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LOW-DIMENSIONAL SYSTEMS

Photoresistance of Si/Ge/Si Structures with Germanium Quantum Dots

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Abstract—An exponential decrease in the resistance of a Si/Ge/Si structure containing germanium quantum dots with an increase in the band-to-band optical excitation intensity is observed at 4.2 K. Two different exponential regions in the dependence of structure resistance on the optical excitation intensity are observed in elastically strained structures, but only one such region is observed in unstrained structures. The experimental results obtained are explained within the model of the hopping conduction of nonequilibrium electrons, which are localized at and between quantum dots in the strained structures, but are localized only between quantum dots in the unstrained structures. *© 2000 MAIK "Nauka/Interperiodica".*

INTRODUCTION

Studies of self-organizing quantum dots (QDs) have evolved recently into a rapidly developing field of semiconductor physics; this field is important both from the fundamental and applied points of view. A major concept of the method for self-organizing QD formation consists in the growth of a thin layer of one semiconductor with several monolayers in a matrix of another semiconductor with highly mismatched lattice parameters. Owing to the mechanical strains appearing for a definite critical layer thickness, formation of the islands becomes energetically favorable (the Stranski–Krastanov mechanism) [1–8]. The properties of Si/Ge/Si-structures are studied most actively by the methods of electron and atomic-force microscopy [9–13], photoluminescence [10–16], and Raman scattering [4, 5, 10, 17]. The transverse tunneling transport of charge carriers was studied previously [3], and the transport over the QD layers was studied in [8]. In this study, the dependence of planar resistance of Si/Ge/Si structures with QDs on the band-to-band optical excitation intensity was measured and analyzed for the first time.

EXPERIMENTAL

The structures studied were synthesized by molecular-beam epitaxy (MBE) using a Katun' S MBE system. A buffer layer of about 40–100 nm thick was grown on the silicon substrates (*n*-Si:P, ρ = 5–7.5 Ω cm) with (100) orientation; then, a thin layer of germanium was grown, which was covered by a surface silicon layer 20–40 nm thick. All the layers grown were obtained without an intentional doping, the concentration of residual impurities in the silicon being approximately 10^{16} cm^{-3}. The number of germanium monolayers (ML) N_{Ge} in the structures varied from 0 to 25. In the structures with $N_{Ge} \le 4$ ML, the two-dimensional growth of pseudomorphous germanium layers occurs, and in the structures with a large nominal thickness of germanium layer the strained QDs are formed at the wetting germanium layer and have a pyramidal shape. The further increase of N_{Ge} results in the change of the QD shape from the so-called "hut clusters" to "dome clusters" [1–7]. A typical QD height is about 3 nm, and the dimension of the base increases from ≈7 to 30 nm with an increase of N_{Ge} from 6 to 25 ML. Beginning with $N_{Ge} \approx 12$ ML, a relaxation of elastic strains occurs in the structures owing to the introduction of misfit dislocations in them, and at $N_{Ge} \ge 15$ ML, QDs begin to merge [5]. A small planar size of QD was ensured by growth at a low temperature, equal to T_g = 200–300°C. The concentration of QDs in the structures is independent of N_{Ge} and is approximately equal to $N_{QD} = 10^{11}$ cm^{-2}. The structures and methods of their formation are described in detail elsewhere [3, 6–8]. The nonrectifying contacts were formed by deposition of indium on the surface of a structure. The dependence of planar resistance of the structure on the intensity of the band-to-band optical excitation was measured in the constant-current mode at the temperature T = 4.2 K and had a symmetrical shape with respect to the polarity of the voltage applied. A steady-state band-to-band excitation of the structure was performed using a diode emitting light in the red region of the spectrum. The light-emitting diode (LED) was mounted in the immediate vicinity of a reasonably small sample, which ensured the uniform illumination of the sample surface area. The radiation intensity of the light-emitting diode

