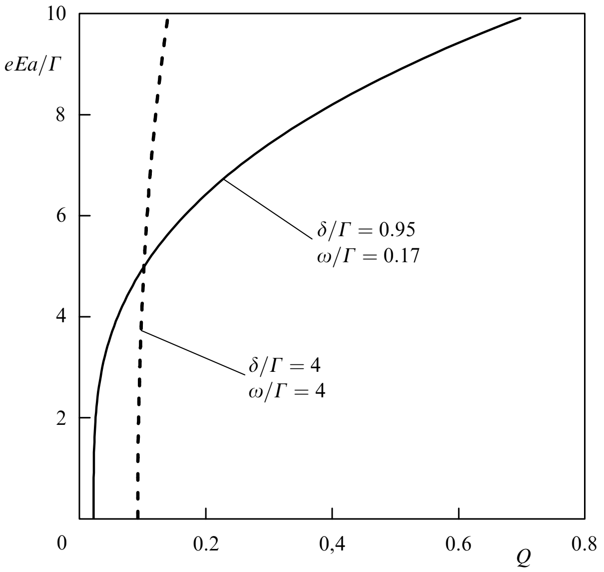

Figure 3. Computed dependences of the generation amplitude on the dimensionless pumping current Q in the 'classical' and 'quantum' regimes of the resonant tunneling diode generation.

Moreover, high-power generation in a resonant tunneling diode is feasible in a new 'quantum' regime at superhigh frequencies, which may vary in a broad range.

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Effects of exciton – electron interaction in quantum well structures containing a two-dimensional electron gas

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It has been thought until recently that the effect of an electron (hole) gas on excitonic states is exclusively confined to their destruction as a result of screening or filling phase space and also to exciton scattering on electrons (holes). However, it was found in 1993 [1] that interactions between excitons and an electron gas in quantum-well structures can be much more diverse. Specifically, such interactions can give rise to trions, i.e., bound states of excitons and electrons (holes), and to combined exciton – electron processes also referred to as combined exciton – cyclotron resonance [2]. The present paper reports experimental manifestations of exciton interaction with a two-dimensional electron gas (2D EG) in structures with quantum wells at relatively low electron densities, when the Fermi energy of the two-dimensional electron gas does not exceed trion binding energy.

We used $ZnSe/Zn_{0.89}Mg_{0.11}S_{0.18}Se_{0.82}$- and $CdTe/Cd_{0.7}Mg_{0.3}Te$-based structures each having a single 8 A wide quantum well delta-doped with donors, 10 A from the well. The electron surface density in the quantum well ranged from 10^9 to 5×10^{11} cm^{-2}. We investigated reflectivity, photoluminescence, and photoluminescence excitation spectra in magnetic fields of up to 8 T in the Faraday geometry.

Figure 1a presents typical reflectivity (R) and photoluminescence (PL) spectra taken from a "specially undoped" reference ZnSe/ZnMgSSe structure with a single quantum well. At energies on the order of 2.82 eV, the reflectivity spectrum of this sample contained a distinct reflection line of a quasi-two-dimensional exciton (X) in the quantum well.

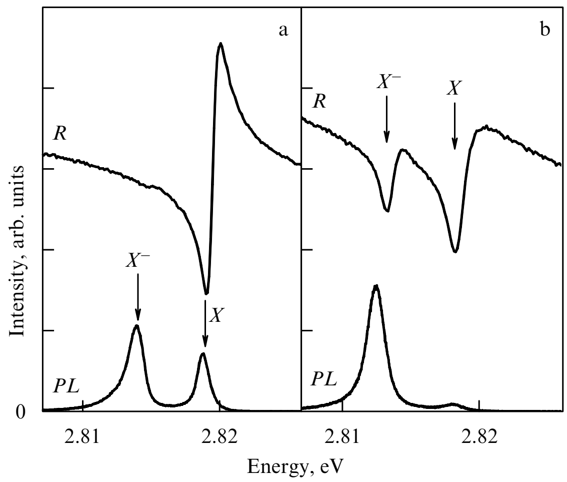

Figure 1. Reflectivity (R) and photoluminescence (PL) spectra in an exciton (X) and trion (X^-) resonance region taken from $ZnSe/Zn_{0.89}Mg_{0.11}S_{0.18}Se_{0.82}$-based structures with a single 8 A wide quantum well: (a) undoped structure; (b) modulated doped structure with an electron density $n_e = 6 \times 10^{10}$ cm^{-2}.

