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Charge capture in AlGaAs/GaAs heterostructures with disordered antidot lattice

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Abstract

We have observed hot electron trapping by DX centers in a mesoscopic sample with disordered antidot lattice. Depending on the maximum applied electric field the potential barriers for trajectories along the sample will increase. The maximum total captured charge is approximately equal to 50 electron.

Keywords: Heterostructures

Trapping centers in AlGaAs/GaAs field effect transistors play a very important part, because they are responsible for instabilities of the device characteristics. Most of these instabilities are observed at high source-drain voltages. It is believed that the charge trapping is caused by the deep donor or DX center in AlGaAs barrier, owing to the capture being thermally activated, even at very low temperature. However instabilities at high voltages are associated with hot electron capture by DX center, rather than thermal capture [1–3]. It is expected from the model where electron states are coupled strongly with the lattice [4]. Experimentally hot electron trapping was studied in short channel modulation doped field effect transistors [1]. Trapping of carrier by DX centers reduces electron density in the channels and, consequently, channels conductivity. Recently in the samples with high mobility 2DEG the lattice of antidots has been fabricated by using electron beam lithography and plasma etching [5]. In this system it is possible to reduce the feature size to below the mean free path, and the short range as a long range scatter potential can therefore be controlled. Moreover, small deviations of the antidots from the regular lattice positions will give rise to a random, strongly disordered potential, as long as the diameter of the antidots (including the width of the depletion region around them) is comparable with the periodicity of the lattice. So this system opens the possibility of studying the electron characteristics by changing the scatter potential in the controllable way. In samples with small area (mesoscopic sample) only few conductive channels can traverse the sample. When the electron is captured by DX center, this local change in charge may alter significantly the landscape of the disordered potential and charging effect may be seen in the percolation trajectories through the sample. Thus, from the measurement of the hot electron trapping in these devices it is possible to see the local charge trapping, and probably, single electron capture by DX center.

The samples consist of hall bridges on standard AlGaAs heterostructures with a two-dimensional (2D) electron gas with a carrier density 5 10^{11} cm^{-2} and electron mobility 200 10^3 $cm^2 Vs^{-1}$. A lattice of antidots was patterned in the bridge of size 1×1 μm^2 using electron beam lithography with a Proxy Writer system. The lattice period is 0.2 μm, and the lithography size 50 nm (see Fig. 1). The disordering of the antidot lattice was accomplished using a random number generator to

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determine the shift in the position of each antidot with respect to the position in an order lattice. The standard deviation of their shifts was 0.025 μm. Several samples have a periodical antidot lattice without disordering. We measured $I-V$ characteristics at different maximum voltages at temperatures 300 K, 77 K and 4.2 K. To avoid the contact effect we used potentiometric probes. We did not use pulse technique, therefore, we were not able to avoid increase in the lattice temperature. However, we did not emphasise in this work which mechanism was responsible for the electron trapping-thermal electron capture or entering of hot electrons to DX level without the assistance of the thermal phonons. Thus, we looked for the possibility to find the local charge capture of the hot electrons by DX centers. Fig. 2 shows some example of the series of $I-V$ curves at 77 K at various maximum voltage V^{max}. We see, that at low V^{max} $I-V$ characteristic is linear in the whole region of V. With increasing of V^{max} the curves begin to convert to the $I-V$ dependence which is similar of the Zener diode characteristic; it has a lower slope at smaller voltage, however this slope is increased at higher voltages. At high V^{max} the conductivity are equal to zero at low voltages and the sample becomes nonconductive. The switching between this curves with different $I-V$ characteristics occurs over several seconds. This length of time is a characteristic of the DX center, therefore we did not suggest any other mechanism of the electron trapping, as for example, capture of electrons by the quantum dots, which are formed in between 4 neighbouring antidots. This time it also depends strongly on the temperature, as was observed also in Ref. [2], with increase in temperature, the switching time is decreased. Other evidence observed from trapping by DX center is that curves become metastable and the sample remains in a nonconductive state, even if the value of V^{max} is decreased. After

