=1.8$ K and $T=4.2$ K are reported. The sample was then illuminated by a light-emitting diode to increase the electron density ($N_s=5.07\times10^{11}$ cm^{-2}) and the results are reported in Fig. 5(b) for $T=1.5$ K and 50 mK. Two important remarks can be made: (i) for even filling factor, the plateaus are nonsymmetrical with respect to the classical Hall effect ρ_{xy}^0 but now the width increases toward higher magnetic field values; (ii) for odd filling factor [$\nu=1$ in Fig. 5(a) and $\nu=3$ in Fig. 5(b)], when the temperature is low enough, the whole plateau is shifted toward high magnetic field. However, the symmetry of ρ_{xx} and ρ_{xy} is conserved with respect to the middle of the plateau. We observe also that, as demonstrated theoretically, the increase of the plateau width for a lower value of the additional impurity density, in the case of acceptors, is stronger than for additional donor impurities (sample SA14). Depending on filling factor value (even or odd), the width of the Hall plateaus shows different behaviors as a function of temperature when the sample is doped with acceptors or donors. For even values of ν (Landau gaps), the increase is asymmetric and the asymmetry depends on the nature of the impurity. However for odd values of ν (exchange gaps), the

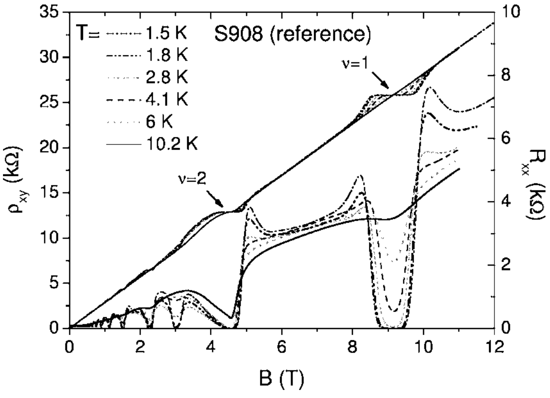

FIG. 3. Resistivity components ρ_{xx} and ρ_{xy} vs magnetic field at different temperatures (1.5–10 K) for reference sample S908.

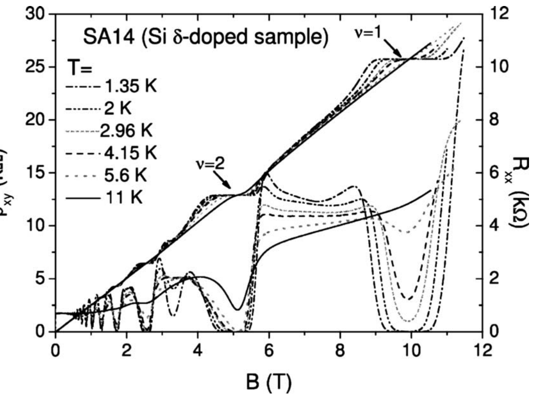

FIG. 4. Resistivity components ρ_{xx} and ρ_{xy} vs magnetic field at different temperatures (1.35–11 K) for sample SA14 with an additional δ-doped layer of 2×10^{10} cm^{-2} Si donors atoms in the GaAs channel at $z_0=+20$ Å from the interface.

