Optical observation of the formation of an electric-field domain in an n^+–i–n^+ GaAs/AlGaAs superlattice with wide quantum wells

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(Submitted 31 January 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **61**, No. 5, 399–404 (10 March 1995)

The nucleation of an electric-field domain in a superlattice with wide quantum wells (a multilevel system) has been detected through a comparison of data found from measurements of the photoluminescence spectra and electrical measurements and also on the basis of an observed current bistability. This process has been studied. © *1995 American Institute of Physics.*

The vigorous research on semiconductor quantum-well structures has resulted in the observation of several new transport and optical effects.[1] Of particular interest are vertical transport phenomena in superlattices, because of, in particular, possible applications of these phenomena in ultrafast electronic devices. A factor of importance in determining the energy spectrum and dynamic properties of the charge carriers is the distribution of the electric potential along the growth axis of the superlattice. It has been learned that during transverse current flow the volume of a superlattice may break up into two or more regions with different electric fields (electric-field domains), separated by space-charge regions.[2] The strengths of the electric fields in the various domains are not arbitrary; they are directly related to the distance between the quantum-well energy subbands in the superlattice. Manifestations of electric-field domains have been detected on the basis of quasiperiodic oscillations on the current–voltage characteristics, with a period corresponding to the energy distance between the corresponding subbands in neighboring quantum wells.[2–5] Electric domains have also been observed in measurements of the photoconductivity and photoluminescence of p–i–n structures.[6]

In this letter we are reporting detection (by an optical method) of the nucleation of an electric-field domain in a long-period superlattice. We used a unipolar n^+–i–n^+ structure based on GaAs/AlGaAs in a special geometry. In our arrangement we were able to avoid an effect of carriers of the opposite sign. As the electric field was raised, we observed the formation, in the spectrum of intervalley photoluminescence, of lines corresponding to domains of different types, as the result of a Stark shift of the ground state. We made a direct comparison of the data from optical and electric measurements. This comparison yielded an explanation of the features detected in the vertical transport due to a resonant tunneling of carriers in the long-period superlattice.

The experiments were carried out on a GaAs/Al$_x$Ga$_{1-x}$As ($x = 0.3$) superlattice with

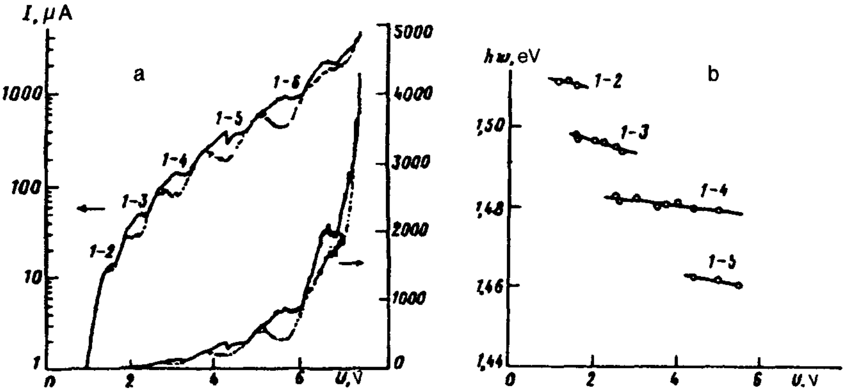

FIG. 1. a: Measured current–voltage characteristic of a GaAs/AlGaAs superlattice in linear scale (curves at right) and in logarithmic scale (curves at left). Solid curve—Measurements with increasing applied voltage U; dashed curve—with decreasing U. b: Energy positions of the photoluminescence lines and regions in which they exist along the scale of the applied voltage (the numerals specify the types of corresponding intersubband transitions).

