Now we turn to a quantitative description of the spectrum of Q2D magnetoplasmons. There exist a large number of theoretical studies devoted to the plasmon spectrum in Q2D systems. In most of these the plasmons were investigated in the absence of a magnetic field (e.g. see Refs [4–6]). The researchers found that there are two plasmon branches: intrasubband plasmons related to electron oscillations in the ground 2D subband, and intersubband plasmons related to virtual transitions between 2D subbands. The first have a gapless spectrum, while the second exhibit a weak dispersion and a gap with a width equal to the sum of the intersubband energy Δ and the depolarization energy. The interaction of intersubband and intrasubband modes in the absence of a magnetic field is extremely weak even for a specially selected geometry of the structure [7]. A number of papers have been devoted to calculating the spectrum of Q2D plasmons in a magnetic field (e.g. see Refs [8–11]). The results contain an extremely rich structure of the spectrum of such magnetoplasmons but very strongly depend on the approximations employed and the type of a system. We calculated the magnetoplasmon spectrum in the random phase approximation for the structure studied in our experiment. Since plasmons are excited in the process of 2D $\rightarrow$ 2D tunneling in the symmetric system, only antisymmetric (with respect to the barrier's center) plasmon modes are of interest. The result was obtained in the dipole approximation [small wave vectors $\mathbf{q} = (q_x, q_y)$] for fairly strong magnetic fields, when the filling factor is $\nu < 4$.

Our finding is depicted in Fig. 4, where four magnetoplasmon branches are shown, namely, the intersubband branch *1*, the intrasubband branch *2*, and the combined resonance branches *3* and *4* related to virtual transitions between the states $(n = 0, N = 1)$ and $(n = 1, N = 0)$ as well as $(n = 0, N = 0)$ and $(n = 1, N = 1)$. The depolarization energy in this case is close to 4 meV. At $q = 0$, the magnetoplasmon energies coincide with the energies of single-particle excitations depicted in Fig. 4 by lines consisting of small open circles and crosses. Possibly, it was the anticrossing of the branches *1* and *4* that was discovered in our experiments due to the high density of states on these branches. The observed anticrossing of the two peaks can be interpreted as relaxation on 'hybrid' intra- and intersubband magnetoplasmons. The unusual shape of the anticrossing in Fig. 3 is, possibly, related to the effect of branch *2* in Fig. 4.

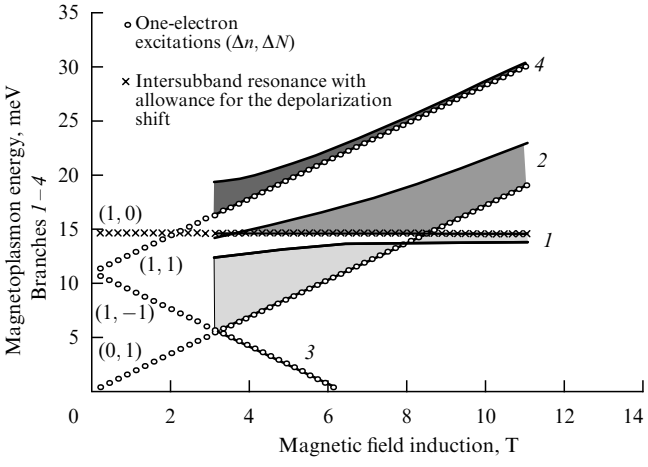

Figure 4. Magnetoplasmon energy (four branches) as a function of magnetic field induction for different wave vectors q. The shaded regions correspond to values of q ranging from zero to 5×10^5 cm^{-1}. Branch *1* represents an intersubband plasmon, branch *2* an intrasubband plasmon, and branches *3* and *4* represent plasmons of a combined resonance with transitions $\Delta - \omega_c$ and $\Delta + \omega_c$, respectively. Lines consisting of small open circles indicate the energy of single-particle excitations $(\Delta n, \Delta N)$; $\Delta = 11$ meV is the intersubband energy.

5. Conclusions

We have studied tunneling between highly disordered 2D electron systems in a quantized magnetic field parallel to the current. A strong interaction between the Landau levels belonging to different 2D subbands has been discovered. We proposed an explanation for the observed anticrossing related to the excitation of intra- and intersubband magnetoplasmons in a Q2D system.

