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Metastability of the quantum Hall states in asymmetric two-layer systems

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Abstract. A GaAs–$Al_xGa_{1-x}As$ asymmetric double-quantum-well structure exhibits a metastability in the quantum Hall regime when the system is illuminated, under a high magnetic field sufficient to depopulate the excited-state subband. The photo-generated electrons are transferred to the excited-state subband when its bottom Landau level falls below the Fermi level at lower magnetic fields. The metastability is attributed to the potential renormalization associated with the charge transfer. The amount of the transferred charge can be controlled by varying the minimum magnetic field and remains unchanged as long as the magnetic field stays above the previous minimum value.

The space charge accumulation in a quantum well has been known to be responsible for an intrinsic bistability of resonant tunnelling diodes [1]. When electrons are dynamically stored in the well, the bottom of the subband that mediates the resonant tunnelling is shifted upward in energy. The resonance condition is thus maintained up to higher biases. As this is not the case when the bias is decreased from the off-resonance condition, i.e., when the subband level is below the states in the emitter and hence the well is empty, a hysteresis appears in the current–voltage characteristics [1].

We show in this paper that the space charge accumulation gives rise to a metastability of the quantum Hall states in a double-quantum-well (DQW) structure having different well widths. In contrast to the dynamical effect in the resonant tunnelling diodes, the metastable states show up at the 'equilibrium' condition. A key procedure for realizing the metastability is to illuminate the device in high magnetic fields, where the subband in the narrow well is depopulated. The potential renormalization associated with the interlayer charge transfer gives rise to a situation in which the additional electrons are exclusively accommodated in the excited-state subband (ESS) when the Landau-level crossing takes place at the Fermi level [2–4]. Due to the depopulation of the ESS, the electrons released from the DX centres remain in the $Al_xGa_{1-x}As$ layer as *nonequilibrium* carriers. With decreasing magnetic field (after the illumination is turned off), the ESS can be filled with electrons when its bottom Landau level falls below the Fermi level. It is found that the charge transfer is strongly restricted again as a consequence of the potential renormalization. We demonstrate that the amount of charge transfer can be regulated systematically by lowering the magnetic field. Each metastable state is maintained until the magnetic field is lowered beyond the previous minimum value after the illumination, resulting in a hysteresis in magnetoresistances.

The GaAs–$Al_{0.3}Ga_{0.7}As$ asymmetric DQW structure was grown by molecular-beam epitaxy on a semi-insulating GaAs substrate. The conduction region consists of GaAs wells 15 nm and 10 nm wide separated by an $Al_{0.3}Ga_{0.7}As$ barrier that was 3 nm thick. The wider quantum well is located closer to the surface. A Si δ-doped layer of density 2×10^{16} m^{-2} was inserted in the $Al_{0.3}Ga_{0.7}As$ barrier layer adjacent to the wide quantum well with a spacer of 10 nm. This Si plane was buried underneath an $Al_{0.3}Ga_{0.7}As$ layer that was 100 nm thick and a GaAs cap layer doped with Si that was 10 nm thick at a density of 2×10^{24} m^{-3}. Another δ-doped sheet was inserted on the other side of the DQWs with a doping density of 3×10^{15} m^{-2}. This additional doping layer is separated from the narrow quantum well by a spacer that was 20 nm thick. The heterostructure was patterned into a Hall-bar geometry by conventional photolithography and wet chemical etching. Ohmic contacts connect both wells. Resistances were measured using standard low-frequency lock-in techniques at $T = 0.3$ K. We varied the electron density n_s in the system by illuminating the devices using a red-light-emitting diode (LED). The nominal low-temperature electron mobility at $n_s = 9 \times 10^{15}$ m^{-2} was $\sim$40 m^2 V^{-1} s^{-1}. No illumination was applied during the magnetoresistance measurements. The magnetic field B was varied at a rate of $\leqslant$0.4 T min^{-1}.