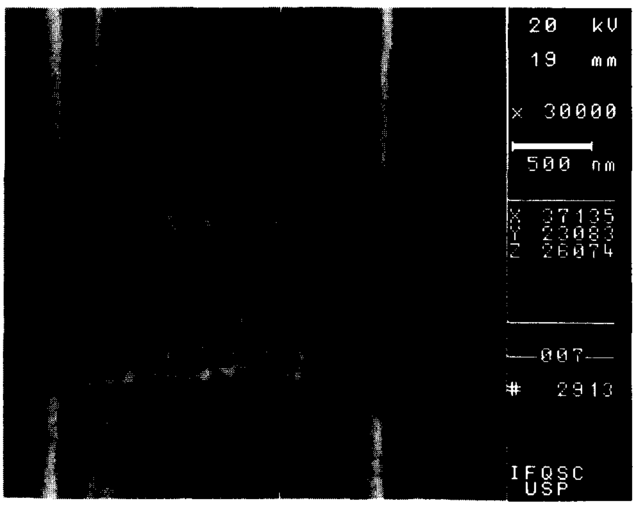

Fig. 1. An electron micrograph sample with disorded antidot lattice.

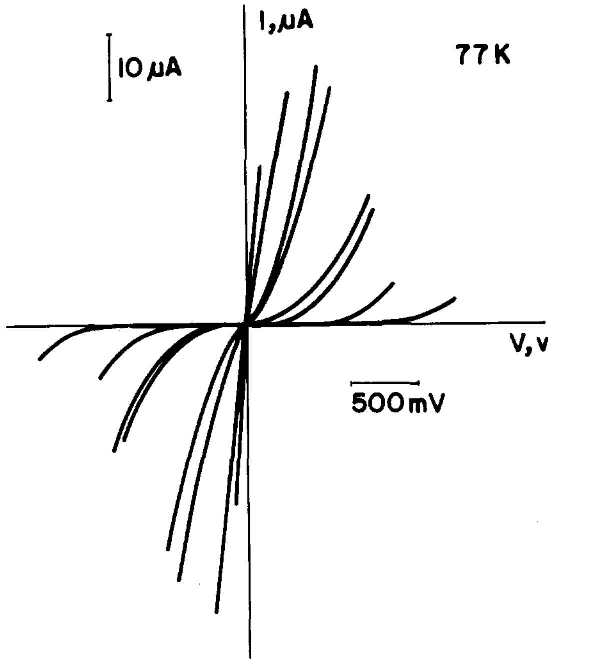

Fig. 2. $I-V$ characteristics of sample with disorded antidot lattice at various maximum voltage.

sample illumination, $I-V$ curves become linear again for low V^{max} and we may repeat all this cycle again. Thus, we observe that resistance at low voltage R_0 is strongly dependent on the value of the maximal voltage, which is applied to the sample. Fig. 3 shows this dependence at $T = 4.2$ K. We observe that R_0 has a linear dependence up to 400 mV, and after resistance starts to increase dramatically. The threshold resistance is equal approximately 12 kΩ, which is close to the resistance of one quantum channel $h/2e^2$. In this case we can suggest that only one channel is along our sample. The barrier for this channel increases lineary with the voltage, which is proportional to the captured charge. After threshold voltage the transmission coefficient starts to be dependent on the captured charge

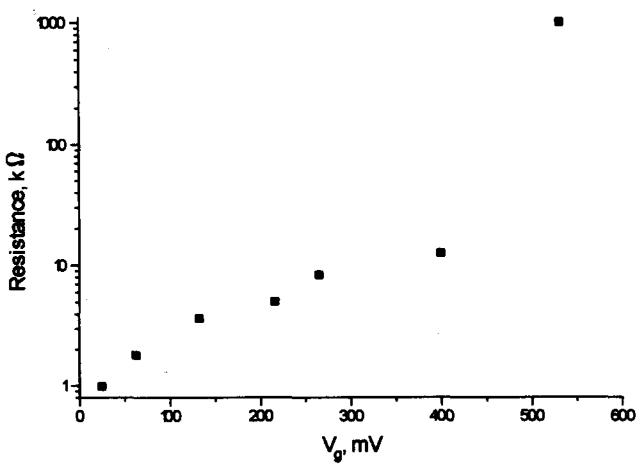

Fig. 3. The dependence of the resistance near zero voltage on the maximum voltage, $T = 4.2$ K.