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Quantum dot Ge/Si heterostructures

A V Dvurechenskiĭ, A I Yakimov

1. Introduction

Determining the parameters of the energy spectrum, the kinetics of the transitions between electronic states, and the interaction of elementary excitations and establishing the correlation effects constitute the basis for current fundamental research in the field of quantum dots (QD). Among the numerous heterostructures with quantum dots (see Refs [1–4]) that are being actively studied the silicon-based structures have always provoked special interest, due to the promising integration of the results of such research and the basic silicon technology used in building modern semiconductor devices and circuits. The substantial advances in the epitaxy of Ge on Si and the prospects for using Ge/Si heterostructures formed the natural basis for systems with quantum dots. From the viewpoint of fundamental research,

the Ge/Si system form type-II heterostructures. In such systems the localized states for electrons and holes are formed on different sides of the interface in self-consistent potential wells. The electrons and holes in such states are spatially separated, and a transition between these states is indirect in space.

In this report we present some of the data on the electronic properties of the QD array in germanium that forms on the Si(100) surface due to the effect of spontaneous morphological transformation of an elastically strained Ge layer grown in MBE conditions and then overgrown by a Si layer. In the first papers devoted to the study of such structures we discovered the Coulomb-blockade and size-quantization effects in the hole energy spectrum [5, 6]. We also found the conditions needed for low-temperature heteroepitaxy to be carried out, conditions that lead to the formation of nanometer-size islands with a surface density of $(3-5)\times10^{11}$ cm^{-2} [3]. The average size of Ge clusters shaped as pyramids was 15 nm (the pyramid's base), the pyramid height was 1.5 nm, and the spread of sizes was no greater than 17%.

2. Energy spectrum of hole states

In the Ge/Si system with Ge clusters, the relative arrangement of the energy bands forms a potential well only for holes. The geometry of the germanium island leads to a great difference between the size-quantization energy in the base plane of the pyramid and that in the direction of growth (the pyramid height is much smaller than the base size). Since the symmetry of the problem is close to that of a disk, the ground energy level corresponds to an *s*-shaped state, and the first excited level to a *p*-shaped state. Calculations have shown that the difference in the energies of the *s* and *p* states is quantized in the pyramid's base plane [7]. Thus, optical transitions between the given states are possible if the light is polarized in the pyramid's base plane (under normal incidence of the light onto the structure, which is especially important for practical implementations).

Electron spectroscopy studies of QD arrays of Ge in Si have shown that the hole state spectrum is discrete. What makes this type of QD array special is that the average cluster size is comparable to the cluster separation (a dense array). In such a system, the size quantization energy E_q and the Coulomb interaction energy E_c are of the same order, in contrast to the large clusters often described in the scientific literature, in which $E_c \gg E_q$ [1]. In dense QD arrays, both the interaction of carriers inside a single dot and the interaction with the surroundings contribute to E_c, as distinct from the case of a rarefied array, where the interaction with the surroundings can be ignored. The data gathered by different methods suggest that for the selected Ge/Si object with quantum dots one obtains $E_q \approx 75$ meV (the distance between the ground and first excited states on the energy scale). The energy of the ground state (measured from the top of the valance band in Si) is in the 405–430-meV energy range, and E_c is approximately 36 and 18 meV for the ground state (two holes) and the first excited state (four holes), respectively. The smaller value of E_c for the excited state is due to the larger value of the hole localization radius: 7.6 nm for the ground state, and 15.0 nm for the excited state. When these states are occupied, the contribution to E_c from the interaction of holes inside a single quantum dot amounts to 11 meV for the ground state and 5.4 meV for the excited state [8, 9].

3. Energy structure of excitons and exciton complexes

In conditions where the hole density in the QDs is zero (the QDs are occupied with electrons), optical transitions of electrons from the QD to the Si conduction band become possible [9, 10]. The formation of an exciton corresponds to a Gaussian-shaped absorption band with the peak at 770 meV and a width of 50 – 70 meV, apparently caused by the Ge cluster shape and size fluctuations. The energy of electron localization near the Ge/Si interface proved to be approximately 30 meV, the oscillator strength f was 0.5, and the band-to-band absorption cross section was 2.5×10^{-16} cm^2. The last value is more than 10 times the typical photoionization cross section for deep level impurities in Si. The value of f is approximately 20 times smaller than the oscillator strength for direct excitons in the InAs/GaAs system, where $f = 10.9$, which is a direct consequence of the spatial separation of an electron and hole in the Ge/Si system (a type-II heterostructure).