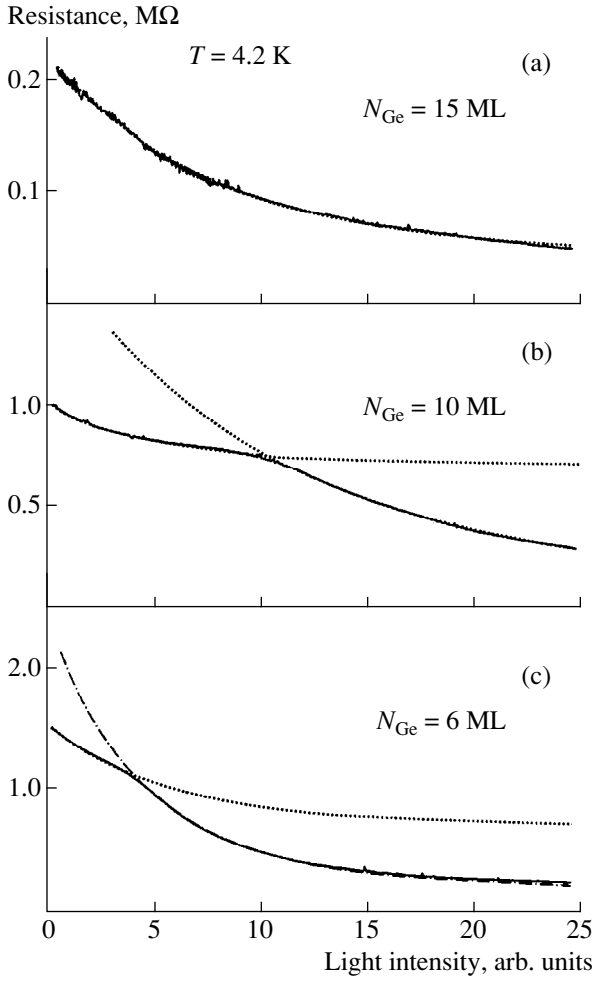

Fig. 1. Experimental dependences of the resistance of Si/Ge/Si-structures with the nominal thickness of germanium layers N_{Ge} = (a) 6, (b) 10, and (c) 15 ML on the band-to-band optical excitation intensity. T = 4.2 K. The current flowing through the structures is equal to (a) 8.7, (b) 5.0, (c) 3.6 Å. The dotted curves were obtained using formula (1) and the dashed curves were obtained using formula (2). Formulas are given in the text.

was governed by the current flowing through the LED and did not exceed 2 mW/cm^2.

EXPERIMENTAL RESULTS

The typical experimental dependences of the resistance (R) for three structures with N_{Ge} = 6, 10, and 15 ML on the excitation intensity (I) for a fixed magnitude of the current flowing through the structures are shown in Fig. 1. In the unstrained structures (N_{Ge} = 15 and 25 ML), the experimental curves are accurately described by the following dependence:

$$R = \Delta R_0 \exp(-I/I_0) + R_\infty. \quad (1)$$

Here, $\Delta R_0 = R_0 - R_\infty$, R_0 is the resistance of the structure in the dark, R_∞ is the resistance of the structure for a fairly high light intensity (R_∞ is independent of the light intensity); and I_0 is the illumination intensity at which ΔR_0 decreases by e times. The magnitude of ΔR_0 is about 80% of that of R_0. As the current through the structure increases, an increase in I_0 and in the relative fraction of R_∞ is observed as a rule.

In the strained structures (N_{Ge} = 6 and 8 ML), the curve $R(I)$ for low values of current through the structures is described by the exponential (1), and, as the current increases, the second portion appears, which also has an exponential shape

$$R = \Delta R_1 \exp[-(I/I_1)^{1/2}] + R_{1\infty}, \quad (2)$$

as can be seen from Fig. 1a for the structure with N_{Ge} = 6 ML. In the structure with N_{Ge} = 10 ML, both portions of the curve $R(I)$ (see Fig. 1b) are described by the same expression (1), but with different characteristic intensities (I_0 and I_0') and with different values of R_∞.

In the structures with $N_{Ge} \le 4$ ML, in which the self-organizing QDs have not yet been formed, the resistance is inversely proportional to the optical excitation intensity in a wide range of excitation intensities. Such a dependence testifies a band mechanism of conduction, when the concentration of nonequilibrium charge carriers is proportional to the excitation intensity.

The dependences of the I_0^* and I_1^* on the nominal thickness N_{Ge} of a germanium layer are shown in Fig. 2; this thickness governs the size of the germanium QDs. The values of I_0^* and I_1^* were obtained from the corresponding values of I_0 and I_1 by extrapolating to zero the magnitude of current flowing through the structures. Thus, the influence of the electric field on the nonequilibrium conduction of structures and the tunneling processes is eliminated; the latter are considered elsewhere. It can be seen from Fig. 2 that, for the strained structures with 10 ML, the magnitude of I_0^* is larger by about a factor of 4 than in the structures with 6 and 8 ML and the magnitude of I_1^* decreases almost by a factor of 3 as N_{Ge} increases from 6 to 8 ML. The value of $I_0'^*$ for the structure with N_{Ge} = 10 ML is also given in Fig. 2; this value by approximately an order of magnitude exceeds that of I_1^* for N_{Ge} = 8 ML. In the unstrained structures, as can be seen from Fig. 2, the magnitude of I_0^* insignificantly decreases with increasing N_{Ge}.