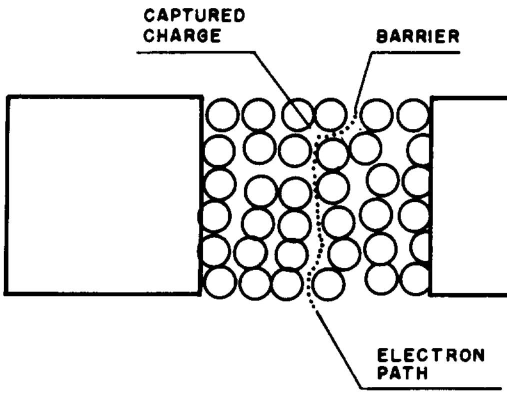

Fig. 4. Schematic view of sample.

exponentially. Thus the conductance of the system with the single tunnel barrier is given by the equation $\sigma = 2e^2/hT$, where T is the transparency of the barrier which can be written as

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

where $a = (2m^*(V-E))^{1/2}$, m^* is effective mass, b is the thickness of the barrier and $V-E$ is the difference between barrier height and the electron energy. As the resistance is of the order of the quantum resistance 12 kΩ, the transparency $T \approx 1$, and $V \sim E$. The change in the barrier with the modifications in the potential is then given by $\Delta T \approx 4\Delta V/V$, i.e. proportional to the change in the barrier potential that we found in the experiment. If we suggest that captured charge is proportional to the maximum voltage, and if resistance is larger than $h/2e^2$ the transparency becomes exponentially small, and resistance increases dramatically with the barrier height, that we also found in experiment (Fig. 3). Thus, the threshold behaviour of the resistance with V^{max} and their universal value $h/2e^2$ support our suggestion, that we measured current through a single barrier, which is controlled by the local capture of the carriers near this barrier. A schematic diagram of this situation is shown in Fig. 4. In this case we can estimate the captured charge. For the 2D electron gas we have screening of the charge, therefore potential on the distance r is equal to:

$$V = \frac{Qa_b^2}{4\pi r^3}$$

where $a_b = 100$ Å in GaAs, Q is the captured charge. For resistance $R = h/2e^2$ we have $T \approx 1$, and $eV \approx E_F$, where E_F is the Fermi energy. If the distance is in order of the period of antidot lattice, as shown in Fig. 4, we have the value of the captured charge $Q \approx 2\ 10^4\ e$. This value is very large, which means that all electrons in the sample with a size of $1 \times 1\ \mu m^2$ are captured. Thus, the screening of the charge captured potential is not 2D, and $V \approx \sim Q/r$. It is more reasonable, because we have very inhomogeneous 2D electron gas owing to the antidot lattice. Some local places, for example antidots, do not contain 2D electrons, therefore potential is unscreened. In this case we have $Q \approx 50\ e$, and the distance, where $QV \approx E_F$ is equal to 0.1 μm, and so approximately equal to the lattice periodicity. The schematic view of the sample with captured charge, shown in Fig. 4, is supported by a simple calculation. In this case it is possible to study the single electron capture by DX centers, and the measurement of this effect is now in progress. It should be noted that we did not find similar effect in the periodical antidot lattice. It supports our suggestion, that electrons are captured in a single local place, where large barriers exist for them. In this case the capture of the first electron starts to increase voltage drop in this place, which increases probability to the capture of the next electrons and so on until the moment when all DX centers are occupied. It is not the same case as in the periodical lattice, where capture of single electron in some places can only redistribute the current through other constrictions.

In summary, we observed trapping approximately 50 electrons by the many DX centers after applying the high voltage to the sample with disordered antidot lattice. It opens the possibility of studying single electron capture by the single DX center and, probably, choosing between different theoretical models of this center.

Acknowledgements

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