An analysis carried out in the self-consistent field approximation with allowance for inhomogeneous elastic strains has shown that during exciton formation in the Ge/Si system with quantum dots the electron is localized in the vicinity of the vertex of the Ge pyramid (where the stresses are at their maximum in Si), while the hole is localized near the pyramid's base (see Fig. 1). The main contribution to the energy of electron localization at the Ge/Si interface is provided by the electron–hole Coulomb interaction

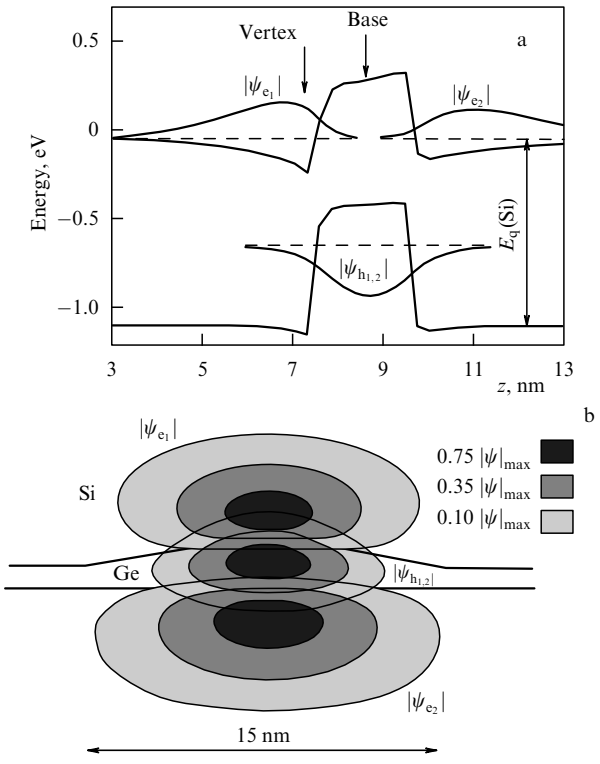

Figure 1. (a) Calculated profile of the potential, in which the electrons and holes constituting an exciton complex move, along the *z*-axis passing through the Ge pyramid vertex. (b) Two-dimensional image of the moduli of the electron $|\psi_e|$ and hole $|\psi_h|$ wave functions in the transverse section of a quantum dot and its surroundings. The degree of occupancy corresponds to regions at the boundaries of which the wave functions fall off to levels amounting to 75%, 35%, and 10% of the maximum value [10].

(28 meV). The contribution of the inhomogeneous strain distribution to potential-well formation amounts to 9 meV. In a complex consisting of two excitons, electron repulsion leads to their spatial separation, as a result of which the second electron proves to be bound at the boundary between Si and the continuous Ge layer on which the pyramids are arranged.

It has been established that the formation of charged exciton complexes (two holes – one electron) and exciton – exciton complexes in type II QDs leads to a shift in the exciton absorption energy into the short-wave region. This blue shift for charged complexes is caused by the spatial separation of electrons and holes in type II QDs, as a result of which the Coulomb interaction between the two holes in a QD dominates the electron – hole interaction. In a biexciton, the electrons are localized in different places in space, and the second electron is localized in a shallower potential well than the first. Thus, the biexciton's short-wave line shift is due to the difference in the energies of electron size quantization in different potential wells.

When a Ge/n-Si structure with quantum dots is illuminated by light that causes band-to-band transitions, negative photoconductivity comes into play. This is, probably, due to the trapping of electrons into states in the potential well formed at the interface of Ge/Si by nonequilibrium holes in Ge nanoclusters [11].

4. Interlevel optical transitions in quantum dots

In the particular case of a quantum well with a parabolic potential, the energy of an optical transition between subbands depends neither on the number of electrons in the well nor on the electron – electron interaction and is equal to the size quantization energy [12, 13]. For a nonparabolic potential and also when the contribution of the Coulomb interaction between quantum dots is substantial, the optical transition energy may differ substantially from the size quantization energy. The reason for this lies in the formation of collective oscillations in the system initiated by an incident electromagnetic wave (the depolarization effect observed in two-dimensional systems). Since the discovery of quantum dots (in which charge carrier motion is limited in all three dimensions), the question arose as to whether there exist collective effects in growth-plane-polarized optical transitions. Theoretical estimates have shown that a depolarization shift of the optical resonance can be observed when the layer concentration of the carriers is higher than 10^{11} cm^{-2}. In this sense our Ge/Si system with a dense QD array was an ideal object for establishing the presence of collective effects in interlevel optical transitions. Studies of the optical transitions between the levels in quantum dots in the Ge/Si system in the 70 – 90-meV energy range revealed an absorption maximum corresponding to a hole transition from the ground state to an excited one [10, 14]. The oscillator strength of such a transition amounted to 0.95, and the absorption cross section to 8×10^{-16} cm^2. A much smaller magnitude (1.6×10^{-16} cm^2) for interlevel hole transitions was obtained earlier for the InAs/GaAs system with quantum dots. It was found that at a small degree of occupancy of Ge quantum dots, the width of the absorption line is determined by the size variance of the nanocrystallites. The discovered shift of the absorption line into the short-wave region, the narrowing of the line, and changes in the line shape brought on by the increase in hole concentration in the ground QD state are characteristic manifestations of the depolarization effect.

5. Devices with built-in QD layers

The silicon field-effect transistors with a built-in germanium quantum dot layer contained, under the gate, from 10^3 (the size of the subgate region was about 1×1 μm^2) to 10^9 quantum dots [8]. The transistor channel and source – drain regions were boron doped, so that when the bias voltage across the gate was zero the channel conductivity was high. As the gate voltage became positive and grew, the conductivity exhibited a sharp drop (to zero at low temperatures), which was due to the formation of a depletion region. A further increase in the bias voltage was found to result in well-resolved current peaks related to hole transport through the discrete states in the quantum dots (Fig. 2). A decrease in the area of the region under the gate (a decrease in the number of quantum dots) allows one to observe the source – drain current oscillations as a function of the gate voltage at higher measurement temperatures (up to room temperatures). These data suggest that the Ge/Si heterostructures with a built-in QD layer are a promising material for building one-electron transistors.

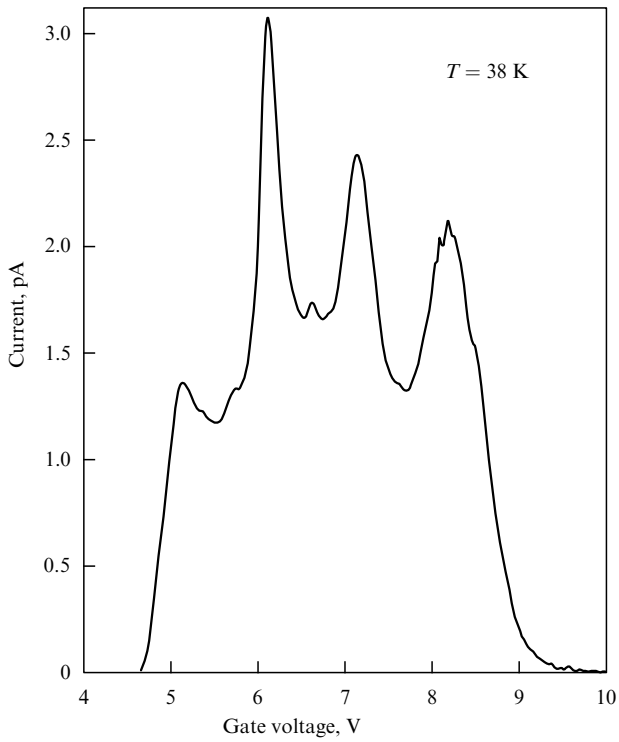

Figure 2. Source – drain current as a function of gate voltage in a field-effect transistor with 10^3 Ge quantum dots below the gate.

Studies of photoconductivity in Ge/Si structures with a built-in QD layer have revealed the possibility of creating photodetectors with a tunable spectral response. The maximum detectivity of a Ge/Si structure with quantum dots acting as a photodetector was 1.7×10^8 cm Hz$^{1/2}$ W^{-1} at a wavelength of 20 μm, and 0.7×10^8 cm Hz$^{1/2}$ W^{-1} at a wavelength of 10 μm at 300 K [15].

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Exciton Bose condensate control and the phonon laser

Yu E Lozovik

There exists a fruitful analogy between a system of quasi-particles, electrons and holes in excited semiconductors, on the one hand, and a system of 'true particles', electrons and protons (or, in a more general case, positive ions), on the other, since the laws of interaction in these systems are the same. The systems differ dramatically in the corresponding scales: the effective Bohr radius for excitons, which may be much larger than the Bohr radius, the exciton binding energy Ry*, which is much lower than the binding energy of the hydrogen atom, etc. This analogy opens an enticing possibility not only of predicting as yet undetected phases of the electron–hole system but, on the contrary, to model (via the electron–hole system) various phases of particle systems in extreme cosmological conditions [1], unattainable in laboratory experiments, in particular, in ultrahigh magnetic fields (e.g. for the detection of the anisotropic phase of polymer chains consisting of electric quadrupoles of atoms or excitons, extended along the magnetic field, or for magnetic dissociation and transformation of the type of molecular or excitonic bonds in ultrahigh magnetic fields, and so forth).

This analogy really exists. Indeed, the quasi-particle analogs of molecules are biexcitons, those of clusters are small electron–hole drops, and that of the liquid phase is the electron–hole liquid. The possibility of other phases is also being discussed.

However, there are important differences between these systems. Electrons and holes, in contrast to particles, usually 'exist' in an anisotropic (and largely 'random', due to defects) world of semiconductors and are often characterized by a complex (multivalley) dispersion law. This can lead to a phase diagram differing from that for a system of electrons and protons (e.g. stabilizing the metallic liquid phase, the electron–hole liquid [2]). Another bare parameter, the ratio of the masses of the positive and negative charges, also plays an important role: it controls the contribution of the zero-oscillation energy and determines whether there exists a crystalline phase as yet undetected in an electron–hole system.

In view of the amazing achievements in the technology of fabricating quite perfect nanostructures there has emerged another remarkable possibility, namely, to control the effective dimensionality and even the topology of the space where the quasi-particles 'exist'. This possibility broadens the variety of phase states and kinetic properties of the systems consisting of electrons and holes.

An interesting system in this respect is the quasi-two-dimensional system of spatially separated electrons and holes in coupled quantum wells [3] or the similar one-dimensional system in coupled quantum wires or in the zero-dimensional system of coupled quantum dots [4]. The quasi-zero-dimensional situation is also realized in an electron–hole system residing either in a single quantum well or in coupled quantum wells in quantizing magnetic fields [5–7] (however, the effective dimensionality in an interacting e–h system may depend on the occupancy of the Landau level).

When discussing the above systems with different dimensionalities, it must be kept in mind that here one is actually dealing with two radically different physical realizations.

The first realization corresponds to electrons and holes in a semiconductor's excited state that is generated, for instance, by laser radiation and exists over intervals shorter than the recombination times. The latter may be significantly increased, for instance, by virtue of a weak overlapping of the wave functions of the spatially separated electrons and holes in coupled quantum wells, and so on. This fact favors the possibility of establishing a partial thermodynamic equilibrium in the system and observing the different phase states of the electron–hole system in coupled quantum wells [3–13] (for similar phases in a three-dimensional system see Ref. [14]).

The second physical realization corresponds to an equilibrium system of spatially separated electrons and holes in coupled type II quantum wells (such a system in the coherent phase may manifest, due to particle tunneling through potential barriers between wells, several effects similar to the Josephson effect; see Ref. [15]).

I believe that there is one more system of keen interest: the disbalanced steady-state system of two identical coupled electron layers in a strong magnetic field [6]. The 'disbalance' of the two layers is achieved by applying a voltage V between them. Suppose that at $V = 0$ the two layers entirely fill a single (zeroth) Landau level. Then there is a system of excess electrons on the first Landau level in one layer and an equal number of unfilled positions (holes) on the zeroth Landau level in the other layer (or, when the disbalance is great, the electrons and holes are in different layers on the same Landau level). A situation that is even more curious