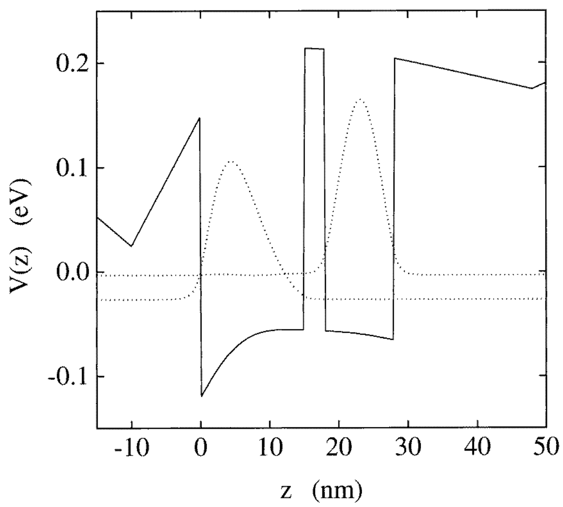

Figure 1. The potential profile $V(z)$ of the asymmetric double-quantum-well structure. The dotted lines show the threshold energy and the probability distribution of the lowest two subbands. The Fermi energy is set to zero.

Because of the asymmetry in the well width and the doping, the probability distributions of the ground-state subband (GSS) and ESS localize, respectively, in the wide and narrow quantum wells, as shown in figure 1. Note that the doping density in the subsidiary δ-doped plane is low, so the donors at $z = 48$ nm are expected to be fully ionized.

The phase diagram [5, 6] of the quantum Hall effect in this asymmetric DQW structure is shown in the inset of figure 2(b). Here, the position of the Shubnikov–de Haas (SdH) peaks in the longitudinal resistivity ρ_{xx} is plotted as a function of n_s determined by low-field Hall-effect measurements [7]. The solid lines indicate the Landau levels belonging to the wide quantum well. The two dotted lines represent the spin-polarized states of the $N = 0$ Landau level originating from the narrow quantum well. Electrons already occupy the ESS in the dark condition. The critical electron density for the occupation of the ESS is estimated to be $\sim 6.8 \times 10^{15}$ m^{-2}, which corresponds to an energy separation of 24 meV

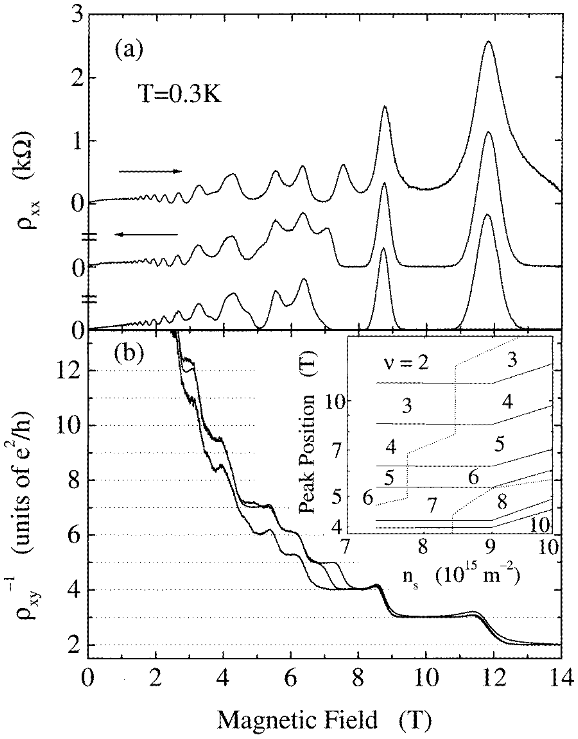

Figure 2. The metastability observed in (a) the longitudinal resistivity ρ_{xx} and (b) the inverse of the Hall resistivity ρ_{xy}^{-1} at $B \sim 7$ T. The arrows indicate the direction of the magnetic field sweep. The sample was illuminated at $B = 14$ T after the bottom curves were obtained. Inset: the phase diagram of the quantum Hall effect in the asymmetric double-quantum-well structure. The solid and dotted lines represent Landau levels originating from the wide and narrow quantum wells, respectively. The number of occupied spin-polarized Landau levels ν, determined by the quantized value of the Hall resistance, is indicated.

between the two subbands.