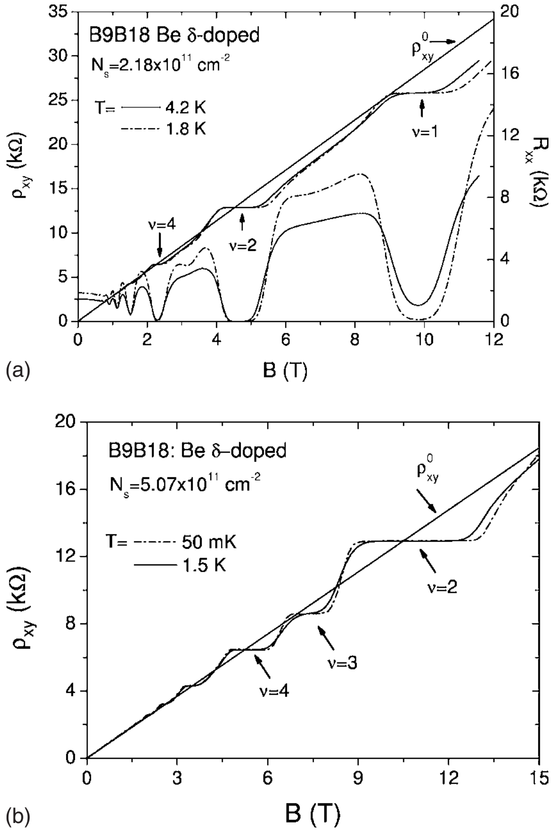

FIG. 5. Resistivity components ρ_{xx} and ρ_{xy} vs magnetic field for sample B9B18 with an additional δ-doped layer of 1×10^{10} cm^{-2} Be acceptor atoms in the GaAs channel at $z_0=+20$ Å from the interface. Figure 5(a): ρ_{xx} and ρ_{xy} measurements under dark conditions ($N_S=2.18\times10^{11}$ cm^{-2}) for $T=1.8$ K and $T=4.2$ K. Figure 5(b): ρ_{xy} measurements under illumination ($N_S=5.07\times10^{11}$ cm^{-2}) for $T=1.5$ K and $T=50$ mK.

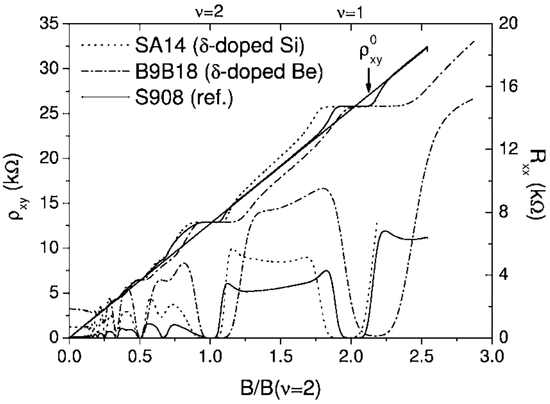

FIG. 6. Resistivity parameters ρ_{xx} and ρ_{xy} vs magnetic field normalized by the value of B giving the filling factor $\nu=2$ for samples S908 (reference sample), SA14 (Si δ-doped sample), and B9B18 (Be δ-doped sample). Measurements at $T=1.8$ K.

increase is in all cases symmetric with respect to the middle of the plateaus.

All these cases are summarized in Fig. 6 where the three previously discussed samples are reported. The resistivity parameters ρ_{xx} and ρ_{xy} are shown at 1.8 K vs the magnetic field B normalized by the value of B giving the filling factor $\nu=2$. This value of B ($\nu=2$) is determined using the value of the surface density N_S measured at low magnetic field by using the classical Hall effect ρ_{xy}^0.

Samples 35A52 (reference), 35A53, 35A54, and 35A55 have been grown on the same wafer and under the same conditions with different Be impurity concentrations and positions (Table I). More, sample 35A54 presents two δ layers of 2×10^{10} cm^{-2} Be atoms, the first one at the interface and the second one at $z_0=+25$ Å from the interface in the GaAs channel. Figure 7 depicts the evolution of the Hall resistivity ρ_{xy} versus the normalized magnetic field for those samples. It is clearly shown that the increase of the width of the $\nu=2$ plateau toward the higher magnetic field values as well as the shift of the whole $\nu=1$ plateau are more and more pronounced when the density of acceptor atoms increases and when the acceptor atoms are closer to the 2DEG.

