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OBSERVATION OF THE COULOMB BLOCKADE AT 77 K IN A LATTICE-MISMATCHED GaAs/Si HETEROJUNCTION

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We investigated current–voltage characteristics of a lattice-mismatched GaAs(n)/Si(p) heterojunction. For low bias voltages at 77 K it exhibits a behaviour characteristic of the Coulomb blockade. We discuss why this unexpected phenomenon can occur in the investigated structures.

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Fabrication of GaAs-based structures on Si substrates gives possibilities of easy integration of silicon electronics with optical devices. A major obstacle for a success of such technology are lattice defects, e.g. antiphase boundaries, twins, and dislocations, which are generated in GaAs by the lattice mismatch to Si [1]. A substantial contribution of charged misfit dislocations to electronic vertical transport in those structures is then expected.

In this work we investigated a system consisting of GaAs layer grown by molecular beam epitaxy on p^+-type Si (for growth details see Ref. [2]). Formation of antiphase domains in that polar-on-nonpolar system was suppressed by simple misorienting the Si (001)-oriented substrate slightly toward the [011] direction. The nominally undoped GaAs epitaxial layer of 2 μm thickness was n-type with Si concentration of 10^{15}–10^{16} cm^{-3}. Typically, as verified by secondary ion mass spectroscopy (SIMS), the Si atoms move into the GaAs layer, and Ga atoms diffuse into the Si substrate. Moreover, a site exchange mechanism can occur by which Si donors on Ga sites move to As vacancies, thereby creating acceptor sites. This process is tremendously enhanced near the interface by the high density of lattice defects in heteroepitaxial layer. As a result the p–n junction is shifted to GaAs side with respect to the Si/GaAs interface [3].

The lattice constant of GaAs is about 4% larger than that of Si. This mismatch leads to the formation of a two-dimensional network of misfit dislocations at the interface whose Burgers vectors lie in the ⟨110⟩ directions. Consequently, there are two orthogonal dislocation arrays with a spacing between parallel dislocations in each array of roughly 10 nm.

Typically, dislocations accept majority carriers, i.e. holes in our case, from the surrounding material thus becoming positively charged. The charged-dislocation network gives rise to a potential barrier for holes diffusing through the p–n junction.

We investigated samples etched from the heterostructure into mesas of the area ≈ 0.04 mm^2. The samples were supplied with good ohmic contacts: AuGe/Ni/Au alloy to n-type GaAs, and evaporated Al to p-type Si. These samples have been prepared to be studied as photodetectors [2]. We examined the current flowing throughout the heterojunction under forward bias at temperatures down to 77 K. No current measurement was possible in the temperature range of liquid helium so as the current carriers in Si were then frozen out. The samples displayed current–voltage characteristic, $I(V)$, which was deviated from that of an ideal p–n junction (Fig. 1). In a wide range of bias voltages the overall $I(V)$ curve could be described by an expression

$$I = I_0\left[\exp\left(\frac{e(V - IR)}{nkT}\right) - 1\right]$$

with $R \approx 2.5$ kΩ and $n \approx 10$ at room temperature.

Striking deviations from this expression have been observed under low forward bias at 77 K, being just the subject of the present communication. They manifest themselves as follows. No measurable current flows through the junction up to a certain bias voltage beyond which the current increases nonmonotonously with the voltage, displaying steps, which are distinctly seen in the differential conductance of the junction (Fig. 2). It is worth noting that the extension of the second step (and further ones) is twice as large as that of the first one. This behaviour resembles strikingly the Coulomb blockade and Coulomb staircase which, however, normally appears only in mesoscopic systems at very low temperature [4].

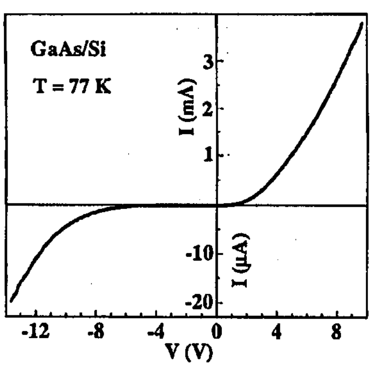

Fig. 1. Current–voltage characteristic of the investigated GaAs(n)/Si(p) heterojunction measured at a temperature 77 K. Note different current scales for forward (positive) and reverse (negative) bias voltages.

