Semiconductors, Vol. 39, No. 1, 2005, pp. 44–49. Translated from Fizika i Tekhnika Poluprovodnikov, Vol. 39, No. 1, 2005, pp. 53–58.
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LOW-DIMENSIONAL SYSTEMS

Current Oscillations under Lateral Transport in GaAs/InGaAs Quantum Well Heterostructures

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Submitted June 1, 2004; accepted for publication June 14, 2004

Abstract—The current–voltage (*I*–*V*) characteristics were measured and the current-pulse oscilloscope patterns were obtained for multilayer *n*-InGaAs/GaAs quantum-well heterostructures and *n*-GaAs epitaxial layers with various doping levels. It is shown that the *I*–*V* characteristics flatten at low doping levels in fields of 300–400 V/cm. In more heavily doped samples, current oscillations are initiated with a period corresponding to a drift velocity of (3–3.5) $\times 10^5$ cm/s at $\mathbf{E} \parallel [110]$ and are approximately larger at $\mathbf{E} \parallel [100]$ by a factor of 1.5. The results obtained are attributed to the formation of, respectively, stationary and moving acoustoelectric domains in the structures. In fields above 1.5 kV/cm, high-frequency Gunn oscillations corresponding to a drift velocity of 1.5×10^7 cm/s were observed. © *2005 Pleiades Publishing, Inc.*

1. INTRODUCTION

The phenomenon of spatial transport of carriers in semiconductor heterostructures with selectively doped barriers (in particular, δ-doped) in a strong lateral (i.e., directed in the well plane) electric field was actively studied in the 1980s (see, e.g., review [1]). Due to heating of carriers by the electric field, they can be carried away from quantum wells into doped barrier layers. As a result, the carrier mobility decreases due to the onset of the mechanism of scattering at ionized impurities, which can cause a decrease in the current, i.e., the formation of *N*-type negative differential conductivity (NDC), as is the case in the Gunn effect in GaAs-type semiconductors (see, e.g., [2]). The *N*-type NDC formation can give rise to electronic instability, in particular, the formation of stationary or mobile domains of strong field. The spatial transport of hot carriers from quantum wells (QWs), where their mobility and effective temperature are rather high, into higher-lying energy states with low mobility, where the effective temperature decreases, can cause population inversion [3–8].

This paper is devoted to the experimental study of electric transport of hot carriers in *n*-InGaAs/GaAs QW heterostructures in strong lateral electric fields. Previously [9–11], flattening of the current-voltage (*I*–*V*) characteristics and the initiation of current oscillations was observed in such structures at liquid-helium and liquid-nitrogen temperatures in fields of 300–1000 V/cm. This behavior was related to spatial transport of hot carriers and the *N*-NDC arising under these conditions. In this study, we compared the *I*–*V* characteristics and current-pulse oscilloscope patterns measured in *n*-InGaAs/GaAs QW heterostructures and *n*-GaAs epitaxial films with the published data on GaAs/AlGaAs heterostructures. Based on this comparison, we concluded that the observed oscillations are associated with the development of acoustoelectronic instability in the samples.

Since GaAs is a piezoelectric, a strain caused by a transverse acoustic wave propagating in the [110] direction induces a macroscopic electric field. This results in the intense interaction of electrons moving in the same direction with lattice vibrations. Therefore, as the electron velocity exceeds the propagation velocity of the acoustic wave, electrons begin to actively emit phonons (an analogue of Cherenkov radiation) [12–14].