The reflectivity spectrum of a doped ZnSe/ZnMgSSe-based structure having a quantum well (Fig. 1b) contains two lines. One is the reflection line of the quasi-two-dimensional exciton observed in the undoped structure, the other is a new reflection line X^- shifted 5 meV toward the long-wavelength region relative to line X. We believe that the reflection line X^- may be associated with the formation of a charged exciton – electron complex (trion), which is in fact a bound state of an exciton and an electron. Trionic states in ZnSe-based quantum-well structures were examined in greater detail in Refs [3, 4].

Photoluminescence (PL) spectra of the two structures contain both the exciton PL line and the trion PL line. This is due, first, to the low level of background impurities in the specially undoped structure and, second, to the short exciton – electron binding time comparable to the duration of exciton radiative recombination. The shortness of the trion formation time is confirmed by characteristics of the photoluminescence spectrum of the doped structure (Fig. 1b) in which the trion *PL* intensity is far greater than the exciton *PL* intensity.

An important property of trionic states is the strong circular polarization of their lines in the reflectivity and absorption spectra in a magnetic field. Figure 2 shows reflectivity spectra of a ZnSe/ZnMgSSe-based quantum-well structure with electron density $n_e \propto 6 \times 10^{10}$ cm^{-2} recorded in a 7.5 T magnetic field for two circular polarizations, σ^+ and σ^-. Evidently, the trion reflection line X^- appears only for the σ^+ polarization and is practically absent from the reflectivity spectrum for the σ^- polarization. Such a strong circular polarization of trion lines is related to the fact that the trionic ground state is a singlet; that is, the two electrons that enter into a trion have opposite spin orientation [1, 5]. As a result, in a sufficiently strong magnetic field, where all electrons in a two-dimensional electron gas are spin-polarized, a trion can manifest itself only in one circular polarization of an incident photon. The trion triplet state in low magnetic fields is not bound and cannot be observed.

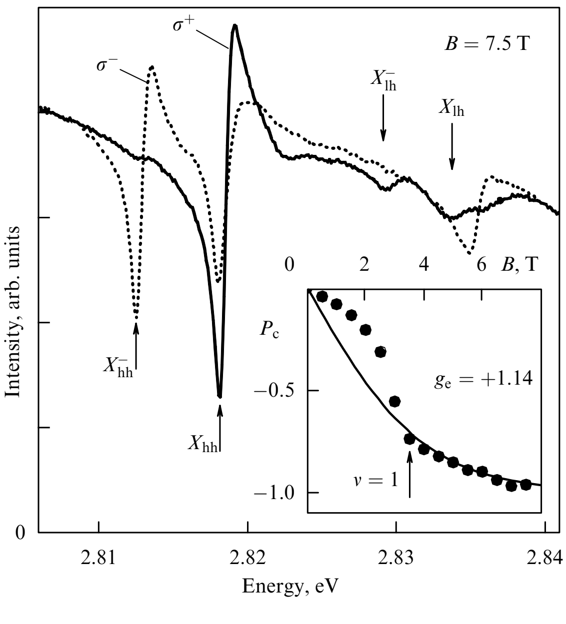

Figure 2. Reflectivity (R) and photoluminescence (PL) spectra in an exciton ($X_{\rm hh}$) and trion ($X^-_{\rm hh}$) resonance region taken from ZnSe/ZnMgSSe-based structures with a single quantum well at the electron density $n_e = 6 \times 10^{10}$ cm^{-2} in a 7.5-T magnetic field in the right- and left-hand circular polarizations. The inset displays the dependence of the degree of polarization of the trion reflection line on the magnetic field.

