Tunnel current oscillations in a GaAs/AlAs double-barrier heterostructure

A. E. Belyaev, S. A. Vitusevich, and R. V. Konakova
Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, 252028 Kiev, Ukraine

T. Figielski, A. Makosa, and T. Wosinski
Institute of Physics, Polish Academy of Sciences, Warszawa, 02-668, Poland

L. N. Kravchenko
Science and Research Institute of Molecular Electronics, 103460 Moscow, Russia

(Submitted 8 August 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **60**, No. 6, 403–405 (25 September 1994)

A fine structure (oscillations) of the tunnel current in resonant, tunneling, double-barrier quantum heterostructures based on AlAs/GaAs/AlAs with a wide spacer layer was observed. The period of the oscillations is close to $\hbar\omega_{\rm LO}/e$, where $\hbar\omega_{\rm LO}$ is the longitudinal optic phonon energy in GaAs. A model is proposed to explain such a LO phonon-related oscillatory structure in the tunneling devices. According to this model, the carriers injected from the n^+ emitter lose energy gained in a strong electric field as a result of the emission of LO phonons in the accumulation layer on the emitter side or in the depletion region adjacent to the collector barrier in the dependence on where the spacer layer is situated. © *1994 American Institute of Physics.*

The remarkable oscillatory structure in the current-voltage characteristics, I-V, of single and double barrier tunneling devices based on AlGaAs/GaAs heterostructures has recently been investigated by several groups.[1–4] In some cases, the oscillations have a period which is close to $\hbar\omega_{\rm LO}/e$, where $\hbar\omega_{\rm LO}$ is the longitudinal optical phonon energy in GaAs. To explain such a LO phonon-related oscillatory structure in the n- or p-type tunneling devices, we propose a model, according to which hot carriers (electrons or holes) injected through the tunnel barrier lose energy as a result of the emission of LO phonons. This occurs in the depletion layer which is adjacent to the collector contact. On the other hand, the oscillations can also arise due to the interference effects in the wide well.[4] At the same time, there are no experiments in which the oscillatory picture due to the processes occurring in the accumulation layer has been observed.

In this paper we report the observation of LO phonon oscillations on the I-V curves of a double-barrier AlAs/GaAs/AlAs heterostructure. In our opinion, the processes connected with the energy losses of carriers injected from a virtual cathode play a crucial role in the appearance of these oscillations. The samples used in this study were grown by MBE, and the layer structure is as follows: i) n^+-(100)GaAs substrate; ii) n^+-GaAs(100 nm, N(Si)$=10^{18}$ cm^{-3}); iii) undoped GaAs ($\sim$100 nm) spacer layer; iv) undoped AlAs(2 nm); v) undoped GaAs(4 nm); vi) undoped AlAs(2 nm); vii) n^+-GaAs(100 nm, N(Si)$=10^{18}$ cm^{-3}) top contact layer. Two quasi-bound states of the well are expected to

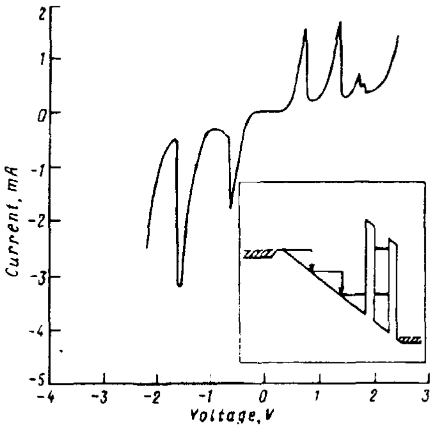

FIG. 1. Current-voltage characteristics of the double-barrier structure measured at T=77 K. In the inset the potential profile of the conduction band for the double-barrier structure is shown in the forward bias.

appear in this structure: E_0=0.18 eV and E_1=0.68 eV. We measured the current-voltage characteristics (I-V) and the differential conductance, G=dI/dV, of square mesa diodes of area (32 μm)^2 which were fabricated from this structure. A typical liquid-nitrogen-temperature I-V curve is shown in Fig. 1. Surprisingly, three resonant peaks were observed at low temperature when electrons were injected from the spacer side (forward bias), instead of two peaks which actually appeared when the bias polarity was reversed. The LO phonon-related oscillatory structure is too weak to be seen directly on the I-V characteristic, but is clearly revealed by voltage modulation. Up to ten peaks are seen in Fig. 2, which are $G(V)=f(V)$ plots obtained for various temperatures. The oscillations occur in both bias directions on the low-voltage slope of the first and second resonant peaks. There are no oscillations for the third resonant peak in the forward bias. The oscillatory structure has a well-defined period, ΔV=(36±1) mV, for the first peaks and ΔV=(38±1) mV for the second peaks. This period is very close to the LO phonon energy in GaAs. The oscillation period does not depend on the temperature, while their amplitude decreases linearly with increasing temperature up to 120 K. It should be noted that the amplitude increases monotonically with applied voltage, in contrast with the cases described previously.[2,3] The interference effects cannot be a reason for the appearance of fine structure in our case, because the expected period must be noticeably greater

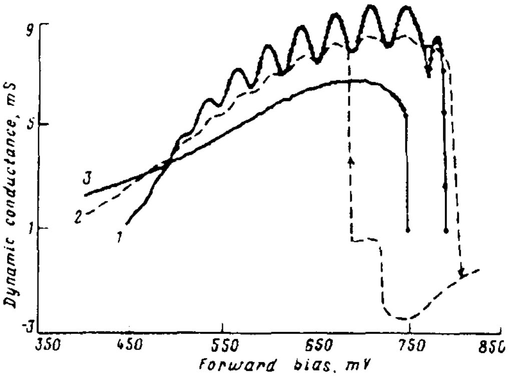

FIG. 2. Dynamic conductance versus applied voltage which corresponds to the first peak. T, K: 4.2—*1*; 80—*2*; 140—*3*.

for the well of width[4] 4 nm. To explain the above-mentioned features of the $G(V)$ we must first discuss the mechanisms by which the tunneling in the structure studied by us occurs. In the reverse bias the voltage drop occurs entirely across the double-barrier structure and the depletion layer on the collector side. The influence of the accumulation layer on the emitter side can be ignored in this case. This case is very similar to that observed in Refs. 2 and 3, taking into account the small width of the barriers and the well in our structure. In the reverse bias the oscillations of $G(V)$ are therefore determined by the modulation with a periodicity $\hbar\omega$ of the impedance in the region adjacent to the collector barrier. In the forward bias the situation is quite different. In this case the emitter side of the structure contains an undoped GaAs layer. The applied voltage produces an accumulation layer in the region close to the emitter barrier because of the light doping. In the off-resonance regime, when the current through the structure is small, this layer is in thermodynamic equilibrium with the emitter and does not differ from the proper enriched layers of the heteroboundaries. In the resonance regime, when a noticeable ballistic current flows through the structure, the accumulation layer is formed as a result of dynamic equilibrium between the electrons which escape from the ballistic regime and which are thermalized in the accumulation layer and those which escape from the layer as a result of thermal activation.[5] The voltage drop in the case of forward bias is expected across the accumulation layer and the double-barrier structure. The depletion layer on the collector side can be ignored due to heavy doping of the n^+-GaAs top contact layer. Thus, under the forward bias conditions the electrons can be injected into the well from the n^+-type emitter either ballistically or via the subband of the accumulation region in the spacer layer. This circumstance leads to the appearance of an additional peak and to the bistability because of space charge builtup. On the other hand, if the accumulation layer length d_{ac} is shorter than the mean free path of the accelerating electrons, l_{opt}, then the latter can be reflected several times at the right and left boundaries of the accumulation layer before emitting the LO phonon. In the opposite case, $d_{ac}>l_{opt}$, the emission of an LO phonon occurs before the electron reaches the emitter barrier (see the inset in Fig. 1). The latter case obviously occurs in our structure. If the energy difference between the virtual cathode and the quantum-size level in the well is $n\hbar\omega_{LO}$, where n is the number of emitted phonons, an increase in the tunneling current may occur. The current can therefore be modulated with a periodicity of $\hbar\omega_{LO}$ because of the electrostatic feedback effect. This does not take place when the electrons tunnel from the subband of an accumulation region in the spacer layer. Therefore, there are no oscillations on the low-voltage slope of the third peak. In conclusion, we should like to emphasize that despite the similarity of the oscillation patterns in the forward and reverse biases, their origins are different.

The authors are indebted to Prof. Z. S. Gribnikov and Dr. E. Kaczmarek for helpful discussions.

This work was supported by the State Committee for Science and Technology of Ukraine, Project 7.01.05/141, and by the State Committee for Scientific Research of Poland, Project PBZ-101-01-11.

[1] R. T. Collins *et al.*, Appl. Phys. Lett. **44**, 532 (1984).
[2] T. W. Hickmott *et al.*, Phys. Rev. Lett. **52**, 2053 (1984).
[3] M. Alikasem *et al.*, Semicond. Sci. Technol. **7B**, 446 (1992).

[4] E. S. Alves *et al.*, Solid State Electronics **32**, 1627 (1989).
[5] I. N. Dolmanov *et al.*, Fiz. Techn. Poluprovodn. **24**, 1574 (1990) [Sov. Phys. Semicond. **24**, 983 (1990)].

Published in English in the original Russian journal. Reproduced here with stylistic changes by the Translation Editor.