CHARGE TRANSFER BETWEEN PERCOLATION LEVELS IN A SYSTEM WITH AN ARTIFICIAL, STRONGLY DISORDERED POTENTIAL.

G. M. Gusev[1*], Ulf Gennser[2], D. K. Maude[2], J. C. Portal[2], D. I. Lubyshev[1*], Yu. V. Nastaushev[1*], J. C. Rossi[3] and P. Basmaji[1]

[1]*Instituto de Física de São Carlos, Universidade de São Paulo, SP, Brazil*
[2]*Service National des Champs Intenses, Centre National de la Recherche Scientifique, F-38042, Grenoble and INSA-Toulouse, 31077, France*
[3]*Universidade Federal de São Carlos, SP, Brazil*

(Received 22 August 1994)

We observe a hysteresis in the magnetoresistance of mesoscopic samples with a disordered antidot lattice. When the Fermi level lies in between two Landau levels, the Faraday electric field induces a change in the charge of two closed, intercalated electron trajectories in the artificial strongly disordered potential. The total transferred charge is approximately equal to 40e. Depending on whether this transfer is towards the inner or outer closed trajectory (which is determined by the direction of the magnetic field sweep) the potential barrier for trajectories that traverse the sample will increase or decrease.

There are still many open questions pertaining to the electron transport in the quantum Hall regime. One of these is the role of charge transfer through delocalised states in the bulk 2-dimensional electron gas(2DEG). When the Fermi level lies between two Landau levels, the current is carried by the edge states, or by delocalised bulk states [1]. Since the scattering between these is suppressed, the resistance is close to zero. As the Fermi level approaches a bulk Landau level, the scattering through this state gives rise to an increase in the resistance. A more complicated situation is found in a sample with a Corbino geometry. In this device the azimuthal Faraday electric field will lead to a charge transfer between the concentric contacts via the delocalised bulk states. This charge depends on the number of flux quanta that are passing through the structure, and hence is determined by fundamental constants [2]; it has been measured in a (2DEG), both in macroscopic MOS transistors and in AlGaAs/GaAs heterostructures [3]. However, the Corbino geometry may not be the only case where charge transfers are of importance, but they are likely to play a role also in the mesoscopic closed, intercalated bulk-trajectories that can be present in a macroscopic sample in the percolation regime of the quantum Hall effect. Here, a local change in the charge may significantly alter the 'landscape' of the disordered potential, and the charging effects may be seen in the percolation trajectories through the sample. As percolation paths are difficult to control, a more favourable system to study this effect in, is a mesoscopic sample with an artificial, strongly disordered potential, such as a 2DEG with a disordered lattice of antidots [4]. Small deviations of the antidots from the regular lattice positions will give rise to a random, strongly disordered potential, provided that the diameter of the antidots (including the width of the depletion region around them) is comparable with the periodicity of the lattice. In this work we report on the magetoresistance of such a system in a strong magnetic field.

The samples consist of Hall bridges on standard AlGaAs/GaAs heterostructures with a (2DEG) with a carrier density $\approx 4\times10^{11}$ cm^{-2} and an electron mobility $\approx 2\times10^{5}$ cm^2/Vs before the fabrication of antidots. A lattice of holes (antidots) was patterned in the bridge of size 2×2 μm^2, using electron beam lithography with a Proxy Writer system. The lattice period d is 0.3 μm, and the lithographic antidot size 0.1-0.15 μm. The disordering of the antidot lattice was accomplished using a random number generator to determine the shift in the positions of each antidot with respect to the position in an ordered lattice. The standard deviations of their shifts is 0.038 μm. The magnetoresistance measurements were performed in a magnetic field up to B = 15 T at a temperature of 0.3 K, using conventional four probe and lock-in techniques. Irradiation by light pulses was employed to persistently decrease the depletion width around each antidot, thus

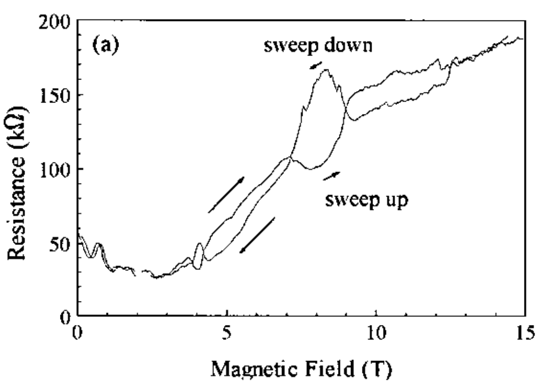
*Permanent address Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia.

