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Resonance tunneling, electric and optical phenomena in long-period semiconductor superlattices

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Introduction

The development of physical principles of amplification, generation, and conversion of electromagnetic vibrations over a broad IR range and the fabrication of active elements based on these principles remains one of the urgent problems of the physics of semiconductors in solid-state electronics. An important step in this field was the discovery of new mechanisms of amplification of electromagnetic radiation based on dynamic heating of current carriers in strong electric and magnetic fields, resulting in the development of lasers and masers on hot holes — the first solid-state lasers operating in the far-IR and submillimeter spectral ranges [1].

Fundamentally new possibilities in this field are opened up by studies of electronic phenomena in quantum-sized structures, in particular, caused by transitions between the size-quantization states. The energy of intersubband transitions can be varied over a broad range, from near- and middle-IR to the far-IR spectral region [2, 3], by varying the parameters of the structures. Very recently, near-IR lasers of a new type were developed based on the concepts of Kazarinov and Suris about resonance tunneling of electrons in superlattices [4]. Lasing was obtained at the intersubband transitions in a system of quite narrow and strongly coupled quantum wells upon current injection (quantum cascade lasers) [5] and optical pumping (fountain lasers) [6]. Population inversion in both these systems is produced due to the difference of carrier relaxation rates caused by the difference between one-phonon and multiphonon processes of scattering of charge carriers by optical phonons.

In this paper devoted to the problem of population inversion in quantum-sized systems, we suggest a fundamentally new approach based on the phenomenon of resonance tunneling in structures with wide quantum wells, in which the difference in energies of the lower size-quantization subbands is less than the energy of an optical phonon. The lifetime of charge carriers in the first excited level in such structures can be determined by comparatively slow relaxation processes, for example, caused by scattering of charge carriers by acoustic phonons. If a sufficiently rapid removal of charge carriers from the lowest state is provided due to resonance tunneling to the neighboring quantum well, one can expect the appearance of strongly nonequilibrium carrier distribution, population inversion and lasing at these transitions.

In reality, the situation is more complicated because of the existence of other relaxation channels (scattering by ionized impurities, interfaces, etc.), which reduce the lifetime of charge carriers in the first excited state and result in the population of the ground state. For this and some other reasons, in particular, the absorption of radiation involving free carriers and phonons, and difficulties of producing an optical confinement in quantum-sized structures at long wavelengths, the problem of resonance tunneling has proved to be one of the most important in this field.

The approach used raises additional problems determined by the special features of systems with wide quantum wells. Of great importance is the degree of overlap of lower subbands in real fabricated structures. Is the resonance tunneling from these states, which would provide the selective removal of charge carriers from one of the subbands, possible? How much are the levels in processes of resonance tunneling matched and how is the resonance structure in an applied electric field changed? In the case of resonance tunneling structures aligned in an electric field, questions arise of regularities of resonance tunneling in such systems, of special features of resonance tunneling and related phenomena taking place in multilayer superlattices with most complicated multiply repeated resonance tunneling element required for increasing optical amplification in quantum-sized structures.

Far-IR resonance tunneling laser operating on intersubband transitions in structures with wide quantum wells

There are several mechanisms of producing a population inversion in lower subbands which can be used for the development of a far-IR resonance tunneling laser operating on intersubband transitions. The concept of optically pumped resonance tunneling lasers operating on intersubband transitions in heterostructures with different compositions of semiconductor compounds in the region of quantum wells is quite promising. Figure 1 shows a scheme of intersubband transitions in the case of resonance tunneling in a transverse electric field. If the structural parameters of a central quantum well are chosen in such a way that the energy distance between the first and second excited states is $\varepsilon_3 - \varepsilon_2 = \hbar\omega_0$ ($\hbar\omega_0$ is the optical phonon energy) and $\varepsilon_2 - \varepsilon_1 < \hbar\omega_0$, then charge carriers appearing due to resonance tunneling from a neighboring quantum well will rapidly relax from the third subband (ε_3) to both lower subbands (ε_2 and ε_1) with times $\tau_{32} \approx \tau_{31} \approx 1$ ps, which are determined by scattering by optical phonons [7]. At the same time, the relaxation of charge carriers upon transitions between two lower subbands ε_2 and ε_1 caused by scattering by acoustic phonons occurs substantially more slowly ($\tau_{21} \approx 200-300$ ps) [7]. In the case of GaAs/Al$_{0.3}$Ga$_{0.7}$As structures, this situation corresponds to quantum wells of width $d_{\mathrm{w}} = 250$ A (the energy spectrum is $\varepsilon_1 = 7$, $\varepsilon_2 = 29$,