DISCUSSION OF RESULTS

A schematic fragment of a structure with QDs in the plane of their formation is shown in Fig. 3a together with the band diagrams for two cross sections of the structure, *A* and *B* (Figs. 3b, 3c). The band diagram of the structure across the cross section *A*, which does not intersect the QD, is shown in Fig. 3c. It can be seen from Fig. 3 that the wetting germanium layer is a quan-

tum well (QW) for holes and a barrier for electrons. Charge carriers generated by the illumination are separated in the space: the holes are localized in the germanium layer, and the electrons are localized near the barrier due to the Coulomb attraction. As a result, in the vicinity of the germanium layer, a quasi-two-dimensional (quasi-2D) layer of nonequilibrium electrons is produced. The energy diagram of the structure in the cross section *B* intersecting two neighboring QDs is shown in Fig. 3b. Due to the large sizes of QDs in comparison with the thickness of the wetting germanium layer, the ground energy level of holes in the QDs is deeper than the hole depth in a 2D germanium QW; therefore, the holes are captured at the QD level and are not involved in the band conduction. As a result of the Coulomb interaction of nonequilibrium electrons with the holes localized at QDs, the state of an electron bound by a QD is produced (localization of type I). Such a state can be considered as an exciton bound by a QD, or as an "artificial" donor. In addition, in the strained structures, electrons can localize in the regions between QDs (localization of type II) [16], where they are confined by the energy barriers. These barriers are formed due to the deformation of a silicon matrix, which contracts near a germanium QD. The magnitude of a silicon lattice strain along the structure plane decreases away from the QD as a result of an increase in the strained silicon volume. If this strain diminishes at a distance comparable with that between neighboring QDs, the edge of the conduction band of the silicon matrix undergoes a planar modulation with the minimums occurring between the QDs (see Fig. 3a). The potential barriers (between the neighboring QDs) induced by the strain probably have a saddle shape (see in Fig. 3b, the dotted curve). One should note that the deformation potential around a QD pushes the localized states of type I into a continuous spectrum. Similar localized states between the neighboring QDs can also be produced for holes. An exact calculation of the energy spectrum of Si/Ge/Si structures containing QDs with allowance made for elastic strain of the silicon matrix, as far as we know, has not yet been carried out. The calculations for GaAs/InAs/GaAs structures with InAs QDs carried out recently [18] show that a characteristic region of the elastic strain relaxation around the QD in these structures is comparable with QD sizes. Both types of localized states for nonequilibrium electrons in the plane of QD formation are schematically shown in Fig. 3a.

The relaxation of elastic strains occurs in the structures with $N_{Ge} > 12$ ML, and the localized states of type II disappear. Such states appear again for $N_{Ge} \geq 15$ ML as a result of electron-motion limitation in the conduction band of the silicon matrix close to Si/Ge heteroboundaries due to merging of QD bases [5]. In this case, no localized states of type I form owing to the disappearance of the closed electron orbit around a QD.

We believe that the observed exponential dependence of the resistance of structures with QDs on the band-to-band optical-excitation intensity may be explained within the framework of the model described above, i.e., the hopping conduction of nonequilibrium electrons over unordered localized states. The conduction along the type-I states is similar to the hopping conduction over the impurity states, and, in this case, we control the concentration of these states by the light intensity. The dependence of the resistivity of structures for the hopping mechanism of conduction on the concentration of the localized states has the following form for the 2D case [19]:

$$\rho = \rho_0 \exp\{\beta/[r(N)^{1/2}]\}. \quad (3)$$

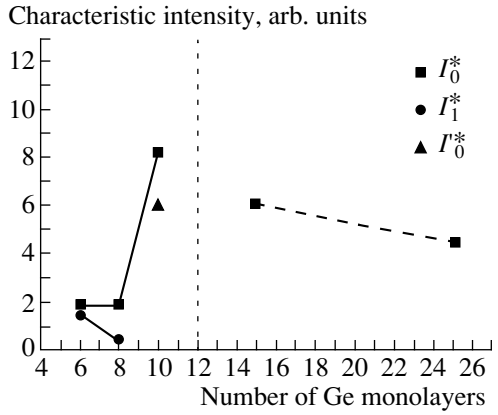

Fig. 2. Dependence of the characteristic optical excitation intensity on the number of germanium monolayers in Si/Ge/Si structures. The dashed line separates the regions of strained and unstrained structures.