When $\hbar\omega_c$, where $\omega_c = eB/m$ is the cyclotron frequency, becomes larger than the impurity broadening of the Landau levels at large B, the density of states (DOS) is no longer regarded as continuous. A single spin-polarized Landau level can contain $(2\pi l_B^2)^{-1}$ electrons per unit area. Here, $l_B = (\hbar/eB)^{1/2}$ is the magnetic length. As the number of available states in each well changes with B, the electrons need to be transferred between the two wells at the Landau-level crossing. In order to make the charge transfer possible, the Landau levels in both quantum wells are pinned at the Fermi level [2, 8]. The charge transfer inevitably involves the potential renormalization, and so the phase boundary exhibits the zigzag behaviour when n_s is changed [3, 4]. The bottom Landau level in the narrow quantum well crosses the $N = 2$ and $N = 1$ Landau levels of the GSS at $n_s = 7.8$ and 8.4×10^{15} m^{-2}, respectively [9]. The electron density in the wide quantum well remains almost unchanged or slightly decreases with increasing n_s for $n_s < 8.9 \times 10^{15}$ m^{-2}. Such a behaviour is generally found around the crossing of the Landau levels at the Fermi level [3]. When n_s is away from the regime of the Landau-level crossing, the electron density increases in both quantum wells. As we show below, the metastability is strongly related to this preferential occupation of the ESS due to the Landau-level crossing.

The metastability of the quantum Hall states is demonstrated in figure 2. The bottom curve in figure 2(a) shows ρ_{xx} at the dark condition. Because of the electron occupation in the ESS, ρ_{xx} reveals a long-period oscillation in addition to the rapid oscillation due to the GSS. Moreover, split-off peaks emerge (for instance at $B = 3.6$ and 4.8 T) on the high-B side of the SdH peaks of the GSS [10]. For $B > 8$ T, the ESS is depopulated, or the Fermi level barely remains in the localized tail of the bottom Landau level. When B reached 14 T, we briefly illuminated the device while the magnetic field was kept at 14 T [11]. The middle curve shows ρ_{xx} when the magnetic field was subsequently swept down after the illumination was terminated. As suggested by the phase diagram, no change is observed for the resistance peaks due to the GSS. A resistance peak due to the ESS passed the $N = 2$ GSS Landau-level peaks and now appears at $B = 7.1$ T. A surprising observation is made for the top curve. When the magnetic field was decreased to zero, ρ_{xx} was measured again while sweeping up the magnetic field. Although no illumination was applied between the middle and top curves, a significant shift of the peak position at $B \sim 7$ T is apparent. Until the device was again illuminated, no further change was observed in ρ_{xx}.

The corresponding curves of the inverse Hall resistivity ρ_{xy}^{-1} are shown in figure 2(b). The Landau level additionally filled with electrons by the illumination is depopulated at $\sim$7 T in the middle curve. However, the depopulation threshold shifts to $\sim$7.5 T in the top curve. The transition between the Hall plateaus coincides with the peak in ρ_{xx}. As the peaks in ρ_{xx} associated with the Landau levels in the wide quantum well do not shift their position in B, it is evident that all of the photo-generated electrons are accumulated in the narrow well in the final state. Some of these electrons, however, were 'missing' in the intermediate state.

When n_s was further increased by illuminations, metastable states around the crossing with the $N = 1$ Landau level of the GSS were observed, as shown in figure 3. Here, the magnetic field was varied as illustrated in the inset. The bottom curves in figures 3(a) and 3(b) show respectively ρ_{xx} and ρ_{xy}^{-1} just before the illumination was applied (step (i) in the inset). As before, the device was briefly illuminated at $B = 14$ T and the LED was turned off. The magnetic field was then decreased to a certain value, B_{min}, and was increased again back to 14 T (steps (ii) and (iii)). We then measured the resistivities, which are plotted in figure 3, in the following step (iv). Similarly to the behaviour shown in figure 2, the curves obtained in steps (i), (ii) and (iii) are different. However, the curves obtained in steps (iii) and (iv) are identical. The rest of the traces plotted in figure 3 show ρ_{xx} and ρ_{xy} when B_{min} descended from 7 T to finally 0 T. (The second curve from the bottom was obtained in step (ii), i.e., just after the illumination, which can be interpreted to be $B_{min} = 14$ T.) We again emphasize that the resistivity curves were reproducible unless B_{min} was reduced to a value below the lowest one in the previous history after the illumination. Thus, the metastable state can be manipulated by varying B_{min}. Notice that ρ_{xy}^{-1} increases by $\sim e^2/h$ between the initial and the final states of the metastability, although the increase of n_s caused by the illumination is considerably smaller than that required to fill a whole Landau level. It is indicated that the Fermi level is located within the extended state of the topmost Landau level of the ESS. In other words, this demonstrates the Landau-level pinning at the Fermi level to enable the charge transfer at the Landau-level crossing to occur.