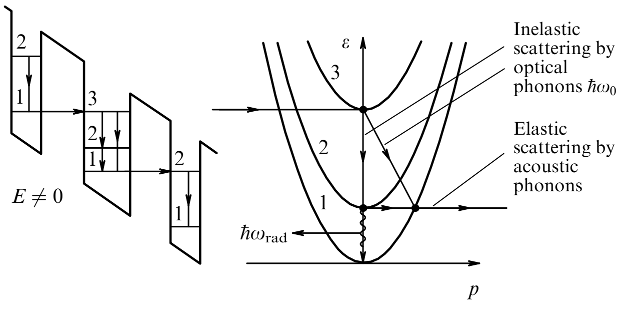

Figure 1. Scheme of intersubband transitions in the laser resonance tunneling structure (the system consists of three GaAs/Al$_{0.3}$Ga$_{0.7}$As quantum wells; the central well width is 250 A, $\varepsilon_3 - \varepsilon_2 = 35$ meV, $\varepsilon_2 - \varepsilon_1 = 22$ meV; the optical phonon energy is $\hbar\omega_0 = 36$ meV).

$\varepsilon_3 = 64$, $\varepsilon_4 = 113$, and $\varepsilon_5 = 173$ meV). Taking into account other mechanisms of scattering (by ionized impurities and interfaces [7]), this width can be substantially smaller. However, as estimates show, the rate of resonance tunneling to a neighboring quantum well can also be high enough, even in structures with not very narrow barriers, providing rapid removal of charge carriers from the lower state, which is required for producing strongly nonequilibrium population inversion in the lower subbands ε_2 and ε_1. The time of resonance tunneling is usually determined from the value of splitting $\delta\varepsilon_{\mathrm{split}}$ of the resonance level: $\tau_{\mathrm{tunnel}}^{\mathrm{theor}} \cong \hbar/\delta\varepsilon_{\mathrm{split}}$. In reality, experimental times are, as a rule, approximately an order of magnitude longer [8]. The values of splitting calculated for the structure shown in Fig. 1 are equal to $\delta\varepsilon_{\mathrm{split}} = 0.5$, 1, and 3 meV for barrier widths $d_{\mathrm{w}} = 60$, 40 and 20 A, respectively. Therefore, $\tau_{\mathrm{tunnel}}^{\mathrm{exp}} \cong 15$ ps ($d_{\mathrm{B}} = 60$ A), 5 ps ($d_{\mathrm{B}} = 40$ A), and 1 ps ($d_{\mathrm{B}} = 20$ A). These estimates, although promising, should be considered only as very approximate. The real situation substantially depends on the technological possibilities and can be estimated based on experimental studies only.

Resonance tunneling and peculiarities of transverse transport in long-period superlattices

We discuss below the results of experimental and theoretical model studies of resonance tunneling and associated phenomena observed in an electric field in long-period (wide quantum wells) superlattices. The main attention is paid to systems with weak coupling, i.e., to structures with quite wide barriers, in which resonance phenomena prove to be most pronounced.

Figure 2 shows that typical current – voltage characteristics measured in the direction perpendicular to the structure plane have a stepwise form, each plateau having a shallow periodic structure [9 – 12]. Such a complex form of the current – voltage characteristic is caused by stratification of the resonance tunneling structure in an electric field into regions with different electric field strengths (domains of electric field) [9 – 13]. Each plateau of the current – voltage characteristic corresponds to the formation of a new type domain with a resonance tunneling structure related to the tunneling to the higher excited subbands. The shallow periodic structure is determined by an abrupt displacement of the domain boundary through the sequence of quantum wells in the superlattice during the expansion of the electric field domain with increasing voltage applied to the superlattice ends. In contrast to the structures with narrow quantum wells, in this case a multistep current – voltage characteristic is observed, which corresponds to the number of excited states in the long-period superlattice (Figs 2 and 3) [9 – 11]. Another feature of the long-period superlattice is a distinct current hysteresis [9, 10] that is especially pronounced (giant current resonance) in structures with the widest quantum wells. The presence of the current hysteresis is explained by the different conditions of the current instability during resonance tunneling in the superlattice upon increasing or decreasing the voltage applied to the superlattice [10]. In the first case, the current instability is determined by the maximum possible electric conductivity of the superlattice under conditions of the best matching of the levels in the weak electric field domain. In the second case, it is determined by the minimum electric conductivity of the superlattice (even under conditions of the worst matching of the levels) in the strong electric field domain. The theoretical description of resonance tunneling transport within the framework of the discrete model [10, 13] allows one not only to adequately explain the features of transverse transport observed in long-period superlattices but also to determine experimentally the effective drift rate of tunneling $v_{\mathrm{drift}}(u_{i,i+1})$ between neighboring quantum wells as a function of the electric field ($u_{i,i+1}$ is the voltage between the wells) [10], which can be used for studying the properties of long-period superlattices under different conditions. In particular, the expansion of the domain boundary and collapse of the current hysteresis were detected as the doping level of the superlattice was decreased. In superlattices containing impurities in a very low concentration, whose electric conductivity proves to be very low compared to that in the region of the domain boundary (even under the conditions of the worst