As a first conclusion we can say that, unlike Haug *et al.*,[4] we observed a shift of the Hall plateaus only for the case of Be repulsive impurities for odd value of the filling factor ν, particularly for $\nu=1$ (see Fig. 7). In other cases, i.e., even values of ν for Be repulsive impurities and even or odd values of ν for Si-attractive impurities, we observed an asymmetrical increase of the plateaus with respect to the classical Hall effect ρ_{xy}^0, as proposed by our model (see Fig. 2).

B. Shift of the whole $\nu=1$ Hall plateau for additional acceptor impurity samples

So the most surprising effect we observed is, for additional acceptor impurity samples, the shift of the whole $\nu=1$ Hall plateau with respect to the curve ρ_{xy}^0 toward the higher magnetic field values. This behavior occurred for all the acceptor δ-doped samples we investigated, even the ones with a low density of additional acceptor atoms and consequently with a relative high mobility. The main difference in the density of states between samples with additional acceptor impurities and samples with additional donor impurities is that, in the first case, the impurity band is formed in the upper energy side of the Landau levels (above the free Landau states), while in the second case, it is formed below the free Landau states.[13,17] Following Gurvitz,[13] who developed a carrier transport model between edge states with resonant scattering on impurities,[22] the localized quasibound states due to repulsive impurities are above the center state of Landau levels, a state which remains delocalized and thus participates to the conduction. Thus under increasing magnetic field, when the acceptor states associated to the last Landau level ($n=0$) overtakes the Fermi level (end of the $\nu=2$ plateau), if the impurity band is well separated from the free $n=0$ Landau states, and if the temperature is low enough, the corresponding localized electrons fall down in these free Landau states. Consequently the free-electron density N_S increases of a quantity ΔN_S and the next plateau ($\nu=1$) is shifted of a corresponding ΔB value. This magnetic delocalization or "magnetic thaw out" is the opposite effect of the magnetic freeze-out effect observed with donor impurities.[21]

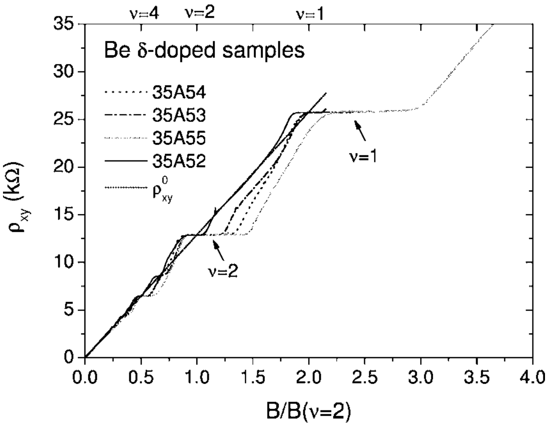

FIG. 7. Evolution of the Hall resistivity ρ_{xy} at 1.5 K vs magnetic field normalized by the value of B giving the filling factor $\nu=2$ for a series of samples with different Be impurity concentration: sample 35A52 is the reference sample, samples 35A53 and 35A55 have an additional δ layer of Be acceptors at 25 Å from the interface with 2×10^{10} and 4×10^{10} cm^{-2} impurities, respectively, and sample 35A54 presents two layers of 2×10^{10} cm^{-2} Be atoms, respectively, the first one at the interface and the second one at $z_0=+25$ Å from the interface in the GaAs channel.

C. Screening effect

We have also studied experimentally the effect of the screening by free electrons of the ionized impurity potentials.[23] We used for this study two different ways: the first one was to change during transport experiments the density N_S of 2D electrons by illuminating the sample; the second one was to perform transport experiments on two samples with different values of N_S. As an example we report in Fig. 8 the transport coefficients measured at 1.8 K (1.5 K) versus normalized magnetic field for sample B9B18 with 1×10^{10} cm^{-2} additional acceptors at $z_0=+20$ Å from the in-