0749-6036/94/050097+03 $08.00/0

changing the strongly disordered potential, and increasing the conductivity.

Fig. 1a shows the magnetoresistance as a function of B for one sample, after a short period of illumination. In a magnetic field up to $B < 3$ T reproducible aperiodic fluctuations are seen, that may be caused by interference of electron trajectories. As the magnetic field increases, the amplitude of the fluctuations decreases. In the region B = 2 T - 3.5 T the oscillations become quasiperiodic with a period ≈ 0.275 T, which is much larger than the period corresponding to the flux $\phi = h/e$ through the area d^2. A possible explanation is that the interference around small accidental potential maxima with size ≈ 0.07 μm is responsible for this period. When sweeping the field up to higher values, two peaks are observed on the linear background of the magnetoresistance. The slope of the background is slightly decreased after the second peak. The position of the peaks in magnetic field differs by a factor of two, and is in good agreement with the Landau level filling factors n = 2 and 4 (without spin splitting), assuming that the electron density is unaltered by the fabrication of the antidot lattice. When the magnetic field is swept down, the peaks change into two minima with almost the same amplitude. We should note, that the sweep up and sweep down curves in fig. 1a are shifted relatively to each other, because of the jump in the resistance, which occurs at 13 T. This shift between the curves gradually disappears as B is decreased. Numerous magnetic field sweeps were carried out in order to verify that these effects were reproducible. We find that the resistance jump may occasionally be towards a lower, instead of a higher resistance value (fig. 1b), and can be explained by a magnetic field induced impurity switching [4]. Fig. 1b shows the dependence of the magnetoresistance on B for the second peak in more detail.

In order to explain the observed hysteresis in the magnetoresistance we consider the picture of the electron trajectories in a disordered antidot lattice, as depicted in fig. 2. For simplicity, only one trajectory traversing the sample through one tunnelling barrier is shown. The absence of the Shubnikov oscillations, which are due to an increased backscattering when the Fermi level is close to a bulk Landau level, indicates that the traversing trajectory is a hybrid between the edge and bulk states. In this case the tunnelling through one barrier (or at most a few barriers) between antidots will play a dominant role in the transport in our system. The linear increase in the magnetoresistance suggests a suppression of the tunnelling in the strongly correlated system [5]. In addition to the trajectory traversing the disordered antidot lattice, closed trajectories exist also, as is shown in fig. 2. When the Fermi level lies in between Landau levels, so that scattering into the bulk states is suppressed, it is still possible to have tunnelling between two closely spaced trajectories. The Faraday



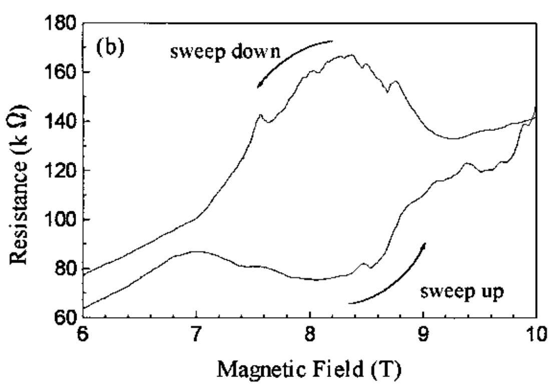


Fig. 1a. Magnetoresistance of the sample at 300 mK after a short period of illumination. The direction of the magnetic field sweep is marked with arrows. The two hysteresis peaks are indicated in the figure.

Fig. 1b. The magnetoresistance for a smaller magnetic field range.

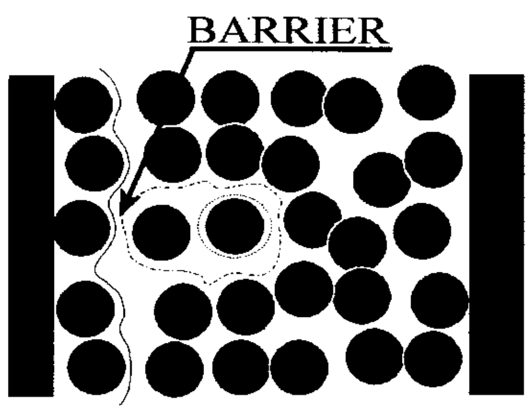


Fig. 2. Schematic illustration of a percolation trajectory (full line) in the antidot lattice. An inner closed trajectory (dotted line) and an outer closed trajectory (dashed line) are depicted. A tunnelling barrier, influenced by the charge of the outer trajectory is also marked.