As an electric field stronger than a certain critical value is turned on along the [110] direction, acoustic waves propagating from the cathode to the anode are amplified in the crystal. As a result, the flux envelope exponentially increases to the anode. Since the acoustic wave causes acoustoelectric current directed opposite to the drift motion of electrons, the voltage drop in the near-anode region increases to retain the total current, and the field decreases in other sample regions. In turn, as the electric field strengthens, the acoustic wave gain increases significantly in this region. Such positive feedback causes the formation of a stationary near-anode electroacoustic domain with strong acoustic and electric fields [12–14], as well as flattening of *I*–*V* characteristics in strong fields. The pattern of acoustic instability development radically changes under conditions of significant amplification (more than 100 dB/cm). In this mode, the acoustic streaming very rapidly reaches a level of nonlinearity, which results in the formation of a mobile acoustoelectric domain. The latter represents a short (~100 μm) packet of acoustic oscillations moving over the sample with a velocity close to the velocity of sound. If the field was applied in other directions, Parameters of the studied n-In$_x$Ga$_{1-x}$/GaAs samples with single and double quantum wells and n-GaAs epitaxial layers (the concentration values correspond to room temperature)

Structure index	x	d_{1QW}, Å	d_{2QW}, Å	Number of periods	Structure thickness, μm	n_s, 10^{11} cm^{-2} (per period)	N_s, 10^{12} cm^{-2} (total)
2987	0.08	200	100	20	2.3	1.1	2.2
3490	0.08	200	100	20	2.3	3.0	6.0
3517	0.08	200	–	20	2.5	3.9	7.8
3518	–	–	–	–	2.5	–	7.0
3628	–	–	–	–	2.4	–	48
3629	–	–	–	–	2.4	–	18.5
3630	–	–	–	–	2.4	–	7.0
3631	–	–	–	–	2.4	–	3.4
3732	0.1	200	–	20	2.5	0.3	0.6
3734	0.1	200	–	20	2.5	2.4	4.8
3735	0.1	200	100	20	2.6	2.0	4.0
4079	0.06	200	–	20	2.6	1.4	2.9
4081	0.06	200	100	20	2.6	2.5	4.9

oblique waves propagating at an angle to the field direction were amplified. Oscillations caused by acoustoelectric domains in GaAs/AlGaAs QW heterostructures were studied in detail in [15]. As the field (applied in the [110] direction) exceeds a critical value, strong current oscillations were observed. The electron drift velocity at the threshold field was 10^6–10^7 cm/s. In layers with nondegenerate carriers, damping oscillations with a frequency corresponding to the drift velocity ~3.5×10^5 cm/s were observed; this velocity is identical to that of acoustic phonons. Oscillations were most pronounced at liquid-nitrogen temperature. As the temperature increased, the oscillation amplitude decreased and ultimately disappeared at $T = 200$ K. In layers with high electron density, current oscillations were not damped, and their frequency was significantly higher.

2. EXPERIMENTAL

The electric transport of hot carriers was studied in pulsed electric fields. The pulse duration τ of the electric voltage up to 1000 V applied to samples was several microseconds. To prevent the sample from overheating, a low pulse repetition frequency (30–10 Hz) was used. The leading-edge duration of the high-voltage pulse did not exceed 30 ns. The voltage-pulse amplitude could be slowly (for a few minutes) varied from zero to the highest value. The pulse shape and amplitude of the voltage and current through the sample were monitored by observing the signal on the screen of a Tektronix TDS3034B digital oscilloscope with a passband of 350 MHz, used also to store signals in a computer's memory. The measurements were carried out at both room and low temperatures ($T = 77$ and 4.2 K). In the latter cases, a sample holder was mounted in transportable Dewar flasks with liquid nitrogen or helium, respectively.

The samples under study were grown using gas-transport epitaxy on semi-insulating GaAs (001) substrates. The sample parameters are listed in the table. Multilayer n-In$_x$Ga$_{1-x}$As/GaAs heterostructures with single and double QWs were studied, as well as thin n-GaAs epitaxial layers. The heterostructures contained 20 pairs of QWs 200 and 100 Å wide, separated by a GaAs barrier 50 Å thick (or 20 separate QWs 200 Å wide) spaced by 800–900 Å. Narrow wells in samples 2987, 4079, and 4081 were δ-doped with silicon; all the other samples were homogeneously doped. The room-temperature electron mobility depended on the doping level only slightly and was ~4500 cm^2/(V s). Rectangular samples 5 × 5 mm in size were cut from the structure. Strip ohmic contacts were deposited and fired in on the sample surface, spaced ~3 mm apart.