quantum wells 350 Å wide and barriers 100 Å wide (there were 30 periods). These superlattices were grown by molecular beam epitaxy on an n^+-GaAs substrate. The superlattices were lightly doped with silicon to a level of 5×10^{15} cm^{-3}. In all the experiments, the positive electrode (the anode), at which a domain should be nucleated,[2,3] was in the upper layer of the mesostructure. The electrical and optical measurements were carried out on mesas 600 μm in diameter. For optical access to the upper part of the superlattice, the electrical contact (AuGa/Ni) which was deposited had a smaller diameter (500 μm). For this purpose, the thickness of the heavily doped upper n^+-GaAs layer was made extremely thin (100 Å). The upper layer and the buffer layers of lightly doped n^+-GaAs (2×10^{18} cm^{-3}) were separated from the superlattice by a barrier 50 Å thick. Photoluminescence spectra were excited by the beam from an argon laser ($\lambda = 5145$ Å, 2.41 eV). This beam penetrated a distance of several periods of the superlattice into the structure. The photoluminescence spectra were measured with a Bomem DA-3 Fourier spectrometer (the detector was a germanium-cooled photodiode). Over the intensity range studied (up to 10 W/cm), we observed no significant dependence of the spectra on the excitation level. The test samples were cooled to 10 K.

Figures 1 and 2 show results of measurements of the current–voltage characteristics during vertical electron transport. These results were obtained on the better mesas, on which the features of the current–voltage characteristics were clearest. We see that the voltage dependence of the current is stepped in a long-period superlattice. The regions of a stable current (the "plateaus") along the U scale are 1.5–1.8, 2.4–2.7, 3.2–6.5, 4.2–4.6, and 5.6–6.4 V. They alternate with regions of a rising current. In the zone of the transition from a rising part of the characteristic to a plateau, and also on the plateau itself, we see a series of regions of a negative differential conductivity—oscillations with a period of several tens of millivolts. The period of these oscillations increases with increasing applied voltage. For each step there is a corresponding energy of the transition

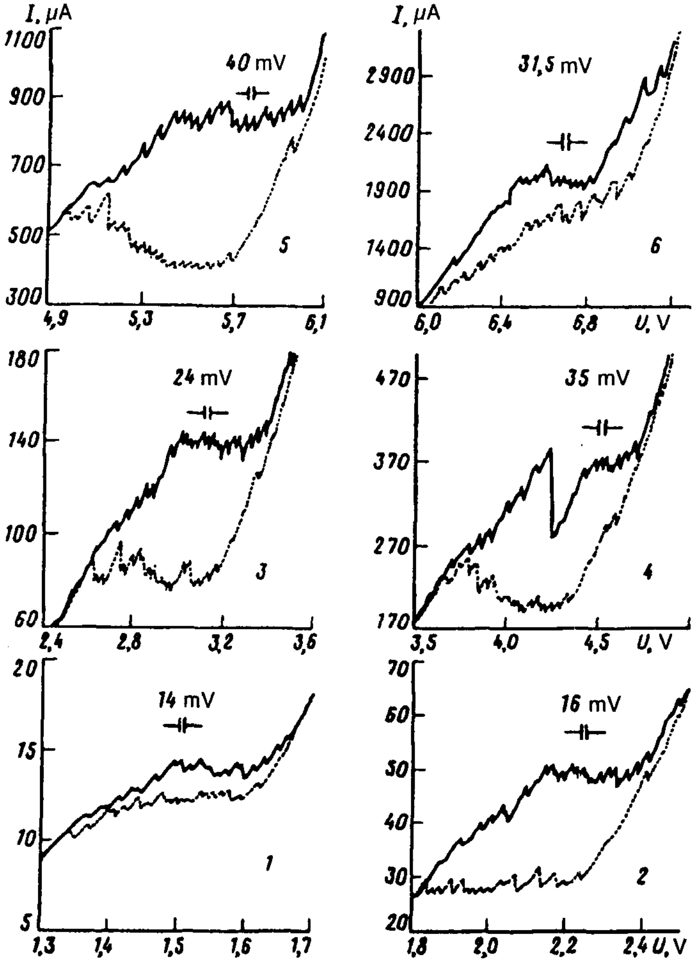

FIG. 2. Results of some more-detailed measurements of the current–voltage characteristics, which demonstrate the oscillations in the negative differential conductivity (each of the six observed features consists of 25–26 oscillations). The oscillation period, found in regions with a plateau, is shown in each fragment.

between the ground level and the excited quantum-well levels for these structures.