electric field generated by closed trajectories will then give rise to a charge transfer from the internal trajectory to an external trajectory [2]. Since $V(t) = 1/c\, d\phi/dt$ and $dQ=Idt$, we have $I/V=c/S\, dQ/dB$, where dQ is the transferred charge , and ϕ is the flux through the area S between closed trajectories. If the closed trajectories are the Landau level one-dimensional edge states (with the filling factor n), we have

$$\Delta Q = \frac{1}{n}\frac{e^2}{h}\frac{S\Delta B}{c} \qquad (1)$$

As the magnetic field is swept down, the Faraday field changes sign, and the charge is instead transferred from the internal to the external closed trajectory. Thus the direction of the magnetic field sweep (up or down) will determine whether the change in charge of the external electron trajectory is positive or negative. When the Fermi level lies in a bulk Landau level, the charge on the electron closed path is not stored, but is scattered through the bulk. Equation (1) can be used to calculate the total charge transferred between the two trajectories. A reasonable assumption for the area S is, as in fig. 2, that the inner trajectory goes around one antidot, whereas the outer trajectory encircles two antidots. This gives $\Delta Q = 100e$ for the peak at $n = 2$ and $\Delta Q = 44e$ at $n = 4$. It is possible to compare these values with the observed resistance peaks. The tunnelling barrier for the traversing trajectory will be influenced by the line charge of the edge state (fig. 2), which leads to the observed hysteresis in the magnetoresistance (fig. 1a, b). When the Fermi level lies in the gap between Landau levels, the screening of the line charge is not complete, and the barrier shows fluctuations, ΔV. If these are small, then $\Delta V/V = \Delta Q/V\langle r\rangle$, where $\langle r\rangle$ is the average distance from the barrier to the charge on the edge state. Assuming a simple triangular barrier, we can calculate the change in resistance due to the fluctuations in the barrier height. The conductance of the system with the single tunnel barrier is given by $\sigma = Te^2/h$, where T is the transparency of the barrier, and can be written as [6]:

$$T = \frac{E(V-E)}{V^2}\exp(-2ab) \qquad (2)$$

where $a=[2m^*(V-E)]^{1/2}/h$, m^* is the effective mass, b is the thickness of the barrier, and V-E is the difference between the barrier height and the electron energy. As the resistance is small, of the order of the quantum resistance h/e^2, we can assume that the transparency $T \approx 1$, i.e. $V \approx E$. The induced change in the tunnelling is then given by $\Delta T \approx 4\Delta V/V$, and hence

$$\Delta R \sim \Delta Q/V\langle r\rangle \qquad (3)$$

Since the change in V is small, and $\langle r\rangle$ will vary only slightly for different Landau levels, we can now compare the ratio between the two magnetoresistance peak heights with the ratio of the corresponding charge transfer: $\Delta R_{(n=2)} / \Delta R_{(n=4)} = 2.6$, and $\Delta Q_{(n=2)} / \Delta Q_{(n=4)} = 2.4$. This is a reasonably good agreement, considering that we have assumed that the induced change in the barrier is small, whereas in actual fact $\Delta R/R \approx 30\%$. We should also note, that the total number of electrons on the internal trajectory, $N \approx 2\pi a l_H/\pi l_H^2 = 2a/l_H \approx 70$ (where a is a radius of the trajectory, and l_H is the magnetic length), is slightly less than the transferred charge at $n = 2$. The discrepancy may be because the area between the closed trajectories in fact is somewhat larger than d^2. In this case the internal line is either completely emptied or charged, and the filling of the next Landau level commences.

In summary, in a disordered antidot lattice, charge can be transferred between different closed trajectories. This charge significantly perturbs the local potential landscape around trajectories: in particular, a jump in the resistance is found (fig. 1a). A decrease in the diameter of the antidots and in the average periodicity of the lattice may even make it possible to observe a single electron transfer, tuned by the magnetic field. A 2DEG in a disordered antidot lattice may therefore be a new tool for the study of the equilibrium tunnelling in the strong magnetic field, and further experiments with this system are now in progress.

Acknowledgements: This work is supported by FAPESP, CNPq (Brazil) and CNRS (France). U.G. acknowledges support by SI and NFR through the HCM program. We thank Dr.H.Raith for the Proxy Writer system used in the electron beam lithogaphy.

