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LETTER TO THE EDITOR

The magnetic-field-tuned impurity level in a mesoscopic $Al_xGa_{1-x}As$/GaAs antidot sample

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Abstract. The magnetoresistance of mesoscopic GaAs/$Al_xGa_{1-x}As$ samples containing differently ordered antidot lattices with the same long-range periodicity of 0.3 μm has been studied. In a periodic lattice, magnetic-field-induced two-level switching of several impurities has been observed. In contrast, in a disordered antidot lattice single-impurity switching dominates as the overlapping of the depletion regions around the antidots allows for only a few conducting channels through the sample. The impurity dwell time of one such level is seen to undergo large variations when sweeping an external magnetic field. It has been possible to observe the influence of other defects in the sample on the dominating impurity level, since fluctuations of the local electron density affect the Aharanov–Bohm oscillations, and therefore also the impurity double-well potential.

Small semiconductor or metal devices can exhibit two-level switching due to tunnelling between two metastable states of a single defect [1]. The observation of the tunnelling of a single defect is possible, since at low temperature the sample resistance is dominated by the interference of a small number of electron paths, which is highly sensitive to the position of the scattering centres [2]. The position of the defects can be changed by interband irradiation [3], or by the application of a strong electric field [4]. In [5] it has been predicted that it should also be possible to alter the position of the defect states, by employing magnetic-field-induced local fluctuations in the electron density. The maximum change in the impurity energy due to such fluctuations in a two-dimensional sample is of the order $\hbar\omega_c(k_F\ell)^{1/2}$ (where ω_c is the cyclotron energy, ℓ is the electron mean free path, and k_F is the Fermi wave vector) for the regime of phase-coherent transport [6], and can be much larger than the thermal fluctuations. Such a variation of a single impurity level with magnetic field has been observed in Bi samples by measuring the conductance switching between two quasi-stable values [7]. The magnetic field led to an overall increase in the energy asymmetry of the defect double-well potential ϵ, but smaller, superimposed features in the ϵ-B diagram were also seen. Detailed measurements of the defect dynamics in Bi microdevices were reported in [8]. Although ϵ was given for only a few different magnetic field strengths, it was found to display large variations even for small changes in the magnetic field. This supports the Altshuler–Spivak mechanism [5] of magnetic field-induced changes in the random potential.

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Here we report on the dynamics of impurity levels in an $Al_xGa_{1-x}As/GaAs$ heterostructure with a two-dimensional electron gas (2DEG). These heterostructures offer many advantages when investigating the effects of impurity potentials on the conduction mechanisms in mesoscopic samples. Using electron beam lithography and reactive plasma etching, it is possible to reduce the feature size to below the mean free path, allowing for the introduction of an artificial lattice of antidots, or scatterers. The degree of randomness of the potential, and the number of conduction channels can therefore be controlled. Owing to the small effective electron mass in GaAs the maximum change in the impurity activation energy, which is proportional to $\hbar\omega_c$ [5], is large even at low magnetic field. This allows us to determine the variations of the switching time as a function of magnetic field, which is similar to magnetofingerprints in the magnetoresistance [9]. Finally, in contrast to the polycrystalline Bi wires, effects of crystal boundaries do not have to be considered.

Hall bridges defined on $Al_xGa_{1-x}As/GaAs$ heterojunctions ($x = 0.3$) were used to realize the antidot lattice. The initial heterostructures had a 2D electron density $n = 4 \times 10^{11}\,cm^{-2}$ and an electron mobility $\mu = 2 \times 10^5\,cm^2\,V\,s^{-1}$. Samples with an area $500\,\mu m \times 200\,\mu m$ were split off, and in the middle part, between the potentiometric probes, a $2\,\mu m \times 2\,\mu m$ square bridge was formed. A lattice of holes (antidots) was patterned in this bridge using electron beam lithography. The lattice period d was $0.3\,\mu m$, and the lithographic (physical) antidot size $c = 0.1$–$0.15\,\mu m$. The samples were then etched using reactive plasma etching, which was stopped before the $Al_xGa_{1-x}As$ spacer. Two disordered antidot lattices, with different degrees of disorder, were fabricated in the same way. The disordering was accomplished using a random number generator to determine the shift in the position of each antidot with respect to the position in an ordered lattice. The standard deviations of their shifts were $0.038\,\mu m$ and $0.15\,\mu m$, respectively. Using transport measurements in macroscopic samples, the depletion region around each antidot was determined to be $0.07\,\mu m$ [10]. Irradiation by light decreases the depletion width. However, even after illumination the strongly disordered sample did not exhibit any conductivity. The sample with small deviations revealed some conductivity in the dark, which increased by two orders of magnitude after illumination. The magnetoresistance was measured using conventional four-probe and lock-in techniques at frequencies between 18 and 700 Hz. The measurements were performed in a magnetic field up to 0.7 T in the temperature range 0.3–4.2 K. Two samples with regular and one with a slightly disordered antidot lattice were used for the measurements.