Under the same conditions, the spectra of interband photoluminescence exhibit the appearance and disappearance of new photoluminescence lines with increasing electric field. Each of these lines is observed in fields corresponding an associated plateau region on the current–voltage characteristics. As the field is raised, the intensity of each line increases sharply; it then goes through a maximum and falls off rapidly. A new peak arises on the long-wave side and goes through the same stages. These photoluminescence lines are observed against the background of two broad bands at 1.516 and 1.496 eV (Fig. 3), which are a consequence of a superposition of the recombination of free carriers, carriers trapped by impurities, and excitons in quantum wells and in the substrate mate-

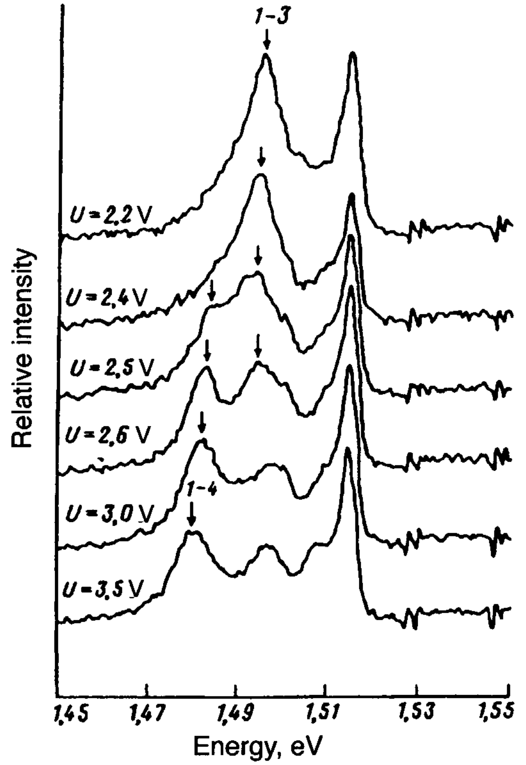

FIG. 3. Photoluminescence spectra measured at various values of the applied voltage U.

rial. Their frequencies are essentially independent of the applied field (Fig. 1). As we see in Fig. 3, a characteristic feature of the effect is the abrupt nature of the changes in the photoluminescence spectrum. The photoluminescence lines appear and disappear in narrow intervals (1.55–1.59, 2.4–2.5, 3.5–3.7 V, etc.) of the applied voltage. The spectral positions of the observed photoluminescence lines and the regions along the electric-field scale in which they exist are shown in the lower part of Fig. 1.

Since a tunneling transport regime prevails in this structure, with its wide barriers, a necessary condition for the flow of an electric current through the superlattice is that there be an exact energy resonance between the quantum-well electron levels in neighboring quantum wells.[2,3] In general, the distribution of the electric field along the superlattice is not uniform. There are instead (two or more) regions (domains) with different electric fields. Each electric field, however, is a characteristic, fixed field for the given type of domain. The strength of this field is determined by the energy distance between the corresponding subbands which are at resonance. Some straightforward theoretical estimates show that the observed plateaus on the current–voltage characteristics have positions along the voltage axis which correspond to different types of domains with $1-i$ resonant levels (1–2, 1–3, 1–4, etc.). The small oscillations of the negative differential conductivity observed in each of the plateaus are characterized by a period corresponding to the energy distance between levels 1 and 2, 2 and 3, 3 and 4, etc. In other words, these small oscillations can be attributed, quite confidently, to an abrupt shift of the wall of a strong-field domain into a neighboring quantum well followed by repetitions of the process over all periods of the superlattice.

The observed photoluminescence lines are evidently due to a recombination of electrons and holes in quantum wells. They can be interpreted, with the help of the Stark shift of the lower electron and hole levels,[5,6] as belonging to different types of domains in the superlattice. Estimates of the Stark shift of the photoluminescence lines for each type of domain carried out in the linear approximation, $\Delta h\nu_i = eF_i d$, where $eF_i = (\epsilon_i - \epsilon_1)/(d_w + d_b)$, agree qualitatively with the experimental results (Fig. 1). Here F_i is the electric field in the domain of type $1-i$, ϵ_1 and ϵ_i are energies of the subbands which are at resonance, and d_w and d_b are the widths of the quantum wells and of the barriers between them.