REFERENCES

1. R. E. Prange and S. M. Girvin, Eds. The Quantum Hall Effect (Springer, Berlin 1987).
2. A. Widom and T. D. Clark, J.Phys. **D 15** L181 (1982).
3. V. T. Dolgopolov, N. B. Zhitinev, and A. A. Shashkin, JETP Lett., **52**, (1990), 196; V. T. Dolgopolov, A. A. Shashkin, N. B. Zhitinev, S. I. Dorozhkin, and K. von Klitzing, Phys. Rev. **B 46** 12560 (1992).
4. G. M. Gusev, U. Gennser, D. K. Maude, J. C. Portal, D. I. Lubyshev, Yu. V. Nastaushev, J. C. Rossi, and P. Basmaji, J. Phys. Cond. Matter **6** L265 (1994).
5. R. C. Ashoori, J. A. Lebens, N. P. Bigelow, and R. H. Silsbee, Phys. Rev. Lett. **64** 681 (1990).
6. A. D. Stone and A. Szafer, IBM J.Res.Dev. **32** 385 (1988).

Instructions to Authors

Manuscripts for publication in *Superlattices and Microstructures* should be submitted either to the Editorial Office or to one of the Editorial Board members. They should be in a camera-ready form as detailed below. The manuscript should be typed *single-spaced* in a single column on standard size, good quality white paper, preferably using and electric typewriter with a *black* ribbon and a 12 point (minimum) Elite, Roman or Times typeface.

Only the *title authors' names and addresses* and *abstract* are to be typed on the first sheet, turned horizontally. The title, not to exceed 20 cm in width, should be typed in *capitals*. Leave single space and type the authors' names and addresses on separate lines, capitalizing the first letter of all the main words. After a single line space, type in a statement about date of receipt of manuscript (and date of receipt of revised copy if any) provided by the editor on the first page of the original manuscript. After a triple line space type the abstract without a heading, to a width of 15 cm.

The text should be typed *single-spaced*, in a single column 10 cm wide, leaving 2·5 cm margins at top and bottom. Each new paragraph should start indented, and only single-spaced from the preceding paragraph. Where necessary, lines containing superscripts (or subscripts) can be separated by an extra half space from the preceding (or following) line. Pages should be numbered consecutively, using a light blue pencil, in the margin at the top of each sheet. Any symbols (i.e. Greek characters or mathematical symbols etc.) which cannot be clearly indicated, should be written in light blue pencil for insertion by Academic Press. These insertions should be drawn to the Publisher's attention by a cross in the margin *outside* the type area. The references are also to be typed in a 10 cm wide column.

Main section headings and subheadings are optional. Main headings should be typed centred on the column, capitalizing the first letter of all main words. Subheadings should be typed in the same style, full left. Use arabic numbers for main section headings. Do not underline the headings and leave a single space between all headings and the paragraphs which precede and follow them.

The acknowledgement statement should be separated by a single space from the text. The word 'Acknowledgement' should be typed full left, followed by a dash and then by the acknowledgement statement itself.

References and footnotes, except those on the title page, are to be indicated in the text by superscript arabic numbers, or by arabic numbers in brackets on-line, in sequence. Footnotes on the title page, such as those indicating present address of authors or research support, should be indicated by superscript single and double asterisks, etc. The list of references including footnotes, should be typed single-spaced, on separate sheets in a single column 10 cm wide. Type the footnotes of the title page as the first entries, and then type the sequence of references and footnotes given in the text. Please ensure that author's names are typed upper and lower case with the initials first. Do not abbreviate journal titles.

Equations should be typed as part of the text in one or more lines, keeping within the designated single column width of 10 cm. Equations which cannot be typed in single-column-width should be typed on a horizontal sheet, keeping within a double-column-width of 20 cm, and their position in the text indicated, by use of a light blue pencil, in the margin.

Small tables should be typed within the type area. Leave one line space in text and type the table heading, including table number, centred over the table. The table should be typed and only horizontal lines should be drawn. Leave one line space at end of table and continue typing text. *Large tables* should be typed on separate sheets. They must not exceed 20 cm in width. Their place in the text should be indicated in the margin using a light blue pencil.

Figures must be submitted in a form suitable for direct reproduction, as original drawings, half-tones or bromides. *Xerox copies are unacceptable.* The size of lettering must be suitable for a reduction of 25 to 50%. Figure number and authors' names on back of figure using light blue pencil. Their place in the text should be indicated in the margin using a light blue pencil. *Figures captions* should not exceed 10 cm in width and should be typed on a *separate sheet.*

Copyright/offprints. Authors submitting a manuscript do so on the understanding that if it is accepted for publication, exclusive copyright in the paper shall be assigned to the Publisher. In consideration for the assignment of copyright, the Publisher will supply 25 offprints of each paper. Further offprints may be ordered at extra cost after acceptance of manuscripts when an order form will be supplied to authors. The Publishers will not put any limitations on the personal freedom of the author to use material contained in the paper in other works.

Papers are accepted for the journal on the understanding that they have not been or will not be published elsewhere in the same form in any language.