We first consider the results obtained in the samples with a periodic lattice. Magnetoresistance oscillations were seen for the whole magnetic field region investigated. We believe that the origin of these oscillations is an Aharanov–Bohm effect due to the magnetic flux through rings with the area $S = \pi d^2/4$, created by the antidot lattice. Hysteresis was seen in the magnetoresistance, as the magnetic field was swept up and down. Figure 1 demonstrates this behaviour; arrows indicate the initial and final points of the sweep, as the magnetic field was changed continuously from zero to 0.4 T and back to zero again. The amplitude of the oscillations is different for the two sweep directions, however the positions of the oscillations are correlated. The sample in the final state was found to have a higher resistance than at the start. This state is metastable, and a relaxation to the initial resistance value was seen as the sample was left at zero field for one minute (see figure 1(a)). Such behaviour suggests impurity switching between metastable states and an influence of the magnetic field on the switching rate. Owing to the interaction between the electronic states and the impurity states, the energy ϵ of the impurities, and hence also the energy barrier between impurity states, is magnetic field dependent, enabling a hopping to occur between states of several different impurities during the magnetic field

sweep. The Aharonov–Bohm oscillations change due to the new positions of the impurities. When the magnetic field is turned off, some defects remain temporarily in the new states, and only hop to their initial states during a slow relaxation process. The number of steps in the resistance relaxation tail (a) indicates that 10–15 impurities switched states due to the magnetic field sweep. The switching time of the different defects varied from 5 s to 1 min. It has been shown earlier [11] that the variation of the apparent periodicity of Aharonov–Bohm oscillations with magnetic field is due to impurity switching, and causes the periodicity to change between h/eS and $h/2eS$.

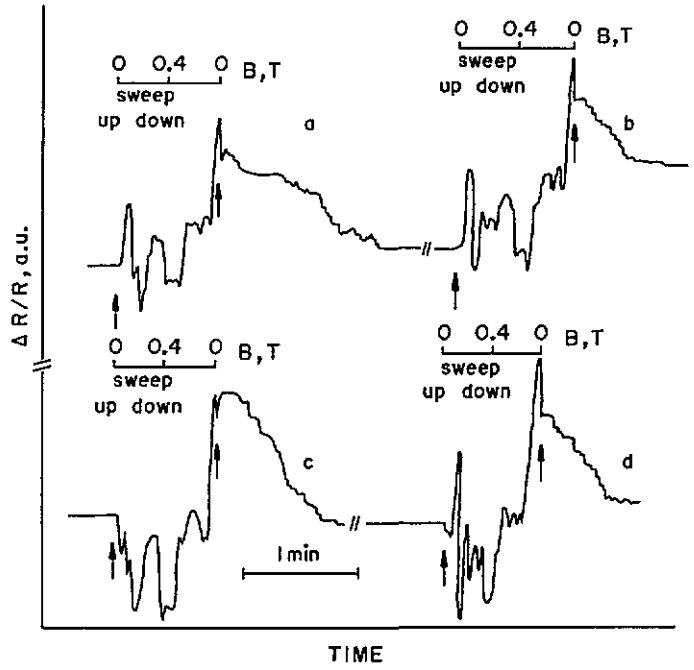

Figure 1. Resistivity as a function of time during a magnetic field sweep and following relaxation in the periodic lattice of antidots, $T = 4.2$ K.

For the slightly disordered antidot lattice the picture is somewhat different. As the electronic diameter of the antidots is very close to the period of the antidot lattice, even a small deviation from the periodic lattice position gives rise to overlapping neighbouring antidots. Therefore, for samples with disordered lattices, a percolation picture for the conductivity is appropriate. After illumination the depletion region around the antidots decreases, and a transition from a slightly to a highly conductive state is observed. The conductance changes from $0.05e^2/h$ to $10e^2/h$, i.e. by a factor of 200. Figure 2 shows the temperature dependence of the disordered antidot sample after illuminating it for a short time, so that the conductance at high temperature (> 1 K) lies close to the value e^2/h. The conductance of the sample exhibits a linear temperature dependence in the range $0.7\,\text{K} < T < 1.5\,\text{K}$. Below 0.7 K there is a deviation from this linear behaviour to a much weaker temperature dependence, as in the case of conduction through percolation levels. This supports the suggestion of percolation levels connecting the electron lakes between the antidots in the artificially created random potential. Electron hopping over the barriers between the antidots may occur through phonon processes.