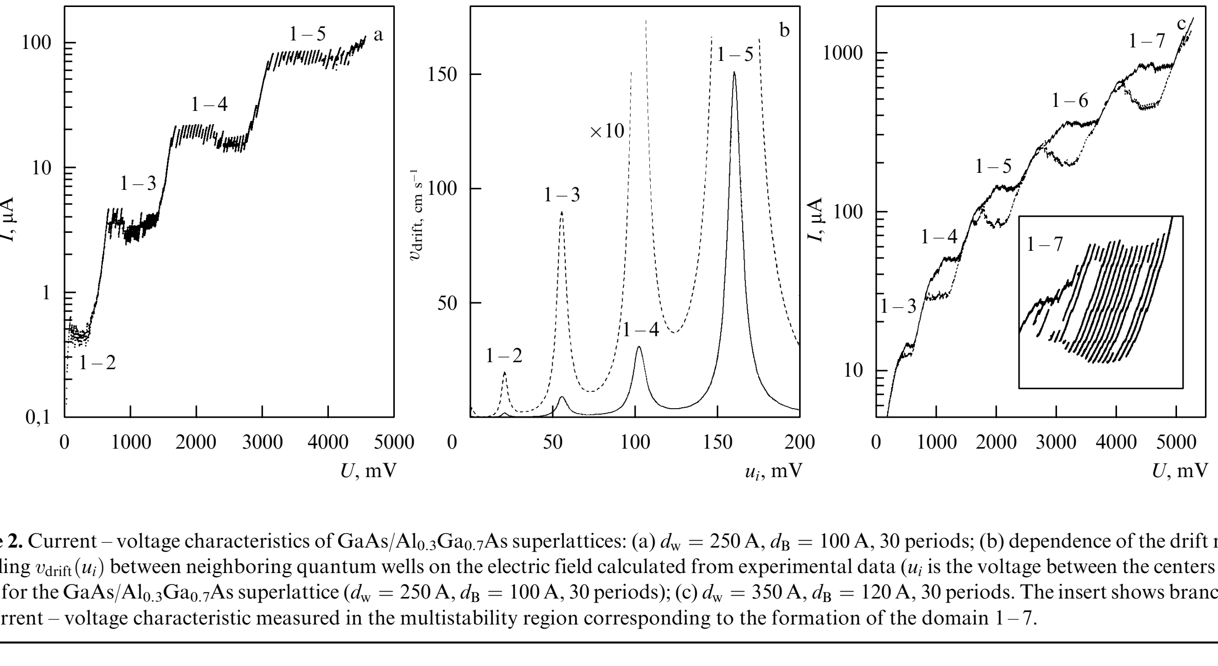

Figure 2. Current – voltage characteristics of GaAs/Al$_{0.3}$Ga$_{0.7}$As superlattices: (a) $d_{\mathrm{w}} = 250$ A, $d_{\mathrm{B}} = 100$ A, 30 periods; (b) dependence of the drift rate of tunneling $v_{\mathrm{drift}}(u_i)$ between neighboring quantum wells on the electric field calculated from experimental data (u_i is the voltage between the centers of the wells) for the GaAs/Al$_{0.3}$Ga$_{0.7}$As superlattice ($d_{\mathrm{w}} = 250$ A, $d_{\mathrm{B}} = 100$ A, 30 periods); (c) $d_{\mathrm{w}} = 350$ A, $d_{\mathrm{B}} = 120$ A, 30 periods. The insert shows branches of the current – voltage characteristic measured in the multistability region corresponding to the formation of the domain 1 – 7.