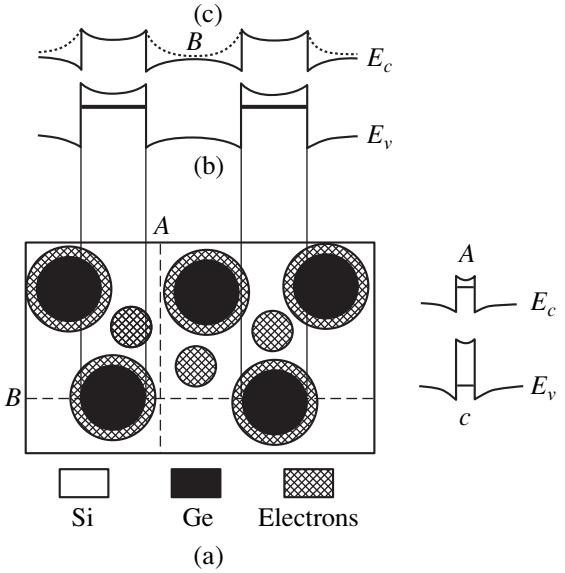

Fig. 3. (a) Schematic representation of the electron localized states for the strained Si/Ge/Si structure with germanium quantum dots; (b) the energy diagram of the structure across the cross section *B*, which intersects two neighboring germanium quantum dots; and (c) the band diagram of the structure across the cross section *A*, which does not intersect the quantum dots.

Here, N is the concentration of QDs, which is equal to $N = N_0 + \Delta N$, where N_0 is the concentration of QDs occupied by the equilibrium charge carriers; r is a radius of the localized state of electrons; and $\beta = 2.39$, according to the percolation theory for the 2D case. Concentration ΔN in the case of the linear recombination of nonequilibrium charge carriers is equal to $\Delta N = \tau I$, where τ is the lifetime of nonequilibrium charge carriers. For the low illumination intensities, when the condition $\Delta N \ll N_0$ is met, formula (3) transforms into a dependence of the form (1). As is known [20], the charge carrier recombination at the traps (the QDs serve as the traps in this case) is linear independent of the band-to-band excitation intensity. Consequently, the first portion of the curve $R(I)$ for the strained structures (Fig. 2), which is described by expression (1), is caused by the hopping conduction over the localized states of type I. We believe that the hole hopping conduction between QDs is insignificant compared to electron conduction, since the probability of a hop between neighboring QDs depends on the carrier localization radius and the localization region of the holes, which is defined by the QD size, and is smaller than the localization region size of electrons around a QD.

The conduction over the localized states of type II, similar to the continuum problem of the percolation theory [19], becomes possible if the nonequilibrium electron quasi-Fermi level μ_F reaches the percolation band level ε_3; the corresponding resistivity is given by

$$\rho = \rho_0 \exp\{(\varepsilon_3 - \mu_F)/kT\}, \qquad (4)$$

where kT is a thermal energy of electrons and $\mu_F = N/D$, with D standing for 2D density of II-type states. Hence, expression (1) follows in the case of a linear recombination of charge carriers and expression (2) for a quadratic-recombination, when $\Delta N = (I/\gamma)^{1/2}$; here, γ is a quadratic recombination coefficient [20]. Then, the second portion of the curve $R(I)$ for the strained structures with QDs of small dimensions (N_{Ge} = 6 and 8 ML) is described by expression (2) and is consistent with the conduction over the localized type-II states of nonequilibrium charge carriers, for which a quadratic recombination is characteristic. In this case, the band-to-band recombination of charge carriers occurs in the relatively large regions of the silicon matrix, which are confined by the saddle barriers of low height. The optical transitions are direct due to the carrier quasi-momentum scattering by QDs [16].

Thus, a complicated shape of experimental curve $R(I)$ for the strained structures is caused by the presence of two types of localized states, over which the hopping conduction of electrons takes place. The total resistance of these structures combines together from two parallel resistance nets, the resistances of which depend differently on the excitation intensity. In the unstrained structures, the dependence $R(I)$ involves a single region, which corresponds to the hopping conduction of electrons over the localized type-II states.