The exciton reflection line in a magnetic field also undergoes circular polarization (line X in Fig. 2). The degree of polarization of the exciton line, unlike that of the trion line, does not exceed 25%. Circular polarization of exciton reflection and absorption lines is apparent only in quantum-well structures in the presence of additional electrons; it is absent in undoped structures. In fact, additional electrons are indispensable for such polarization. There are two reasons for circular polarization of the exciton line in reflectivity and absorption spectra. One is related to exciton scattering in a two-dimensional electron gas [6, 7]; the other, to oscillator-strength redistribution between excitonic and trionic states (see below).

Apart from the bound exciton – electron states, the reflectivity and photoluminescence excitation spectra of modulated doped quantum well structures give evidence of the combined exciton – electron processes during which a "photocreated" exciton excites an additional electron from states below the Fermi level of a two-dimensional electron gas to states above the Fermi level. Naturally, the energy of such jumps is higher than the energy of a pure exciton transition.

Combined processes in the presence of a magnetic field are exemplified by the combined exciton – cyclotron resonance (*ExCR*) during which an incident photon creates an exciton in the ground state and simultaneously excites an additional electron from a lower to one of the upper Landau levels. In quantum-well structures placed in a magnetic field, where the electron energy spectrum becomes discrete, such processes manifest themselves as the appearance of narrow lines in the reflectivity, absorption, and photoluminescence excitation spectra. These lines may be as strong as those in the case of purely exciton transitions.

Figure 3 shows magnetic-field dependence of the energy of combined exciton – electron transitions accompanied by excitation of an additional electron from the zero to the first Landau level. It can be seen that the linear dependence of the transition energy on the magnetic field is roughly similar to that of the cyclotron energy of the electron [2]. In reflectivity and photoluminescence excitation spectra, it is possible to distinguish several *ExCR* lines corresponding to the transitions of an additional electron from the zero to the first, second, etc. Landau levels.

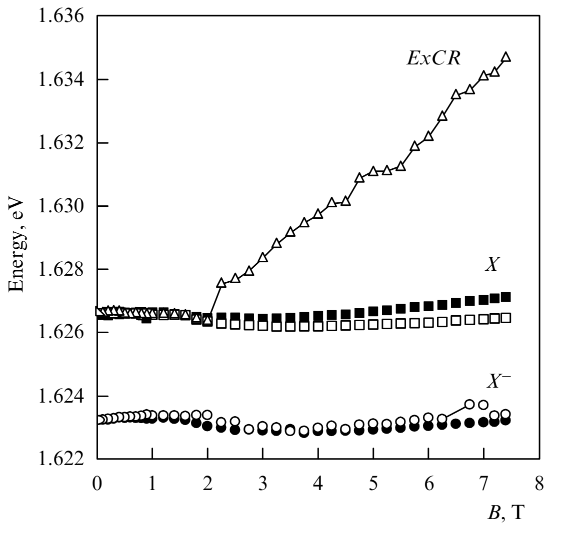

Figure 3. Magnetic-field dependence of the energy positions of the exciton (X) and trion (X^-) absorption lines and combined exciton-cyclotron resonance (*ExCR*) for a ZnSe quantum-well structure at the electron density 4×10^{10} cm^{-2}.

As the magnetic field decreases, all *ExCR* lines come closer together near the exciton resonance line. In a zero magnetic field, combined exciton – electron processes actually reduce to photocreation of an exciton and the concomitant generation of a pair (electron above the Fermi level/hole below the Fermi level). These processes account for the short-wavelength portion of an exciton absorption line. In a magnetic field, they undergo conversion to *ExCR* processes, during which the exciton absorption line shrinks, while its short-wavelength portion gives rise to narrow *ExCR* lines [8].

As the two-dimensional electron density increases, the simple picture with two persistent exciton and trion lines in the reflectivity and absorption spectra changes. To begin with, the strength of the exciton line drops with increasing electron density. Simultaneously, the trion line intensity grows. At a certain electron density, when the Fermi energy (1 – 3 meV) becomes of the same order of magnitude as the trion binding energy (3 – 5 meV) but remains significantly lower than the exciton binding energy (20 – 30 meV), the exciton line is absent from the spectrum. This picture is in conflict with the postulate that a loosely bound state (trion) must be destroyed by an electron gas (by means of screening or filling phase space) at lower electron densities than a tightly bound state (exciton).