It is noteworthy that the curves in steps (i) and (ii) can be almost identical if the illumination is weak, while producing a considerable change in the resistivities in step (iii). Therefore, it can happen that the effect of the illuminations does not show up at all until B is once reduced to $\sim$0.

As we see no change at $\sim$6 T, where the metastability took place in figure 2, it is indicated that the metastability originates from the ESS. In support of this, further meta-

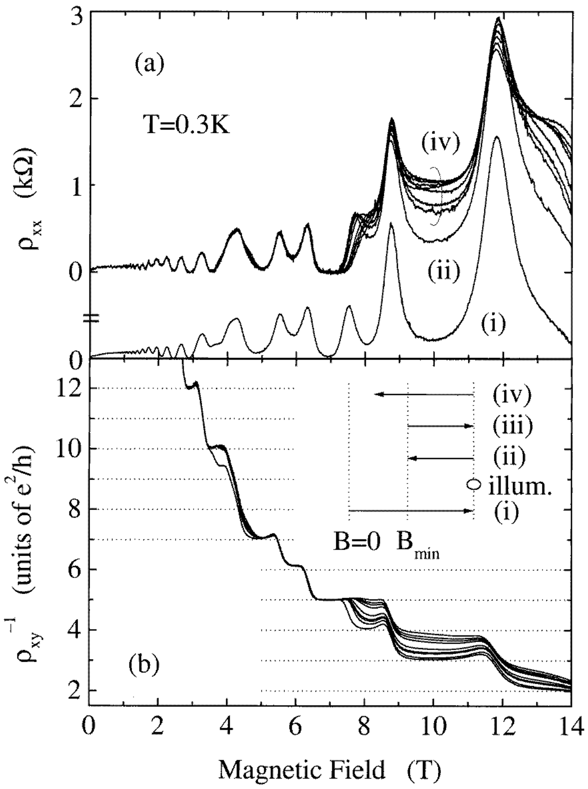

Figure 3. The metastability associated with the crossing of the $N = 1$ Landau level in the wide quantum well. The inset in (b) shows the measurement procedure. See the text for details. The longitudinal resistivity and the inverse Hall resistivity plotted, respectively, in (a) and (b) were acquired in step (iv) with $B_{min} = 14$ (just after the illumination), 7, 6, 5, 4, 3, 2 and 0 T. The bottom curves show the resistivities in step (i), i.e., before the device was illuminated at 14 T.

stability is found around $B = 4$ T. This is caused by the spin-down state of the $N = 0$ ESS Landau level; see the inset of figure 2(b).

We have presented only those examples in which a Landau-level crossing occurs between the initial and the final states. This is not a required condition for the observed metastability. The ESS peak remains on one side of a resistance peak of the GSS if the illumination is moderate. However, this does not imply that the level crossing is not essential for the metastability. On the contrary, all of the additional electrons must be accumulated exclusively in the ESS because of the potential renormalization associated with the charge transfer between the quantum wells. Such a situation is found to be crucial for the metastability. The metastability is absent when the additionally introduced electrons are primarily stored in the GSS for $n_s > 9 \times 10^{15}$ m^{-2}.