3. RESULTS AND DISCUSSION

Typical oscilloscope patterns of current pulses in heterostructures with single and double QWs are shown in Figs. 1 and 2. Beginning with a certain threshold value of the applied voltage ($U/l \approx 300$ V/cm), oscillations arise on the current pulse. The initiation of current instability was observed at $T = 4$ and 77 K; however, oscillations did not arise at room temperature. As the spacing between the contacts was decreased threefold (to $l = 1$ mm), the oscillation frequency increased approximately three times. At the same time, the oscillation frequency and the current oscilloscope pattern remained almost unchanged as the sample width decreased. This observation suggests that the oscillation frequency is independent of the sample resistivity (hence, it is related to the sample length, rather than to the external electric circuit). The structures with double QWs and selective doping (2987 and 4081) were

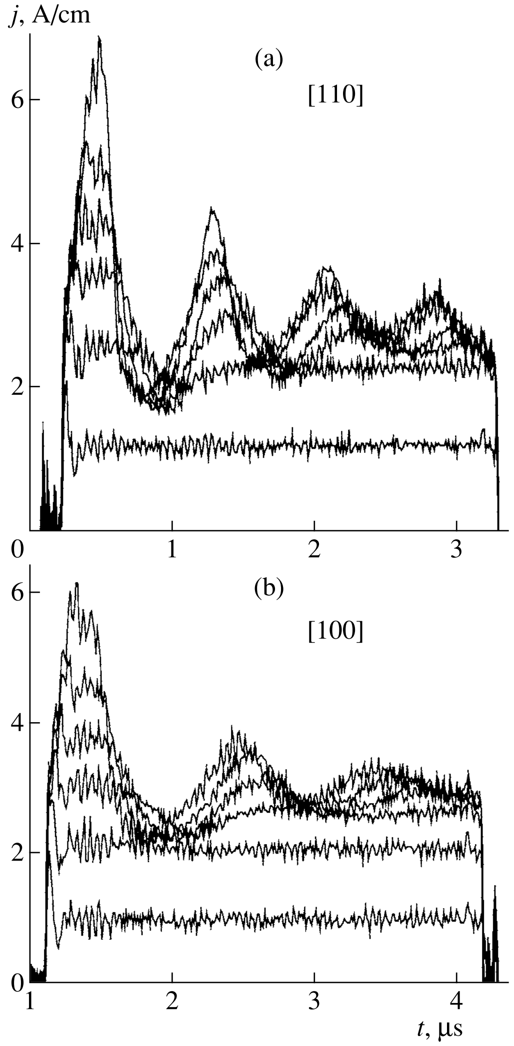

Fig. 1. Current-pulse oscilloscope patterns for sample 3734, measured at (a) **E** || [110] and (b) **E** || [100]; T = 4.2 K, l = 3 mm.