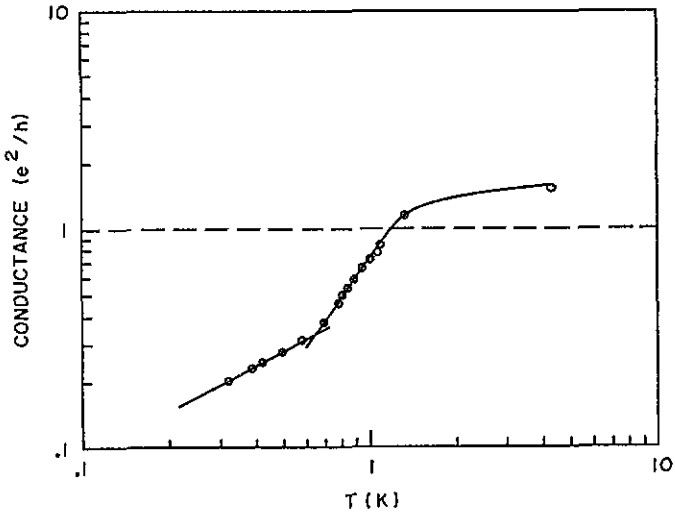

Figure 2. Temperature dependence of the conductance in the disordered antidot sample after moderate illumination. The solid lines are fits to the experimental points.

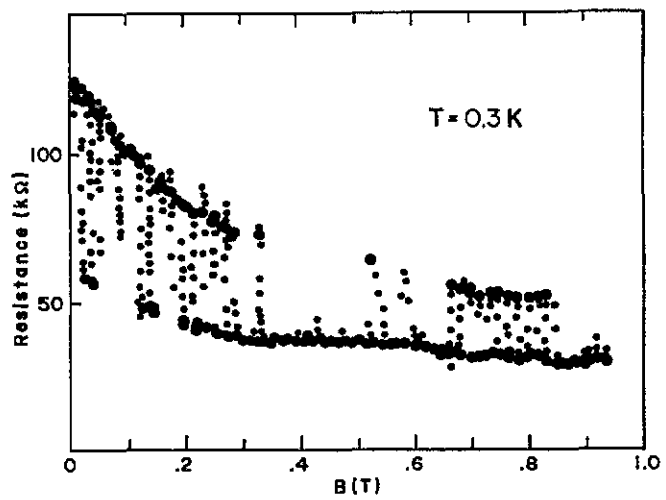

Figure 3. Two resistance states in the disordered antidot lattice at different magnetic fields, measured at $T = 0.3$ K. The magnetic field was swept up in steps of $\Delta B = 0.02$ T. The small points: single switching events; large circles: 40–80 switching events.

It is likely that the influence of a single defect will be important when the sample with the slightly disordered antidot lattice is in the highly resistive state. Indeed, we were able to observe such an effect in our sample. Figure 3 shows the behaviour of the resistance in a magnetic field, where jumps in the resistance between two states are observed. The curve was obtained by the following procedure. The sweep was halted for 10–120 s at fixed values of the magnetic field (with steps of $\Delta B = 0.03$ T), during which time the resistance was monitored. As figure 3 shows, the resistance has two states, and its value is changed by a factor of two due to these jumps. This large relative size of the two-level

noise is of the same order of magnitude as that observed in high-mobility GaAs 2DEG-based quantum point contacts near threshold gate voltage [12], in contrast to the much smaller fluctuations reported for, for example, Bi wires [7]. We believe that, as for the point contacts, single-impurity switching in the antidot lattice is responsible for this behaviour. Changes in the positions of impurities alter the electrostatic landscape near any bottleneck for the current, and have consequently a large effect on the transmission probability for conduction channels. However, the system of disordered antidots differs somewhat from that of a single quantum point contact or wires with point contacts in series. In contrast to wires, in the system of connected rings the Aharonov–Bohm effect may cause a periodic variation of the interference of electron trajectories. We note that in [5] only chaotic variation of energy in mesoscopic conductors is considered, and hence for the geometry employed in our experiments additional theoretical calculations are necessary. Nevertheless, for simplicity we will consider only the chaotic fluctuations.