Although the resistivities were measured in the static state, the metastability is believed to be induced by nonequilibrium electrons generated by photo-ionizing the DX centres. The device was illuminated when the subband in the narrow quantum well was magnetically depopulated. As no states are available in the narrow quantum well, the electrons released from the DX centres have to be accommodated temporarily in the wide quantum well. In fact, it is more likely that the photo-generated electrons remain in the V-shaped potential well produced by the δ-doping, as the self-consistent potential does not allow the additional carriers to dwell in the wide quantum well. Due to the large potential fluctuations in the δ-doped plane, the carriers are localized at such low densities [12, 13], providing no contributions to ρ_{xx} and ρ_{xy}. Though the photo-generated electrons in the V-shaped potential well are not in an equilibrium state, the experimental observations indicate that the relocation of the excess electrons to the narrow well proceeds only partially when the magnetic field is lowered. Once the excess electrons arrive in the narrow well, they remain in the well even when B is increased again, i.e., the potential profile established at lower B is energetically favoured over that of the previous metastable state. However, the complete equilibration of the electron distribution is not achieved until B reaches zero.

The blocking of the charge transfer is attributed to the potential renormalization. If the electrons are localized in close vicinity to the parent donors, the potential modification is minimal. However, when electrons move from the V-shaped potential well to the narrow well, which eventually occurs at lower B when the population threshold energy in the narrow well falls below the Fermi energy, ionized parent donors are left in the δ-doped plane. The charge transfer is hence strongly influenced by the renormalization of the potential. As the resultant space charge creation raises the ESS level (estimated to be $\sim$5 meV per 10^{14} m^{-2} electrons using a simple capacitance model) [14, 15], the transfer of the excess charge is suppressed. Lowering the magnetic field, the number of the transferred electrons increases. A quasi-stable state with the photo-generated electrons partially transferred to the narrow quantum well is anticipated to be established for each value of B.

For $n_s > 8.9 \times 10^{15}$ m^{-2}, the electron addition to the wide quantum well is not blocked, in contrast. As the subband levels are more flexible in energy, the photo-generated electrons can be relocated immediately to the DQWs.

To fully understand the metastability, one would need to carry out a self-consistent calculation [4]. However, reproducing the exclusive occupation of the ESS by increasing the number of electrons near the level crossing alone is not an easy task because of the discrete nature of the Landau-level DOS. Moreover, the electrons responsible for the metastability are generated from the DX centres. Inclusion of such electrons in a numerical calculation requires some kind of assumptions, as they are never in equilibrium until the complete charge redistribution is accomplished at zero magnetic field.

Let us finally remark on the plausible conditions required to realize the metastability. The electron densities in the two quantum wells have to be in appropriate ranges to observe the metastability. If the electron density in the narrow well is too small, on the one hand, the Hartree potential cannot induce an appreciable level shift [4]. On the other hand, the redistribution of the electrons is accomplished without an obstacle if the electron densities in the two layers are comparable. The influence of the charge transfer is more significant for larger distances between the electrons and the parent donors. Therefore, the metastability is less likely to occur in two-subband systems of a single heterojunction. In many experiments, the electron density is varied by a gate. We do not anticipate metastability in this case, as the electrons are supplied by shallow donors. In addition, the screening of the gate bias by electrons in the layer closer to the gate plays an important role in establishing the self-consistent potential in the other layer. The potential renormalization will be considerably different compared to that in the photo-excited situation.

In conclusion, we have demonstrated the existence of a metastability in an asymmetric double-quantum-well structure. The self-consistency of the potential restricts the charge imbalance created in high magnetic fields from being wiped out in the vicinity of the Landau-level crossing. We have shown that the metastable state can be changed by lowering the minimum magnetic field.

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[9] The large spin gap observed in the SdH oscillation is due to the exchange enhancement of the effective g-factor. The actual energy gap between the two spin states is small because of the small effective g-factor in GaAs, and so the ESS Landau level crosses the two spin levels of the GSS Landau level simultaneously.
[10] When the electron density is just above the population threshold of the ESS, all of the SdH peaks of the GSS exhibit a simultaneous splitting; see reference [4]. However, the oscillations when the electron density in the ESS is considerable simply consist of two sets of the SdH oscillations due to the GSS and the ESS. The transition between the two regimes is not well understood because the charge transfer significantly broadens the ESS peak around the level crossing, as seen in figures 2 and 3.
[11] Whether the sample is illuminated at a resistance dip or a peak, for example at $B = 11.8$ T instead of 14 T, makes no difference for the existence of metastability. This insensitivity is understandable, as the GSS does not accommodate the photo-generated electrons.
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