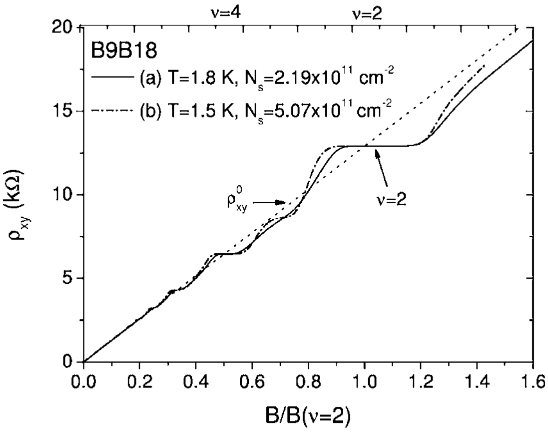

FIG. 8. Hall resistivity ρ_{xy} vs magnetic field normalized by the value of B giving the filling factor $\nu=2$ for sample B9B18, with 1×10^{10} cm^{-2} additional acceptors at 20 Å from the interface. Curve (a) without illumination, $N_S=2.19\times10^{11}$ cm^{-2}; curve (b) under illumination, $N_S=5.07\times10^{11}$ cm^{-2}.

terface in the GaAs channel. Curve (a) shows the Hall resistivity measured without illumination ($N_S=2.19\times10^{11}$ cm^{-2}) and curve (b) shows this resistivity measured under illumination ($N_S=5.07\times10^{11}$ cm^{-2}). We observe that the asymmetrical width increase toward the higher magnetic field values of the even filling factor plateau ($\nu=2$) is less pronounced for the higher value of N_S. This means that in this case, the screening of the short range potential due to the additional acceptors by the free 2D electrons is stronger.

We report also in Fig. 9 the Hall resistivity measured at 1.8 K for sample SA14 ($N_S=2.46\times10^{11}$ and 2×10^{10} cm^{-2} Si atoms in the GaAs channel at $z_0=+20$ Å from the interface) and for sample P810 ($N_S=6.13\times10^{11}$ and 8×10^{10} cm^{-2} Si atoms in the GaAs channel at $z_0=+30$ Å from the interface). The asymmetrical width increase of the $\nu=2$ plateau toward the lower magnetic field values is less pronounced for sample P810, although the density of additional donors is much larger for this sample. We conclude that, in this case too, this results from a larger screening effect of the short range potential by a larger density of free 2D electrons.

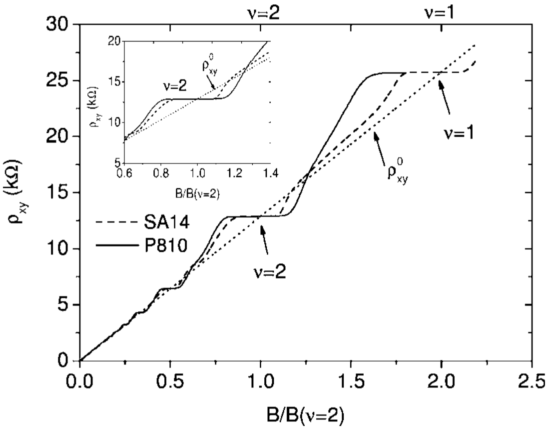

FIG. 9. Hall resistivity ρ_{xy} vs magnetic field normalized by the value of B giving the filling factor $\nu=2$ for two samples with different values of the surface density N_S and of the additional Si donors: sample SA14 with $N_S=2.46\times10^{11}$ and 2×10^{10} cm^{-2} Si atoms in the GaAs channel at $z_0=20$ Å from the interface; sample P810 with $N_S=6.13\times10^{11}$ and 8×10^{10} cm^{-2} Si atoms in the GaAs channel at $z_0=30$ Å from the interface.