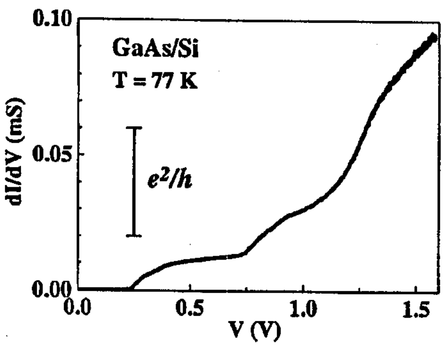

Fig. 2. Differential conductance versus voltage of the same junction as in Fig. 1 measured under low forward bias at 77 K.

A steady degradation of this behaviour during recurrent measurement cycles has been observed.

The appearance of the Coulomb blockade at 77 K in a single macroscopic tunnel junction seems at a first sight to be very unrealistic. Nevertheless, we show in the further part of this paper that owing to specific parameters of our heterostructures such an effect can indeed appear.

The charged dislocation network forms a potential barrier for holes which, owing to a discrete charge distribution on the dislocation lines, is not homogeneous over the interface area but has saddles in the middles of the network meshes. Therefore, the tunnelling of holes, after imposing forward bias on the junction, begins to proceed at the lowest saddle. The latter defines a microjunction suitable for the single-charge-tunnelling (SCT) event.

Crucial for the appearing of SCT effects is a small value of the relevant capacitance, C, of the junction. In a case of metallic capacitor, C should be less than $\approx$ 10 aF in order of the Coulomb charging energy, $E_C = e^2/2C$, to exceed the thermal energy, kT, at 77 K ($\approx$ 6 meV). However, our junction is very unusual in this respect. The electron concentration on the n-type side of the junction is probably as low as 10^{16} cm^{-3}. Then, the charge relaxation time, τ_{rel}, defined either by the Maxwellian relaxation time or by the inverse of the plasma frequency, is not shorter than 10^{-13} s. It is surely longer than the tunnelling time, τ_{tun}, whose actual value is not exactly known (debate on the proper definition of the tunnelling time is still going on [5]) but which lies typically in the femtosecond range. In that case the tunnelling event is completed before the charge equilibrium has time to be reestablished and then the static capacitance of the junction is not relevant to SCT.

We can simply estimate an effective capacitance appropriate to this case. We assume that the tunnelling occurs between two electrodes separated by a distance d, and that $\tau_{\mathrm{tun}} \ll \tau_{\mathrm{rel}}$. When all charges in the electrodes except the tunnelling one are fixed, an increase in the electrostatic energy just after the tunnelling event is $e^2/\varepsilon\varepsilon_0 d$, where $\varepsilon\varepsilon_0$ is the crystal electrical permittivity. It is equivalent to the energy of a single-electron charged capacitance of a value $C_{\mathrm{eff}} = \varepsilon\varepsilon_0 d^2/2d$. The latter value corresponds to a capacitor whose planar electrodes, separated by d, have areas equal approximately to $d^2/2$. Assuming $d = 10$ nm (corresponding to the mesh dimension) one gets $C_{\text{eff}} \approx 1$ aF, in accord with similar value estimated from the experimentally observed voltage of the Coulomb gap of 0.25 V (cf. Fig. 2). In that case, the condition $E_C > kT$, required for the appearing of SCT effects, is fully satisfied at 77 K.

Alternatively, this Coulomb blockade could be explained assuming the tunnelling to occur through small conducting islands (dots) immersed in nonconducting layer [6]. However, nothing allows us to suppose that such a system is actually realised in our case.

In conclusion, we observed an unusual manifestation of the Coulomb blockade at 77 K in a macroscopic heterojunction, which is an interesting contribution to the physics of single-charge-tunnelling phenomena.

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References

[1] H. Kroemer, T.-Y. Liu, P.M. Petroff, *J. Cryst. Growth* **95**, 96 (1989).

[2] F. Riesz, Vo Van Tuyen, J. Varrio, *Acta Phys. Pol. A* **88**, 889 (1995).

[3] K. Wilke, B. Budnick, M.H. Ludwig, G. Heymann, *J. Appl. Phys.* **77**, 653 (1995).

[4] M. Devoret, D. Esteve, C. Urbina, in: *Mesoscopic Quantum Physics*, Eds. E. Akkermans et al., Elsevier, Amsterdam 1995, p. 609.

[5] T. Figielski, *Solid State Commun.* **94**, 113 (1995).

[6] M. Fujii, T. Kita, S. Hayashi, K. Yamamoto, in: *Ninth Int. Conf. on Superlattices, Microstructures and Microdevices, Liege (Belgium) 1996*, Abstract Workbook, p. ThP-95.