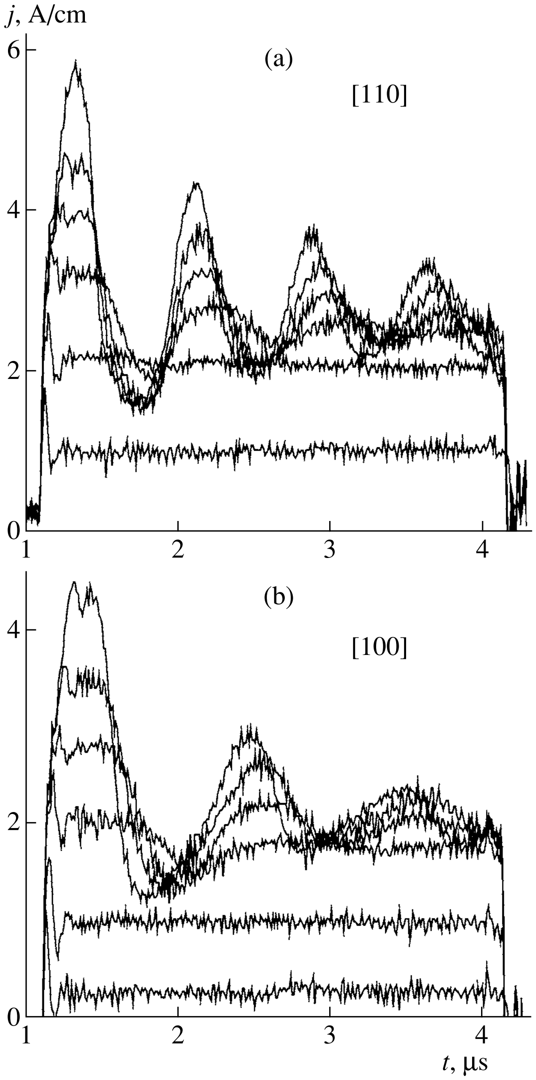

Fig. 2. The same as in Fig.1, but for sample 3735.

“designed” with the purpose to study spatial transport of carriers in strong lateral electric fields. In such heterostructures, the lower level in the narrow (δ-doped) QW is higher by approximately 10 meV than in the wide well, while the Fermi energy is several millielectronvolts.

Thus, most carriers are concentrated in wide wells at low temperatures. As carriers are heated in the electric field, the spatial transport from a wider QW to the higher-lying level in a narrow well (due to scattering at optical phonons) should cause a decrease in the mobility (due to strong impurity scattering in narrow doped QWs) and electron thermalization in narrow wells. A reverse transition appears to be complicated; as a result, the current can decrease and electric instability can develop, which qualitatively agrees with the observed pattern.

Further studies showed that current oscillations are also observed in uniformly doped samples with double QWs (3490, 3735). It was assumed that instabilities under conditions of the spatial transport from wide QWs into narrow QWs are caused by scattering at interface roughness, which should play a larger role in narrower QWs. It is reasonable to assume that the oscillation period is controlled by the time of passage of the domain of the strong electric field through the sample, as in the ordinary Gunn effect, where the domain velocity is equal to the carrier drift velocity. A similar result was also obtained for domain instability in selectively doped GaAs/AlGaAs heterostructures under conditions of spatial transport [1]. In the case under consideration, a drift velocity of about 3×10^6 cm/s corresponds to the instant of instability onset. At the same time, the domain velocity can readily be estimated from the oscillation period, which is approximately 1 μs for a sample 3 mm long. This velocity is as low as 3 ×

10^5 cm/s, i.e., ten times lower than the carrier drift velocity. A similar disagreement also took place for current oscillations observed in *p*-InGaAs/GaAs heterostructures [16], which was inconsistent with the proposed ODP mechanism associated with spatial transport.

In order to gain insight into the conditions of the initiation of the observed current instability, the reference samples that contained separate QWs and uniformly doped *n*-GaAs films (see table) were grown and studied. The *I*–*V* characteristics and current-pulse oscilloscope patterns of samples with double and single QWs are similar to each other (cf. Figs. 1 and 2). The threshold values of the applied electric field, the current densities corresponding to oscillation onset, and the oscillation periods agree with good accuracy. Thus, the measurements carried out showed that double QWs in the heterostructure has almost no effect on the observed current instability; hence, this instability is not related to spatial transport from wide QWs into narrow QWs. It is noteworthy that current oscillations in multilayer $In_{0.16}Ga_{0.84}As$/GaAs heterostructures with individual deeper QWs were previously observed in [17].