Moreover, a rise in the electron density leads to an enhancement of the trion binding energy in proportion to the Fermi energy of a two-dimensional electron gas. This finding is paradoxically at variance with the current concept of screening (Fig. 4). However, this picture reverses with a rise in temperature (up to 35 K), when the trionic states are destroyed; in other words, the exciton line intensity increases, while the trion binding energy drops. This finding indicates that all anomalous phenomena should be attributed to trions rather than electrons.

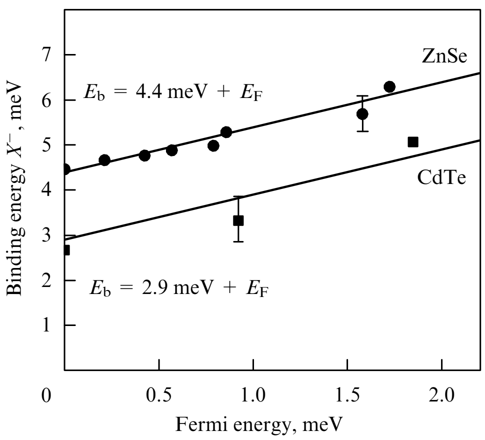

Figure 4. Dependence of the trion binding energy at the Fermi level of a two-dimensional electron gas for ZnSe- and CdTe-based quantum-well structures.

We explain such a behavior by the interaction between exciton and trion modes. The trion binding energy being low compared with the exciton binding energy and close to the uniform and nonuniform exciton broadening, the excitonic and trionic states may be regarded as having similar energies. Therefore, an exciton is readily converted to a trion when it takes up an additional electron. Conversely, a trion becomes an exciton after the loss of an electron. If this process is a coherent one, the modes intermix. In this case, exciton and trion are not independent excitations but should be considered as mixed exciton – trion modes. Such intermingling of exciton and trion excitations becomes more conspicuous with growing electron density and manifests itself as the redistribution of exciton and trion oscillator strengths and also as an increasing energy gap between these two lines.

We have developed a theory of such mixed exciton – trion excitations which agrees both qualitatively and quantitatively with experimental findings.

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Optical properties of strained $Si_{1-x}Ge_x$ and $Si_{1-x-y}Ge_xC_y$ heterostructures

Z F Krasil'nik, A V Novikov

Introduction

Recent progress in studies of silicon-based low-dimensional structures has given rise to a new field of research known as Si-based optoelectronics. Silicon and germanium are nondirect-gap materials, in which radiative recombination processes are hampered. However, low-dimensional structures based on these elements may be expected to show a number of previously unknown light emission characteristics.

On-going studies of novel mechanisms of effective photoluminescence from silicon are proceeding along several lines. One is focused on porous silicon structures and silicon nanoclusters embedded in a wider-bandgap host material. Using porous silicon structures, energies of photo- and electroluminescence in the range from 1 to 2.5 eV were obtained [4] and first integrated schemes were proposed in which light-emitting diodes are coupled to the control transistors [5].

Another line of research is concerned with silicon-based structures doped with rare-earth elements. Light emission by such structures is maintained by virtue of intracenter transitions which take place in rare-earth elements. For example, photo- and electroluminescence of erbium-doped silicon was reported to occur at 1.55 μm over a wide temperature range including room temperature [6]. The molecular-beam epitaxy (MBE) technology using sublimation sources proved very promising for the fabrication of heavily doped structures with a complex profile [7]. A recent publication describes laser generation with light pumping [8].

The third area of research gives priority to heterostructures with quantum wells and quantum dots based on direct-gap III – V semiconductors grown on a silicon substrate. Ref [9] reports the first results of a study of photoluminescence with a wavelength of 1.3 μm from a structure consisting of spontaneously formed quantum dots of InAs on a silicon substrate.

Finally, an important area of research is photoluminescence from $Si_{1-x}Ge_x$ and $Si_{1-x-y}Ge_xC_y$ nanostructures grown on a silicon substrate. Of special interest are the former structures with self-assembled nanoislands, in which intense luminescence near 1.55 μm was observed [10].

The present paper reports the results of a study on the growth of $Si_{1-x}Ge_x$ self-assembled nanoscale islands on