Figure 3 also shows that the measured values of the resistance were sometimes found at intermediate states, almost certainly due to the fast switching time and an averaging over time involved in measuring each point. For some values of the magnetic field, the sample did not switch states (during a measurement time of more than one minute, staying only in the upper or in the lower state—e.g. at 0.1 T or $0.35\,\mathrm{T} < B < 0.55\,\mathrm{T}$ in figure 3). Some switching of the sample resistance to a third state was also seen. However, these jumps showed smaller amplitude and poorer reproducibility, and in the following we will discuss only the observed two-level noise.

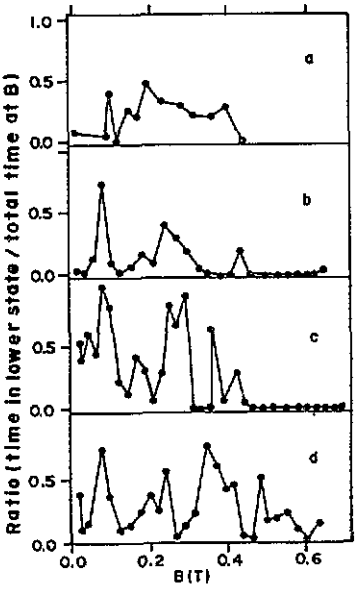

Figure 4. Ratio between the dwell time in the high-resistance state and the total time of the measurement at a given magnetic field, as a function of magnetic field. Curves a, b and c, d were measured immediately after each other, while between b and c the magnetic field was swept up and down several times.

Figure 4 shows the ratio (dwell time in the higher resistance state)/(total time of measurement) as a function of the magnetic field. The lower state is clearly more stable

than the upper state in this trace. However, the fluctuations between the states were found to be dependent on the history of the sample. The same curve was re-measured after rapidly sweeping the field down to zero, but this time an increased fluctuation between the upper and lower states was seen (see figure 4(c), (d)). Two different fluctuation pictures are seen, with only a small correlation between the first and second curve, though the lower state is still more stable than the upper. Further curves (measured after subsequent sweeping up and down of the field) showed even larger fluctuations, where the dwell times of the two states were about equal, and with rapid switching between the states (see figure 4(a), (b)). No correlation is found between curves with such large fluctuations, even when measured directly after each other. We measured the two-level noise over several days and did not find a significant correlation between any of the measured curves.

Several points in our observation call for special attention. The very large change in the conductance between the two states is not simply induced by the absolute value of the magnetic field, but it seems rather that a *change* in B shakes up the system, and leads to a hysteresis in the switching behaviour of the two levels. There are two parts to the change: the transient switching, and the continuous sweep of B. We do not believe that the transient part plays an important role: the superconducting coil used in the experiments has an inductance of $\sim 60\,\mathrm{H}$, giving an estimate of any transient field too small to be significant. Furthermore, many of the curves show a stable resistance at the start of the sweep, and the two-level noise starts only during the quasi-continuous sweep of B. We also exclude any effect from eddy currents heating: the resistance of the sample and hence also the amplitude of the resistance jumps are sensitive to the electron temperature, while at the start of each field sweep the amplitude remains the same. We did not find any apparent difference in the average behaviour of the field dependence of the dwell time when sweeping B with different velocities ($\mathrm{d}B/\mathrm{d}t < 0.3\,\mathrm{T\,min^{-1}}$). The fact, that a weak magnetic field can turn off the impurity state indicates strongly that the mechanism of this behaviour is connected to the electronic environment, which is well known to be sensitive to small B-variations due to the Aharonov–Bohm effect [5]. Such a mechanism leads to a chaotic variation of the energy asymmetry of the defect double-well potential, with a maximum variation of the order of $\hbar\omega_c(k_F\ell)^{1/2}$ [5, 6]. The derivation in [5] assumed phase-coherent transport ($L_\varphi \sim L$, where L_φ is the phase coherence length, and L is the sample size). The observation of Aharonov–Bohm oscillations in the ordered antidot lattice sample indicates that we are indeed in this regime. Measurements on the initial heterostructure show that the factor $k_F\ell$ is quite large. However, the disordered antidot sample, with a bottleneck constriction, is close to a metal–insulator transition ($\sigma \sim e^2/h$), and therefore $k_F\ell \sim 1$. Hence we can assume that the variation of the impurity energy is of the order of $\hbar\omega_c$. Within this boundary there can be smaller fluctuations of ϵ with smaller periodicity, and so on. This means that in a strong magnetic field, where $\hbar\omega_c \gg \epsilon$, the defect falls into one of the states that is thermally stable. A small variation of the magnetic field around its original value will either give rise to a defect jump to another thermally stable state, or will increase the asymmetry between the two levels, in which case the defect remains in the initial state, increasing its stability. Because of the high sensitivity to the magnetic field and poor reproducibility we were not able to determine the temperature dependence of the switching time. However, we believe that thermal activation of the defect over the barrier is dominant in our case, and $\tau_{\mathrm{upper}}/\tau_{\mathrm{lower}} = \mathrm{e}^{\epsilon/kT}$, where τ_{upper} and τ_{lower} are the lifetimes in the upper and the lower state, respectively. If $\epsilon \gg kT$, then $\tau_{\mathrm{upper}} \ll \tau_{\mathrm{lower}}$, and the lower state is stable against thermal excitations. In the traces in figure 3, the magnetic field often had to be changed in several steps from $B = 0$, before switching between the two resistance states was induced. The average number of steps needed (obtained from a large