Sample 3518 is a uniformly doped *n*-GaAs film 2.5 μm thick, which corresponds to the thickness of heterostructures 3490 and 3518 with total carrier concentrations close to that in sample 3490 (see table). In this sample, the current-oscillation dynamics was appreciably different from that in heterostructures. The threshold value of the applied electric field somewhat increased to ≈450 V/cm in comparison with 300 V/cm; however, the threshold current density (hence, the drift velocity) decreased to 1.5 A/cm in comparison with 3–4 A/cm. The oscillation shape significantly changed as well. Instead of weakly damping sinusoidal or spiky oscillations, sample 3518 exhibited a significant “spike” at the leading edge of the current pulse followed by fast-damping oscillations, which is characteristic of the establishment of stationary domain conditions in the ordinary Gunn effect. It follows from the oscilloscope patterns that a pronounced current saturation takes place in strong electric fields, which is also characteristic of static domain conditions. At the same time, the oscillation period remained almost the same as in heterostructures. Since there is no spatial transport in a rather thick epitaxial film, it is clear that current oscillations observed have a radically different origin.

These studies were complemented with electric-transport measurements in a series of epitaxial *n*-GaAs films with various doping levels (sequentially grown samples 3628–3631). As the carrier concentration increased, the static domain conditions in “lightly doped” samples 3631 and 3630 were replaced by conditions of weakly damping oscillations in samples 3629 and 3628.

Apparently, the observed current instabilities can be attributed to the formation of acoustoelectric domains in the samples under study in strong electric fields. As mentioned above, GaAs is a piezoelectric material; hence, the intense interaction of electrons with acoustic phonons takes place. An oscillation period of 1 μs in the samples under study corresponds to a transport velocity of 3.6×10^5 cm/s, which is close to the velocity of propagation of transverse acoustic phonons in the [110] direction. The efficient interaction of electrons with an acoustic wave can take place if this wave induces a longitudinal electric field, i.e., a field directed along the wave propagation. There are only two waves of this type in GaAs and other semiconductors with identical crystal structures: a transverse wave polarized along the [001] crystallographic direction and propagating in the [110] direction and a longitudinal acoustic wave propagating in the [111] direction [17]. In GaAs, the propagation velocity of the above-mentioned TA and LA waves is 3.35×10^5 and 5.4×10^5 cm/s, respectively [18]. In most cases, the TA wave is excited, which interacts more actively with carriers due to a lower velocity. In [15], the initiation of current instabilities in GaAs/AlGaAs heterostructures was observed when the carrier drift velocity was 10^6–10^7 cm/s, i.e., it exceeded by almost ten times the TA wave velocity in the case under consideration.

Thus, by analogy with current instabilities observed in [15], it is reasonable to associate current oscillations we observed in *n*-InGaAs/GaAs QW heterostructures and *n*-GaAs epitaxial films with acoustoelectronic instability. In all the above-described samples, the electric field was applied exactly in the [110] direction, along which GaAs can be easily cleaved, which necessarily prescribed the configuration of samples and strip contacts. To verify the hypotheses of “acoustoelectronic origin” of oscillations, rectangular samples were cleaved in the [110] and [100] directions from heterostructures with single (3732, 3734) and double (3735) QWs (see table). In sample 3732 with a low doping level ($n_s = 3 \times 10^{10}$ cm^{-2} per QW), oscillations were almost not observed. At liquid-helium and liquid-nitrogen temperatures, pronounced flattening in the *I*–*V* characteristic was observed in this sample, which can be attributed to the formation of a stationary near-anode acoustoelectric domain. As can be seen from Figs. 1 and 2, current oscillations with a period of about 1 μs, corresponding to a transport velocity of 3.5×10^5 cm/s close to the TA wave propagation velocity, were observed in heavier doped heterostructures 3734 and 3735 as the electric field was applied in the [110] direction. However, in the samples cleaved from the same structures in the [100] direction, the oscillation period increased approximately by a factor of 1.5. It is reasonable to explain this increase by the fact that acoustic waves propagating in the [110] direction at an angle of 45° to the electron drift direction are still excited in the crystal at $\mathbf{E} \parallel [100]$, which decelerates the domain velocity by a factor of $\sqrt{2}$ [19, 20].

