ATOMIC AND MOLECULAR STATES OF $A(+)$-CENTERS IN GaAs/AlGaAs QUANTUM WELLS

YU.L. IVÁNOV, P.V. PETROV, N.S. AVERKIEV

Ioffe Physical-Technical Institute, Russ. Acad. Sci.
(26, Politekhnicheskaya, Saint-Petersburg 194021, Russia 2927395; e-mail: yuri.ivanov@mail.ioffe.ru)

UDC 539.1

We consider nontrivial impurity states of acceptors that captured an extra hole, the so-called $A(+)$-centers, in GaAs/AlGaAs quantum wells. Practically any reasonable stationary concentration of $A(+)$-centers in quantum wells can be obtained by means of the double selective doping of wells and barriers. It is shown that, along with single atomic $A(+)$-centers, their collective molecular states can be formed in spite of their Coulomb repulsion. Atomic and molecular states of $A(+)$-centers can be discovered in various peaks of photoluminescence which represents the main method of investigation of these states in the work. Different states of $A(+)$-centers are also characterized by different dependences of the circular polarization and the shift of PL peaks in the magnetic field.

It is well known by now that, at low temperatures, neutral donor and acceptor impurities can capture an electron or a hole, respectively, which results in the formation of the so-called $D(-)$ or $A(+)$-centers. These states represent analogs of the negative hydrogen ion that plays an important role in space processes (see, for example, [1]). In view of a low binding energy of $D(-)$-centers, experiments that simulate space processes running at huge magnetic fields of neutron stars can be realized under terrestrial conditions [2]. In essence, this fact determined the primary interest in the investigation of $D(-)$-centers in semiconductors. Later on, however, $D(-)$ and $A(+)$-centers have drawn independent interest particularly due to the basic role they play in processes of hopping conduction in impurity bands. In a bulk material, these centers arise under nonequilibrium conditions, usually as a result of illumination. In materials like GaAs, their binding energy amounts to sub-meV or several meV, but it considerably increases in two-dimensional structures as compared to three-dimensional ones, which facilitates their investigation. At the same time, it is easy to obtain equilibrium $D(-)$ or $A(+)$-centers in two-dimensional structures using the method of double selective doping [3] (simultaneous doping of quantum wells and barriers). Negatively charged shallow donors, $D(-)$-centers, in GaAs/AlGaAs quantum wells were investigated in a large number of works (see, for example, [4, 5]). As for the corresponding states of shallow acceptors ($A(+)$ centers) in GaAs quantum wells, they were studied for the first time in [6], where their activation energy and localization radius were estimated. In this work, we generated $A(+)$-centers by means of the double selective doping of quantum-well structures with beryllium. It turned out that, due to the Coulomb repulsion of two holes localized at the beryllium frame, the localization radius of an $A(+)$-center exceeds the threefold that of an ordinary acceptor and amounts to 110 Å. It was also demonstrated in [6] that the interaction of a photoexcited electron from the conduction band with an $A(+)$-center is, to a great extent, accompanied by the recombination radiation. This experimental fact allowed one to apply the photoluminescence (PL) technique in studying thoroughly a large number of properties of $A(+)$-centers in quantum wells of gallium arsenide.

Works [7, 8] dealt with the experimental and theoretical determination of both the energy structure of $A(+)$-centers in GaAs quantum wells and the dependence of their activation energy on the quantum well width. Experimentally, the activation energy and its dependence on the quantum well width were determined with the help of spectral analysis of photoluminescence. As compared to other procedures of determination of the binding energy of $A(+)$-centers, for example the measurement of the temperature dependence of the Hall effect, the advantage of the PL technique consists in the fact that it allows one to perform measurements at very low concentrations of $A(+)$ centers. The smallness of the concentration of $A(+)$-centers is important for the determination of their binding energy as, due to the large localization radius of $A(+)$-centers, their wave functions start to overlap at considerably lower concentrations than those for ordinary acceptors $A(0)$, which results in both the interaction between them and a widening of the level.

A peculiarity of $A(+)$ and $D(-)$-centers consists in that the wave functions of charge carriers considerably differ, so that one of the particles is located close to the defect, while the other one attracts to a neutral complex as to an electric dipole. The difference between the radii

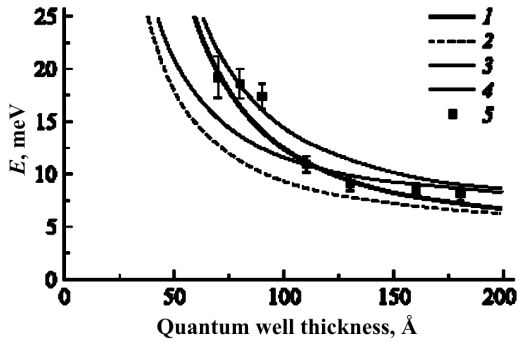

Fig. 1. Dependence of the activation energy of $A(+)$-centers on the quantum well thickness. Curves correspond to the energies E_1 and E_2 in the bulk: *1* and *2* – E_1=5 meV, E_2=5 meV, *3* and *4* – E_1=7 meV, E_2=7 meV. Dots – experiment

of the states of the particles suppresses the exchange interaction of charge carriers, and one can approximately consider that the spin correlations between particles are absent. In this case, the binding energy of the external hole in $A(+)$ as a function of the well width can be calculated by the zero-radius potential technique supposing that the boundary condition for the behavior of the wave function is not changed in quantum wells of different widths.

The results are given in Fig. 1. The theoretical dependences for the ground and excited states are presented by solid curves, the dots correspond to the experimental data for the ground state. The fitting parameter for the calculation is the activation energy of $A(+)$-centers in the bulk GaAs material. One can see that, at an activation energy of 5 meV, the theory agrees with the experiment in the best way.

Thus, it is established that the level of a hole localized at an acceptor splits in GaAs quantum wells, by forming the ground and excited states corresponding to a heavy and a light hole, respectively, and the splitting in a quantum well of 150 Å in width amounts to 1.5 meV.

The further investigation of A(+)-centers in GaAs quantum wells was aimed at the determination of their fine spin structure. For this purpose, we analyzed the circular polarization of the PL related to $A(+)$-centers that was induced by the magnetic field [9]. The basic experiments in this work were performed on samples with the quantum well width W equal to 16 or 18 nm, in which one observed a rather good resolution of closely related PL peaks. One of them is due to the recombination of a free electron from the conduction band with an extra hole of the $A(+)$-center, while the second peak having the lower energy was initially ascribed to the recombination of a bound exciton. An example of the PL spectrum with various circular polarizations in the 2.95-T magnetic field for the F-387 sample with W=16 nm is presented in Fig. 2,*a*. One can see that two peaks are well resolved, and the peak with higher energy is not split practically, though it is polarized. The peak with lower energy is substantially split, but it is practically nonpolarized. Figure 2,*b* shows the polarization degree of the right peak as a function of the magnetic field. Such a behavior of this dependence can be explained by considering the fact that this peak is related to the recombination of a photoexcited electron from the conduction band with a hole localized at an acceptor ($A(+)$ center). Moreover, in weak magnetic fields, the circular polarization of the radiation related to $A(+)$-centers arises due to the spin splitting of the levels of the bound hole and electron as well as their temperature repopulation. In stronger fields, diamagnetic effects become important for localized holes, as the radius of the $A(+)$ ground state is very large, while the first excited state is located at a distance of the order of 1 meV from the ground one (as was mentioned above). So that at $g_h \approx 1$, there occurs the "interaction" of the ground and excited states in fields of about 2 T. (Here, g_h is the g-factor of a heavy hole for the direction normal to the plane of a well). In the theory developed in [9], the important parameter is λ_1 which describes the variation of the energy gap between the ground and excited states. Experimentally, one observes a decrease of the polarization degree in fields of about 3 T (see Fig. 2). According to the selection rules, this can be associated with transitions to the states of a light hole with a spin of $+1/2$ or $-1/2$. Then, the parameter λ_1 must be chosen so as to reduce the initial splitting between the ground and excited states. One can see that the curve calculated with regard for what was said above correctly reflects the dependence $P_{\rm circ}$(H), but the theoretical curve is reduced fourfold in magnitude. It is also worth noting that one observes a fall of the total radiation intensity in the region of the polarization decrease. It is explained by the fact that, within the framework of the model in use, transitions to the ground state of an $A(+)$-center become forbidden in magnetic fields higher than 3 T.

Now let us consider the PL peak with lower energy (Fig. 2). One can see that this peak is considerably split, but it is practically nonpolarized. In [9], the structure was investigated, in which the doping level was as low as possible, so that the concentration of $A(+)$-centers was of the order of 10^{10} cm^{-2}. Later on, structures with a surface doping concentration of 1.5×10^{10}, 6×10^{10}, and 1.8×10^{11} cm^{-2} were grown. Their PL spectra in

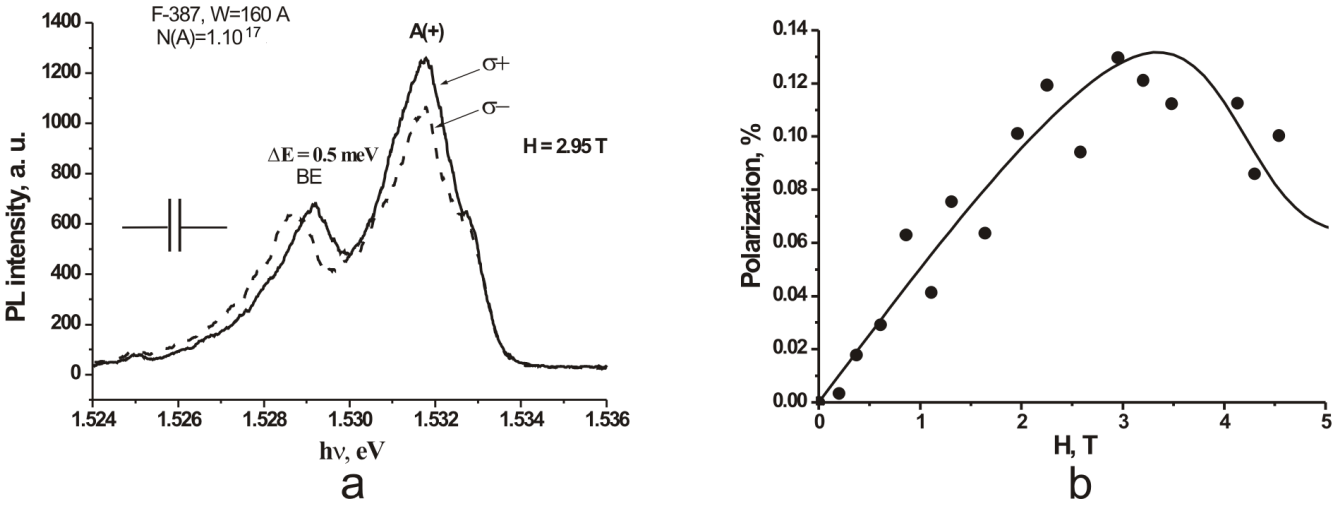

Fig. 2. PL spectrum for two directions of the circular polarization (a), and the dependence of the polarization degree of the right peak on the magnetic field (b). Solid curve – calculation, dots – experiment

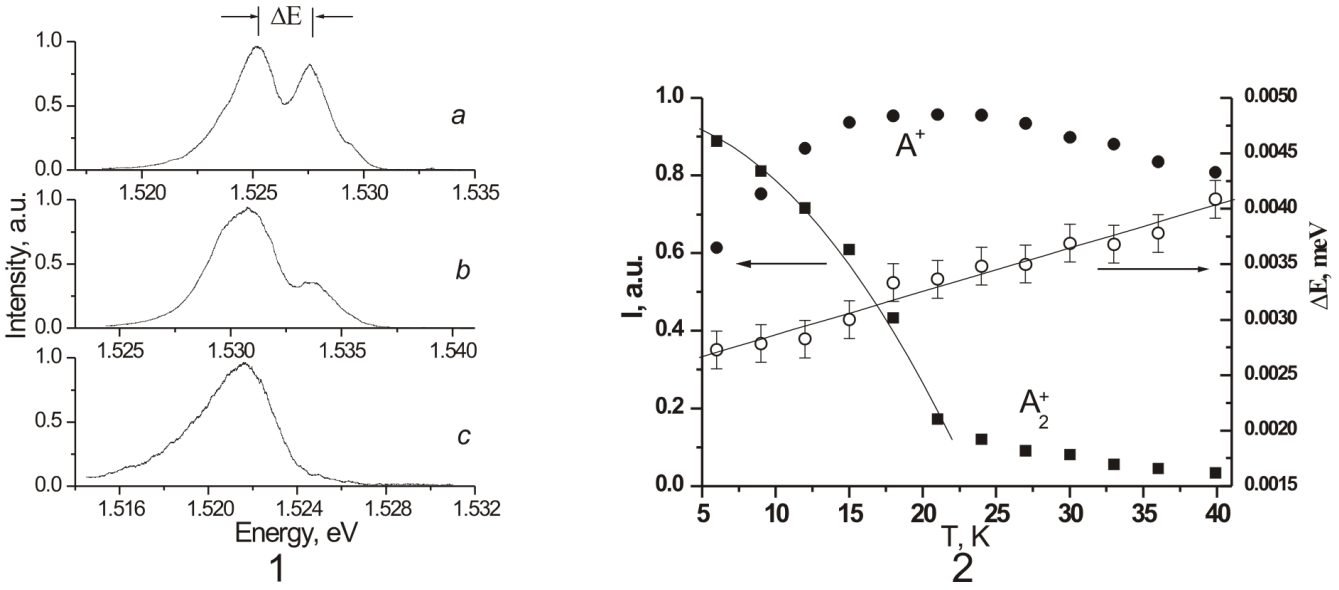

Fig. 3. *1* – Spectra of the samples with various doping levels: a – 1.5×10^{10}, b – 6×10^{10}, and c – 1.8×10^{11} cm^{-2}. *2* – Temperature dependences of the peak amplitudes of $A(+)$ atomic and $(A+)_2$ molecular states

nonpolarized light are given in Fig. 3,*1*. One can see that, with increase in a doping level, the amplitude of the right peak falls, while that of the left one increases.

If we ascribe these peaks to different states of $A(+)$-centers, it is evident that, with increase in a doping level, the centers are "transferred" from one state to another one. The above-cited data on the polarization of the right PL peak and its dependence on the magnetic field are related to a single $A(+)$-center. As for the left peak, it was ascribed in [10] to a paired molecular state of $A(+)$-centers. The radiation in this peak represents a result of the recombination process with the participation of a photoexcited electron and one of two holes (coupled by the exchange interaction and having the opposite spins $+3/2$ and $-3/2$) in a single molecular state of two closely located $A(+)$-centers ($(A+)_2$ state). As the total moment J of such a state equals zero, its hole levels do not shift in the magnetic field, and the probability for a photoexcited electron to be captured by these holes and, along with this, the intensity of electron transitions

to this state are practically the same. However, it is worth taking into account that, for example, after the recombination of the hole with a spin of $+3/2$, there remains the other hole with a spin of $-3/2$, whose energy changes by $(3/2)mg_hB$ in the magnetic field. That is why, the transition with one polarization in the PL spectrum will be shifted from that with the other polarization by $3mg_hB$. The energy splitting observed in the experiment corresponds to the g-factor of a hole of $\approx$0.6, which agrees with the literature data for the ground state of localized holes in such quantum wells [11]. Figure 3,*2* demonstrates the "transfer" of the centers corresponding to the amplitudes of the peaks from one state to the other with increase in the temperature. Naturally, a decrease of the number of molecular $(A+)_2$ states of the centers is accompanied by the growth of the number of their atomic $A(+)$ states.

The unfilled circles in Fig. 3,*2* show the temperature dependence of the binding energy of holes in the molecular state which is determined as the difference between the PL peaks. This definition seems natural due to the fact that it is harder to detach a hole in the molecular state by the magnitude of the binding energy, that's why the PL line has a less quantum energy. The increase of this measured energy is explained by the spread of the energies of interacting pairs. At a higher temperature, only pairs with stronger coupling survive.

Finally, it is worth paying attention to the pronounced nonactivation character of a decrease of the number of $(A+)_2$ centers. In particular, this can be due to the fact that the number of particles in a "molecule" is much larger than two.

The work is supported by the RFFI grants, partially by the grant of the President "Leading Scientific Schools" NSh-5920.2006.2, and the project of the Saint-Petersburg Scientific Center of the RAS.

1. R.O. Mueller, A.R.P. Rau, and L. Spruch, Phys. Rev. A **11**, 789 (1975).
2. V.L. Ginzburg, *Physics and Astrophysics: Articles and Speeches* (Nauka, Moscow, 1992) (in Russian).
3. S. Huant, S.P. Najda, and B. Etienne, Phys. Rev. Lett. **65,** 1486, 1990
4. S. Huant, A. Mandray, J. Zhu, C.G. Louie, T. Pang, and B. Etienne, Phys. Rev. B **48**, 2370 (1993).
5. D. Mikhailov, F.J. Betancur, J.H. Marin, and L.E. Oliveira, Phys. St. Sol. (b) **210**, 605, 1998.
6. N.V. Agrinskaya, Yu.L. Ivánov, V.M. Ustinov, and D.V. Poloskin, Fiz. Tekhn. Polupr. **35**, 571 (2001).
7. Yu.L. Ivánov, N.V. Agrinskaya, P.V. Petrov, V.M. Ustinov, and G.E. Tsirlin, Fiz. Tekhn. Polupr. **36**, 993 (2002).
8. N.S. Averkiev, A.E. Zhukov, Yu.L. Ivánov, P.V. Petrov, K.S. Romanov, A.A. Tonkikh, V.M. Ustinov, and G.E. Tsirlin, Fiz. Tekhn. Polupr. **38**, 222 (2004).
9. P.V. Petrov, Yu.L. Ivánov, K.S. Romanov, A.A. Tonkikh, and N.S. Averkiev, Fiz. Tekhn. Polupr. **40**, 1099 (2006).
10. P.V. Petrov, