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Real-space transfer of electrons under a random potential: a possible mechanism of current instability in heterostructures

V. I. Borisov, V. A. Sablikov, A. I. Chmil' and I. V. Borisova

Institute of Radioengineering & Electronics, Russian Academy of Sciences
Vvedenskii sq. 1, Fryazino, Moscow region, 141120, Russia.

Abstract. A possible mechanism of lateral current instability observed in GaAs/AlGaAs heterostructures is proposed. The mechanism has to do with electron transfer in a heavily doped layer of AlGaAs, which is strongly compensated due to the presence of DX-centers. The heating of electrons in the percolation cluster net and the transfer of these electrons to the random potential wells results in the appearance of a hidden negative differential conductivity. The formation of an electric field domain brings about the conductivity collapse of the 2D electron gas. Experimental results proving this mechanism are given.

Introduction

The electric instability is known to be observed in GaAs/AlGaAs heterostructures under certain conditions. In particular, it results in the almost complete current collapse through 2D electron gas. Although this is a dramatic and very important phenomenon, its nature is not yet understood.

In this paper a possible mechanism for this instability is proposed and experimental results confirming it are given. We suppose that the instability is caused by real space transfer of electrons in a long-range random potential in a heavily doped layer of AlGaAs. Heating the electrons in the percolation cluster results in their transfer to random wells where they become localized. This process gives rise to an N-type negative differential conductivity and an electric field domain formation. One wall of the domain, which is enriched with electrons, blocks the conductivity of 2D electrons.

1 Experimental

The modulation doped heterostructures GaAs/Al_{0.25}Ga_{0.75}As were obtained by MBE. The instability was observed in structures with heavy doping of AlGaAs ($\sim 5 \cdot 10^{18} \text{ cm}^{-3}$), suitably large thickness of the AlGaAs layer ($\geq 500 \text{ \AA}$) and the spacer ($\sim 150 \text{ \AA}$) under temperatures less than 300 K. The amplitude of the current oscillations increases, and its frequency decreases, with lowering the temperature. Various types of current instabilities can be observed, depending on the experimental conditions. In particular, these include continuous oscillations of the current, or, under temperatures less than 150 K, a periodic current collapse with a characteristic turn-off time of $\sim 2 \cdot 10^{-8} \text{ sec}$. Fig. 1 shows the time evolution of the current in the case where a small dc voltage and a large-amplitude voltage pulse was applied to the structure, which triggered the current collapse. A strong decrease of current takes place under the pulse action, and afterwards the conductivity relaxes. Analysis shows the characteristic relaxation time to have a temperature-dependence with an activation energy of approximately 30 meV. This implies that the current electrons become localized under the pulse action, and that the bond energy does not correspond to any known defect level in the AlGaAs/GaAs heterostructure. We show that this energy is close to the random potential amplitude.

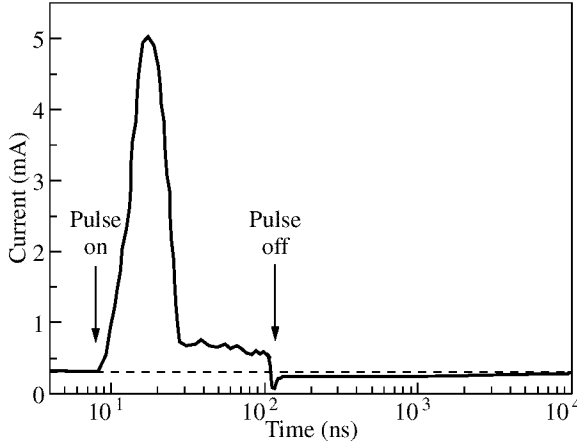


Fig. 1. Evolution of the current during the collapse and subsequent recovery of conductivity. $T = 77$ K, the voltage pulse amplitude is $U = 90$ V, distance between contacts is 5 mm.

2 Real-space transfer in random potential

We draw attention to the fact that AlGaAs layer contains a layer which is not depleted with electrons and this layer is heavily doped and strongly compensated semiconductor due to presence of both shallow donors (Si atoms) and deep levels of DX centers. The concentration of DX centers is not fixed because they are created by Si atoms which are displaced in the cell and capture two electrons. However the concentration of charged DX^- centers is very close to that of donors so that the large-scale random potential appears. The amplitude of the random potential is determined by the fluctuation of the DX^- -center concentration and screening by the 2D electrons. The amplitude of the large-scale potential fluctuation is estimated as

$$\varphi(R_s) \approx \frac{e}{\epsilon} \left(\frac{\pi a N_{\text{Si}}}{2} \right)^{1/2},$$

where a is the thickness of undepleted layer, R_s is the spatial scale of fluctuations, $R_s \approx (2d + a)$, ϵ is the semiconductor's dielectric constant. The random potential amplitude is evaluated numerically as $\varphi \sim 70$ meV and spatial scale is $R_s \sim 600$ Å, i.e. the large-scale potential is close to its maximum value determined by the binding energy of DX centers and essentially exceeds the temperature.

The conduction in an AlGaAs layer occurs through a percolation cluster net. As the temperature dependence of conductivity does not exhibit activation behavior, it seems likely that the level of a chemical potential is greater than the percolation level. However, the chemical potential cannot greatly exceed this level, because otherwise the average concentration of free electrons would be too high. Thus, electrons in percolation clusters move without having to overcome any barriers. Percolation clusters are surrounded by a multitude of random potential wells, in which the electrons are localized.

The height of the potential barriers separating electrons in clusters from the electrons in the wells is evaluated by $\varphi(R_s)$. The mobility of electrons in clusters is expected to be rather high, and hence noticeable heating of electrons by an external electric field occurs. Under such conditions the nonlinearity of conductivity is governed by real space transfer of the heated electrons from the cluster net to the wells. The electrons coming into the wells dissipate their energy via phonons and thus cease to participate in conduction. In such a

way, a priming negative differential conductivity appears.

Above mechanism is also similar to the known mechanism for N-shaped current-voltage characteristics in semiconductors with repulsive impurity centers. Random potential wells play the role of capturing centers in our case.

3 The current instability

The essential difference of the system we consider here, from the well investigated case of real space transfer of electrons in heterostructures [1] consists in the fact that the potential relief is not fixed and is changed when the electron density is redistributed between the cluster and wells. The electron transition to wells results in a change of the latter's potential, and correspondingly in a change in the barrier the electrons must overcome. The number of electrons in a well under non-equilibrium conditions is determined by the balance of electron flows from a cluster into wells and in the opposite direction.

The heating of electrons in the percolation cluster and their transfer to adjacent random wells results in a priming N-type negative differential conductivity in AlGaAs layer. The process is initiated in those places where the conductivity is the lowest one. The electron transfer to the wells leads to the conductivity decrease, which gives rise to a local increase in the electric field and the electron heating and so on. The evolution of instability can be accompanied both by oscillations of a current and the formation of the high field domain.

The threshold electric field F_c for the instability to appear is estimated as

$$F_c \approx \left(\frac{(2\alpha + 1 + k)n_0 T}{3e\mu_n \tau_\varepsilon N} \right)^{1/2}, \quad (1)$$

where μ_n is the electron mobility, τ_ε is the energy relaxation time of electrons, $\alpha = e^2 N w / (4CT)$ is a dimensionless parameter, $N = mT / (\pi \hbar^2)$ is the effective density of states in the two-dimensional case, w is the characteristic well size, C is the specific capacitance (per unit length) of wells with respect to a cluster (of magnitude $C \sim 1$, because cross-sectional sizes of a barrier and wells are of the same order of magnitude. n_0 is the two-dimensional concentration of electrons in a cluster, $k \sim 1/2$. Using the reasonable values of parameters: $\tau_\varepsilon = 3 \cdot 10^{-12}$ sec, $\mu_n = 10^4$ cm²/Vsec, $n_0 \approx N$, the threshold field may be evaluated as $F_c = 500$ V/cm for $T = 200$ K. The average electric field along a layer may be noticeably lower.

The instability in a AlGaAs layer has a crucial influence onto the conductivity of the whole heterostructure, owing to its effect onto 2D electron gas. This effect is determined by two main processes.

The first process is connected to the domain. One of the domain wall accumulates a positive charge while the other wall is charged negatively. The electric field of the negatively charged domain wall pushes out electrons from the quantum well and blocks current through 2D electron gas. Apparently, this is a reason for the collapse of current to occur.

The second process is connected to the presence of the ohmic contacts, which connect the 2D electron layer with highly doped AlGaAs layer. The transfer of the electrons from a cluster into the wells of a random potential results in the violation of an equilibrium between the electrons in a cluster net and the 2D electron gas. This causes the electrons from a quantum well to pass into the cluster net where they are warmed up by the applied electric field and transferred to the wells of a random potential and so on.

The offered mechanism allows one to explain qualitatively the main features of the observed instability. We have done two additional experiments to conform this mechanism of instability.

An effect of homogeneous illumination on the instability was investigated. We have found that the variation in the threshold field caused by illumination correlate directly with photoconductivity of 2D electrons studied in [2]. An increase in the 2D electron density results in increasing the threshold field. This correlation may be understood taking into account that in this case the equilibrium between the electrons in a cluster net and the 2D electron gas is violated. This causes the electrons from a quantum well to pass into the cluster net. A rise in the electron concentration in the cluster net according to the equation (1) results in the rise of threshold voltage.

The second experiment was done using the local illumination of the sample by a focused radiation of the He-Ne laser under the conditions of a current collapse. We found that the full recovery of the conductivity appears if a light spot has a certain position. This position depends on the amplitude of impulse voltage. This fact allows us to conclude that the distribution of the electric field in a sample is non-uniform and that this non-uniformity is not connected to any technological defects. It can be connected to formation of high field domain in the AlGaAs layer.

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