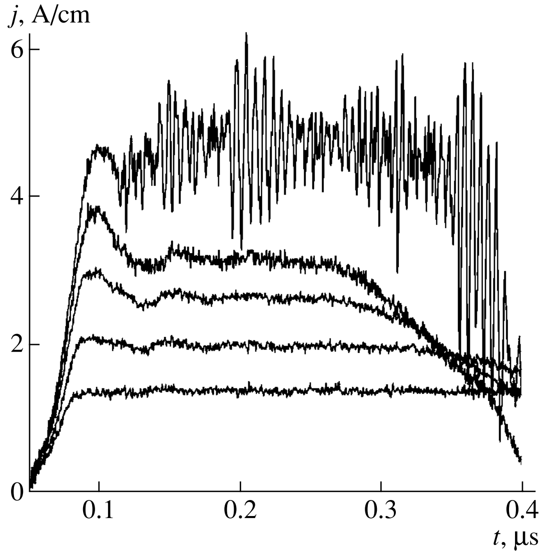

Fig. 3. High- and low-frequency current oscillations measured in sample 4081 at $T = 4.2$ K and $l = 1$ mm.

Apparently, the strong electric field induced in acoustoelectric domains gives rise to surface breakdown of the samples, which does not allow application of a field of several kilovolts per centimeter, which is necessary to implement various mechanisms for generating the inverse distributions of carriers. To diminish the probability of breakdown, we used shorter samples with contacts spaced at 1 mm; the measurements were carried out with shorter pulses with a duration of several tenths of a microsecond. In sample 4081 at $T = 4.2$ K, we observed for the first time current oscillations of two types [21]: low-frequency oscillations associated with the formation of acoustoelectric domains moving in the structure were initiated as usual in fields of about 300 V/cm; in fields of 1.5 kV/cm, high-frequency (~150 MHz) Gunn-type oscillations arose and corresponded to an electron transport velocity of 1.5×10^7 cm/s (Fig. 3). High-frequency oscillations were "modulated" by acoustoelectric oscillations. Simultaneously with the initiation of high-frequency oscillations, intense long-wavelength IR radiation was detected in the structures. At room temperature, acoustoelectric oscillations were not initiated, and only high-frequency oscillations were observed. In sample 4079 with a lower level of doping, mobile acoustoelectric domains were not formed and high-frequency oscillations were observed in strong fields. Rather low values of the applied electric voltage (~1.5 kV/cm at $T = 4.2$ K), at which Gunn oscillations were initiated, can be explained by a nonuniform field distribution in the sample in the presence of a mobile or stationary acoustoelectric domain.

4. CONCLUSIONS

Thus, *I–V* characteristics and current pulse oscilloscope patterns of multilayer *n*-InGaAs/GaAs quantum well heterostructures and *n*-GaAs epitaxial films with various doping levels were measured. It was shown that the *I–V* characteristics flatten at low doping levels ($N_s \approx 6 \times 10^{11}$ cm^{-2} for heterostructures and $N_s \approx 3 \times 10^{12}$ cm^{-2} for GaAs films) at $T = 4.2$ and 77 K in the fields of 300–400 V/cm. In more heavily doped samples under the same conditions, current oscillations are initiated with a period that corresponds to the transport velocity of $(3–3.5) \times 10^5$ cm/s at $\mathbf{E} \parallel [110]$ and a period by a factor of ~1.5 longer at $\mathbf{E} \parallel [100]$. The results obtained are explained by the formation of, respectively, stationary and mobile acoustoelectric domains due to the fact that TA waves propagating along the [110] crystallographic direction are excited by hot electrons. At applied voltages above 1.5 kV/cm, high-frequency oscillations corresponding to an electron transport velocity of 1.5×10^7 cm/s develop in the structures, which is related to the formation of the Gunn domains.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project no. 02-02-16763), the International Science and Technology Center (project no. 2293), the Ministry of Industry, Science, and Technologies of the Russian Federation, and the Federal program Integration.