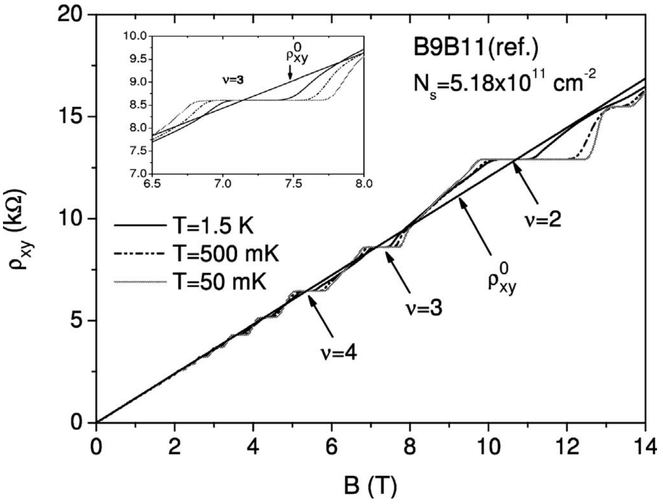

FIG. 10. Hall resistivity ρ_{xy} vs magnetic field measured under light at three different temperatures for the reference sample B9B11. This sample has not additional δ-layer impurities but it was grown in the same MBE machine as the Be δ-doped structures.

D. Spatial distribution of the additional impurities

We have also measured transport coefficients under light for a reference sample B9B11 which has no additional δ-layer impurities. However this sample was grown in the same MBE machine as the Be δ-doped structures and consequently has a residual density of Be acceptors in the GaAs quantum well. The Hall resistivity ρ_{xy} is reported in Fig. 10 for three different temperatures: 1.5, 0.5, and 0.05 K. We see that, while at 1.5 K the plateaus are almost symmetrical, the width increase of the $\nu=2$ plateau toward the higher magnetic fields becomes very strong for 0.5 K and even more for 0.05 K. This behavior is different (when compared to Fig. 5) from the one observed for samples with an additional δ layer of Be impurities and can be related to the presence of randomly distributed residual impurities in the channel: the difference lies in the strength of the Coulomb potential, which is much smaller in the case of residual doping than in the case of an additional δ layer of Be in the channel.

Nevertheless, in this case too we observe a shift even at 1.5 K, of the $\nu=3$ plateau, which also shows a symmetrical increase with respect to the center of the plateau when the temperature is decreased. More, we can notice that the $\nu=5/3$ plateau (many-body gap) which appears for 0.5 and 0.05 K at 13.4 T is clearly shifted with respect to classical Hall effect toward the higher magnetic field values.

V. SUMMARY

We have studied the consequences on transport coefficient in the quantum Hall effect regime of the presence of additional attractive or repulsive ionized impurities close to a two-dimensional electron gas. We showed, by calculations based on the fifth Klauder's approximation, that the asymmetrical width increase (which depends on the nature of impurities) observed for the even filling factor Hall plateaus (Landau gaps) is well explained by the asymmetry induced in the density of states by the presence of these disruptive impurities. We showed theoretically and we verified experimentally that this effect is stronger in the case of repulsive additional Be acceptors compared to the case of attractive additional Si donors and that the asymmetrical width increase is more pronounced when the temperature is decreased. For odd filling factor plateaus (exchange gaps), we observed experimentally in the whole investigated temperature range a symmetrical width increase with respect to the middle of the plateaus both for additional acceptors and additional donors structures. We have no explanation for this specific behavior.

We have also experimentally underscored the effect of screening by the free 2D electrons of the resulting disorder short range potential and we showed that the size of the increase of the plateaus width depends strongly, at a given temperature, on the distribution of the additional impurities.

More, in the case of additional repulsive Be acceptors, we observed a shift of the whole $\nu=1$ plateau with respect to the classical Hall effect which can be explained by the "magnetic thaw out" of electrons from the upper energy impurity band into the free states of the last $n=0$ Landau level at the end of the $\nu=2$ plateau. This effect is the opposite effect of the magnetic freeze-out effect.

ACKNOWLEDGMENT

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