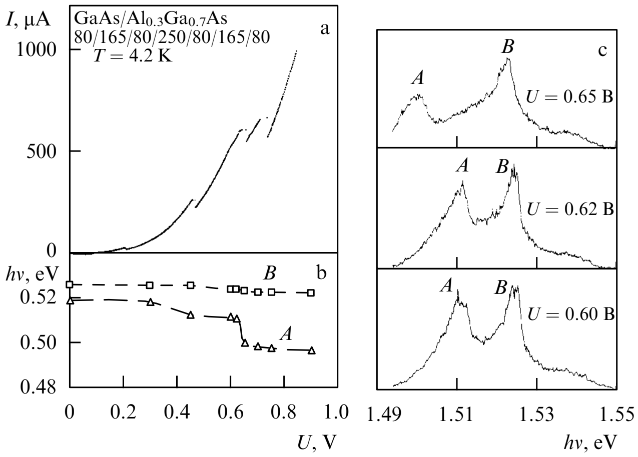

Figure 3. (a) Current – voltage characteristics of a resonance tunneling structure containing three $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells (80 A/165 A/80 A/250A/80 A/165 A/80 A); (b) dependences of the positions of the photoluminescence lines on the voltage applied to the structure [lines A and B corresponding to narrow (165 A) and wide (250 A) quantum wells]; (c) photoluminescence spectra of the same structure in an electric field in the region of switching of the tunneling resonance.

matching of levels at the interface between domains), the formation of the electric field domain becomes impossible, and the above-mentioned effects disappear. The existence of the current multistability branches connecting the upper and lower branches of the current hysteresis (Fig. 3) found in Ref. [14] means that there are several stable current states for the same voltage applied to the superlattice, each of which corresponds to a certain position of the domain boundary in the superlattice. In Ref. [14], the effect of switching between these branches was experimentally observed using short (10^{-7} s) rectangular electric pulses of the required polarity and intensity. In these experiments, the situation typical for solid-state elements of multilevel logic was in fact realized.

These phenomena caused by specific features of resonance tunneling and formation of domains of electric field in the superlattice can be confirmed by optical measurements (photoluminescence (PL) spectra, PL excitation spectra and photoconductivity (PC) spectra [9, 12, 15]). In particular, the appearance [9] and formation of domains in the superlattice [9, 12] can be monitored by the Stark shift of the PL lines related to the interband recombination of charge carriers. This method proves to be especially efficient for measuring the electric field strength in structures with a nonuniform field distribution, which is difficult to measure by other methods.

Optical studies of PL excitation spectra and PC spectra upon selective interband optical excitation showed that the lowest subbands are distinctly manifested even in sublattices with the longest period ($d_w = 350$ A) [15]. Analysis of electric measurements shows that the same subbands are also distinctly pronounced in processes of resonance tunneling in an electric field (Figs 2 and 3) [10]. The results of these studies suggest that resonance tunneling can lead to the efficient depletion of the levels, producing strongly nonequilibrium distributions of charge carriers in lower subbands in structures with wide quantum wells.

The studies performed allow us to make another important conclusion regarding the degree of matching of the resonance levels in processes of resonance tunneling. An analysis of studies performed in different electric fields shows that the resonance tunneling structure in electric field, as a rule, is far from the resonant type due to the mismatch of the levels caused by the redistribution of space charge in the structure [10]. The same effect is actually responsible for the formation of the electric field domains in superlattices. We can conclude that effects caused by the space charge play an important role in resonance tunneling processes and should be taken into account under consideration of the formation of a population inversion in quantum-sized structures.

Level mismatch effects and the rearrangement of the resonance tunneling structure in an electric field in systems with several quantum wells

Effects caused by the redistribution of the space charge are especially significant in processes of resonance tunneling in complex semiconductor structures consisting of quantum wells and barriers of variable widths. These effects, well known in double-barrier resonance tunneling diodes, lead to a rather complicated distribution of the electric field in structures with many quantum wells. In particular, this is illustrated by electric and optical studies performed for structures of the type shown in Fig. 1. One can see that current – voltage characteristics measured in structures with three quantum wells and four barriers are quite complicated including several segments that reflect the rearrangement of the resonance tunneling structure with increasing electric field. It is difficult to understand these variations without the use of special theoretical calculations, in particular, because of the complicated potential profile in near-contact regions. For this reason, it is appropriate to use optical studies for estimating the electric field strength in the structure. The results of these studies are presented in Fig. 3. In the zero field, two PL lines were observed at 1.527 and 1.519 eV, which are related to the interband recombination from the ground states of the narrow ($d_w = 165$ A) and wide ($d_w = 250$ A) quantum wells. As the voltage applied to the structure increases, both lines are shifted, the Stark shift in the case of the wide quantum well being more pronounced, which allows one to estimate the electric field strength and to understand the variations in the resonance structure in the electric field. The main effect found in these experiments is that the position of the recombination line in the intermediate region between regions of the rearrangement of the resonance tunneling structure remains in fact invariable. In this case, a rather general regularity is manifested, which consists in the fact that the space charge formed in quantum wells is redistributed in the system in such a way as to maintain the resonance tunneling structure as long as possible before it transforms to a new state.