REFERENCES

1. Z. S. Gribnikov, K. Hess, and G. A. Kozinovsky, J. Appl. Phys. **77**, 1337 (1995).
2. M. Shur, *GaAs Devices and Circuits* (Plenum, New York, 1987; Mir, Moscow, 1991).
3. V. Ya. Aleshkin, A. A. Andronov, A. V. Antonov, *et al.*, Phys. Status Solidi B **204**, 563 (1997).
4. V. Ya. Aleshkin, A. A. Andronov, A. V. Antonov, *et al.*, Physica B (Amsterdam) **249–251**, 971 (1998).
5. V. Ya. Aleshkin, A. A. Andronov, A. V. Antonov, *et al.*, Inst. Phys. Conf. Ser., No. 162, 105 (1999).
6. V. Ya. Aleshkin and A. A. Andronov, Pis'ma Zh. Éksp. Teor. Fiz. **68**, 73 (1998) [JETP Lett. **68**, 78 (1998)].
7. V. Ya. Aleshkin, A. A. Andronov, and A. A. Dubinov, Fiz. Tekh. Poluprovodn. (St. Petersburg) **37**, 224 (2003) [Semiconductors **37**, 215 (2003)].
8. V. Ya. Aleshkin and A. A. Dubinov, Fiz. Tekh. Poluprovodn. (St. Petersburg) **36**, 724 (2002) [Semiconductors **36**, 685 (2002)].
9. V. Ya. Aleshkin, A. A. Andronov, A. V. Antonov, *et al.*, Proc. SPIE **4418**, 192 (2001).
10. R. Kh. Zhukavin, S. G. Pavlov, V. N. Shastin, *et al.*, in *Proceedings of the Conference on Nanophotonics* (Inst. Fiziki Mikrostruktur Ross. Akad. Nauk, Nizhni Novgorod, 2000), p. 157.

11. A. V. Antonov, V. I. Gavrilenko, B. N. Zvonkov, *et al.*, in *Proceedings of the Conference on Nanophotonics* (Inst. Fiziki Mikrostruktur Ross. Akad. Nauk, Nizhni Novgorod, 2002), p. 215.
12. V. M. Rysakov, Usp. Fiz. Nauk **161** (12), 1 (1991) [Sov. Phys. Usp. **34**, 1027 (1991)].
13. V. M. Rysakov, Fiz. Tverd. Tela (St. Petersburg) **39**, 835 (1997) [Phys. Solid State **39**, 741 (1997)].
14. Yu. K. Pozhela, *Plasma and Current Instabilities in Semiconductors* (Nauka, Moscow, 1976) [in Russian].
15. N. Balkan, B. K. Ridley, and J. S. Roberts, Superlattices Microstruct. **5**, 539 (1989).
16. V. Ya. Aleshkin, A. A. Andronov, A. V. Antonov, *et al.*, in *Abstracts of International Symposium on Nanostructures* (St. Petersburg, 1996), p. 443.
17. B. K. Ridley, Semicond. Sci. Technol. **3**, 542 (1988).
18. J. Blakemore, J. Appl. Phys. **53**, R123 (1982).
19. A. V. Antonov, A. V. Gavrilenko, V. I. Gavrilenko, *et al.*, in *Proceedings of Meeting on Nanophotonics* (Inst. Fiziki Mikrostruktur Ross. Akad. Nauk, Nizhni Novgorod, 2003), Vol. 2, p. 215.
20. A. V. Antonov, A. V. Gavrilenko, V. I. Gavrilenko, *et al.*, Izv. Ross. Akad. Nauk, Ser. Fiz. **68** (1), 68 (2004).
21. A. V. Antonov, V. I. Gavrilenko, E. V. Demidov, *et al.*, in *Proceedings of Meeting on Nanophotonics* (Inst. Fiziki Mikrostruktur Ross. Akad. Nauk, Nizhni Novgorod, 2004), p. 195.

Translated by A. Kazantsev