The meaning of the characteristic quantity I_0^* consists in the fact that this is the excitation intensity for which the neighboring localized states of type I in the strained structures are populated by electrons. The further increase in the excitation intensity does not affect the concentration of the occupied localized states, which cannot be larger than the concentration N_{Ge} but results in the formation of multiple-charged centers at QDs. Knowing the QD concentration, one can estimate the lifetime of nonequilibrium charge carriers localized in the type-I states from the expression $N_{QD} = \tau I_0^*$. The values of lifetime for such charge carriers in the structures with N_{Ge} equal to 6, 8, and 10 ML are 10^{-4}, 10^{-4}, and 3×10^{-5} s, respectively. The value of lifetime of the nonequilibrium charge carriers obtained for the structure with N_{Ge} = 6 ML is considerably larger than $\tau_1 = 3.9 \times 10^{-6}$ s s obtained in [16] from the measurements of the photoluminescence-decay kinetics for a structure with the same value of N_{Ge}, but synthesized at a higher growth temperature. This difference is caused by the fact that QDs in the structures we studied have considerably smaller planar sizes than the QDs in the structures studied in [16]. The decrease in the lifetime with increasing N_{Ge} up to 10 ML is likely to be connected with a sharp increase in the deformation potential around a QD, which is caused by the change of the QD shape from the hut- to dome-shape clusters [1, 7]. The latter process occurs in the structures studied by us with an increase in N_{Ge} from 8 to 10 ML.

The physical meaning of the characteristic optical excitation intensities I_1^* and $I_0'^*$ in the strained and I_0^* in the unstrained structures consists in the fact that, for this excitation intensity, the electron quasi-Fermi level reaches the percolation level. The evaluation of the percolation level from the experimental data is hampered owing to the uncertainty of parameters D, γ, and τ. The behavior of the characteristic values of the excitation intensity, which describe the localized type-II states (see Fig. 2), reflects a qualitative dependence of the percolation level magnitude on N_{Ge}. By changing N_{Ge} from 8 to 10 ML, as can be seen from Fig. 2, a significant increase in the characteristic excitation intensity is observed, as well as the change in the shape of dependence from (2) to (1); the latter describes the second region of $R(I)$. These features are connected, in our opinion, with the QD-shape change that results in a considerable increase in the amplitude of the saddle barrier, which separates the localized type-II states, i.e., in an increase in the percolation level. As a consequence, the appearance of the levels of quantum-confinement type-II states (zero-dimensional traps) takes place, which actually explains the change in the recombination type observed. The reason for the decrease in the value I_1^* with an increase in N_{Ge} from 6 to 8 ML is not yet clear.

A comparatively slight change in the value of I_0^* characteristic of dependence $R(I)$, which describes the conduction over the localized type-II states by transition from the strained structure with $N_{Ge} = 10$ ML to the unstrained structure with $N_{Ge} = 15$ ML (Fig. 2), is indicative of the proximity of the percolation level values, though the nature of the saddle barriers is different. With a further increase in N_{Ge} from 15 to 25 ML, a decrease in I_0^* is connected with the decrease in the sizes for localized type-II states, which results in an enhancement of the quantum-size energy for electrons and in a reduction in the number of levels below the percolation level; the number of such levels apparently tends to a constant value.

CONCLUSION

In this study, the influence of a steady-state band-to-band optical excitation on the planar resistance of Si/Ge/Si structures containing self-organizing germanium QDs was investigated. The exponential decrease in the structure resistance with the increase in the band-to-band optical excitation intensity was observed. In the elastically strained structures with small QDs, two different exponential portions of this dependence are observed, and, in the unstrained structures with large QDs, a single is observed region. The experimental results obtained are explained within the framework of the model of nonequilibrium-electron hopping conduction over the localized states of the two types. The states of type I are formed by filling the germanium QDs with nonequilibrium holes, and the states of type II are localized between the QDs. In the strained structures, the localization of the type-II charge carriers is caused by the deformation potential of the silicon matrix, and in the unstrained structures, by the heteroboundary Si/Ge barriers of the merging germanium islands. In the strained structures, the first portion of the structure-resistance dependence on the excitation intensity is connected with the change in the concentration of localized type-I states, and the second, with the occupation of the type-II states. As the nominal thickness of germanium layer in the strained structures increases, a sharp increase in the characteristic optical excitation intensities is observed as well as the change of dependence $R(I)$, which is caused by the change of the germanium island shape. In the unstrained structures, the localized type-I states disappear, and the dependence observed is caused by the occupation only of the localized type-II states by the nonequilibrium electrons.

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