Strongly nonequilibrium carrier distributions in lower subbands in wide quantum well structures

As already mentioned, the current in weakly coupled superlattices is determined by sequential resonance tunneling, when charge carriers tunnel from the lower subband of the quantum well to one of the resonance upper subbands in the neighboring quantum well, then rapidly relax to the lowest subband in the same quantum well, and again tunnel to the next quantum well. Because the relaxation time determined by the emission of optical phonons is substantially shorter than the tunneling time, the upper subbands are weakly populated, and their contribution to the tunneling is usually neglected. In Refs [16, 17], an effect of successive resonance tunneling over the excited states in long-period superlattices was found, which was accompanied by the appearance of resonance features in current – voltage multistability branches. These experiments demonstrate the existence of a new type of the electric field domain with the excited-to-excited states resonance in neighboring quantum wells. The results of these studies also lead to a fundamental conclusion about the strongly nonequilibrium distribution of charge carriers in lower subbands with energies less than the optical phonon energy [16, 17], in accordance with the measurements of radiation at the intersubband transitions in analogous superlattices [11].

Conclusions

We considered the problem of the development of lasers of a new type operating on intersubband transitions using resonance tunneling in quantum-sized semiconductor structures with wide quantum wells. The results of investigation of resonance tunneling in an electric field in long-period superlattices and structures with wide quantum wells are presented. It was shown experimentally that the resonance tunneling in these structures could lead to efficient and selective depopulation of the levels, resulting in a population inversion for charge carriers in lower subbands. The important role of the spatial charge was shown in processes resulting in the mismatch of the resonance levels and transformation of the resonance tunneling structure itself in an electric field. Based on these studies, a conclusion is made about the structure and structural parameters which are the most promising for producing a population inversion and stimulated radiation at the intersubband transitions in systems with wide quantum wells.

Acknowledgements
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Blue-green lasers based on short-period superlattices in II – VI compounds

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Introduction

Heterostructures based on wide-gap II – VI compound semiconductors (Fig. 1a) still remain the most promising candidates for the development of commercial green laser diodes needed for the laser projection TV and other laser applications requiring laser radiation tunable over the entire visible spectral range. Despite recent attempts to optimize laser diodes with quantum wells (QWs) based on ZnSe, only a slight increase in their life has been achieved so far [1, 2]. Rapid degradation of the laser structures is mainly caused by the nonradiative recombination at defects in the active region [2], resulting in the formation and development of new defects due to the extremely low energy of defect formation, which is typical for most wide-gap II – VI compounds [3].

In this paper, we suggest a new concept for the active region of the II – VI laser structures with the aim of increasing their lifetime. The basic principles of our concept are: (1) The protection of the active medium from the penetration and development of extended and point defects and (2) the spatial separation of defects and sites of radiative recombination of charge carriers directly in the active region. The first problem is solved by introducing a waveguide based on an alternately strained (Zn, Cd)Se/ZnSSe (or BeZnSe/ZnSe) short-period superlattice (SL) in ZnMg(Be or S)Se/ZnCdSe DHS lasers with separate confinement (DHS SC) (Fig. 1b), which results simultaneously in the improvement of the electronic and optical confinement. The replacement of the QW in the recombination region by a CdSe fractional monolayer (FM) insert of thickness 2 – 3 monolayers (ML) in ZnSe solves the second problem due to transformation of the CdSe FM under certain molecular-beam epitaxy (MBE) conditions to a set of self-organizing CdSe-enriched nanoislands, which strongly suppress migration of nonequilibrium carriers towards defects (Fig. 1c). It is also expected that the use of Be chalcogenides, which possess the maximum hardness among all of the II – VI compounds, will result in an increase in the activation energy of formation and development of defects [3, 4].

Experimental

To study the properties of the active region we suggest that optically pumped (Zn, Mg)(S, Se) DHS SC lasers were grown by MBE on GaAs(001) substrates. Also, (Be, Mg, Zn)Se laser diodes with an SL waveguide and two types of recombination regions (the ZnCdSe QW and CdSe FM) were manufactured.