number of traces of the same type) gives us the correlation field B_c (near $B = 0$). We found $B_c = \epsilon m/e\hbar = 0.05$–$0.1$ T, corresponding to the energy $\epsilon = 0.09$–0.18 meV, which is 4–8 times larger than kT.

Due to the chaotic nature of the energy fluctuations at high magnetic fields ($B > B_c$), it is possible to find regions of the magnetic field where the resistance is stable (e.g. figure 4(c), $0.45\,\mathrm{T} < B < 0.7\,\mathrm{T}$), and regions where it jumps between two different values after a variation of B of more than B_c (figure 4(d)). The poor reproducibility of the oscillations is probably due to the switching of other impurities in the sample. Because of electron scattering, the contribution to the conductivity from these defects is much smaller than that induced by the dominant impurity. However, changes in other defect states can lead to variations in the local electron density. Defects lying near the closed electron trajectories connected with the main percolation levels in particular can therefore contribute to the conductivity through non-local effects [9]. If these defects have metastable states with a long lifetime, their switching will lead to changes in the electron interference, and hence also to a variation of the local electron density near the dominant impurity. The step-like resistance decay of the sample with a periodic antidot lattice demonstrates that the number of switching impurities is 10–15 (figure 1). We should note that in the disordered antidot lattice, single-defect switching is observed when the sample is in a relatively high resistance state, i.e. in an intermediate regime between weak and strong localization. It gives rise to large amplitude jumps in the resistance. The calculation in [5] was performed for the metallic case, i.e. $\Delta\sigma \sim e/h \ll \sigma$. Thus, the large variations in the conductivity could also change the interference picture, which in turn also influences the impurity state, and so on. More theoretical calculations are necessary to resolve this problem. In order to shed further light on the somewhat complicated picture in this system, we also plan to measure the temperature dependence of the switching time to determine the energy ϵ as a function of magnetic field.

In summary, we have observed a hysteresis behaviour of Aharanov–Bohm oscillations in a sample with a mesoscopic, ordered lattice of antidots. We attribute this to impurities that relax into their lowest state, after having been shaken up by the magnetic field. The conductance in a sample with a disordered antidot lattice at low temperature seemed to be governed by percolation, and hence was limited by a single-impurity state. Fluctuations between two fixed conductance states were found when a magnetic field was applied. The relative amplitude of this two-level conduction fluctuation is much larger than what has been observed in, for example, Bi wires [7], and of the same magnitude as that previously reported in high-mobility GaAs 2DEG-based quantum point contacts near threshold gate voltage [12]. A magnetic field larger than 0.1 T could induce energy fluctuations large enough to overcome the barrier between two impurity states. The influence of other defects on the dominating impurity level in the sample could be observed, since fluctuations of the local electron density affect the Aharanov–Bohm oscillations, and therefore the impurity double-well potential. The energy asymmetry of the defect double-well potential may vary chaotically due to electronic environment being very sensitive even to small variations of the magnetic field. This explains the large differences in the fluctuations between the impurity states that we observed even when the measurements were repeated under almost identical conditions. Further experimental and theoretical work is needed to obtain a fuller understanding of the dynamics of the impurity switching in this system.

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