Since the increase in the intensities of the photoluminescence lines is quite sharp, occurring over a narrow interval of electric fields (not proportional to the volume of the expanding domain), and since the regions in which each new line appears correspond to features on the current–voltage characteristics, it can be concluded that we have directly observed the instant of the nucleation of an electric-domain field domain in these experiments. Comparison with these current–domain characteristics reveals that the narrow electric-field intervals just mentioned correspond to a transition of the current–voltage characteristic into a region of stabilized current (a plateau) and to the appearance of a new series of small, negative, differential conductivities, with a period δU_i corresponding to the energy distance between the levels determining the given resonant type of domain in the superlattice: $\delta U_i = (\epsilon_i - \epsilon_{i-1})/e$ (δU_2–11 mV; δU_3–19 mV; δU_4–27 mV; δU_5–34 mV; δU_6–40 mV; δU_7–46 mV).

Taking these results into account, we can explain the structural features on the current–voltage characteristics of a long-period superlattice. At low voltages the current is due to a resonant flow along low-lying levels in the quantum wells, the potential is distributed in a quasilinear fashion along the superlattice growth axis, and the mismatch of the levels in neighboring quantum wells is offset by the natural width of these levels. The current increases exponentially with the field, because of an increase in the potential difference at the emitter–superlattice interface and because of an increase in the injection from the heavily doped emitter region.[5,7] In fields at which the level mismatch begins to exceed the width of the levels ($U < 1.5$ V), a linear potential distribution becomes unstable, and a domain of a strong electric field arises near the anode at $U = 1.55-1.59$ V. In this domain, there is a resonance between the ground level (1) and the first excited level (2) in neighboring wells (this is a 1–2 domain). At the same time, we detect the onset of the first of the photoluminescence lines corresponding to this domain. As the voltage is raised, there is an abrupt expansion of the domain region to neighboring quantum wells, accompanied by the appearance of the first series of small, negative, differential conductivities, with a period along the voltage scale corresponding to the difference between the energies of levels 1 and 2. As a domain is nucleated, the electric current stabilizes (this is the beginning of a plateau on the current–voltage characteristic), since the field in the superlattice and that at the emitter–superlattice interface stabilize. The stabilization of the current is a consequence of a screening of the applied voltage by a space-charge region at the domain wall. The change in the voltage on the superlattice is due entirely to an expansion of the domain region. As the voltage is raised, and the domain wall moves toward the emitter, the cancellation becomes incomplete, and the current begins to rise again (growth region 1.6–2.2 V). When the domain reaches the emitter region, the potential distribution becomes quasilinear again. In the anode region, a new domain, of type 1–3, is nucleated. The previous line in the photoluminescence spectrum is quenched, a new line arises, and the current–voltage characteristic goes into the region of the next plateau (2.2–2.4 V), with a new period of the oscillations of the negative differential conductivities, corresponding to the energy distance between levels 2 and 3 in neighboring quantum wells. The process continues in the same fashion. We detected a total of six such stages, corresponding to domains with resonant structures: 1–2, 1–3, 1–4, 1–5, 1–6, and 1–7. The abrupt quenching of an "old" domain peak upon the formation of a new one, at the time at which the new domain occupies only a small fraction of the volume of the superlattice, is evidently confirmation that the nucleation of a new domain occurs in the anode region of the superlattice.

Further evidence in favor of this picture of resonant tunneling in a long-period superlattice comes from observations of a hysteresis (bistability) in these experiments. The onset of a current bistability at those field values at which a new line appears in the photoluminescence spectrum, on the one hand, and the transition of the current–voltage characteristic into a stabilized-current region with a new period of the small negative differential conductivities (oscillations), on the other, suggest that this effect may be due to (a) a predominant alignment of the space charge near an interface between domains and (b) the dynamics of the propagation of this charge, along with the domain wall, as the latter moves through the series of quantum wells of the superlattice. This picture stands in contrast with the behavior observed in the case of two-barrier structures.[8]

This study had financial support from INTAS (93-1704) and the Russian Fund for Fundamental Research (Project 94-02-06012).

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Translated by D. Parsons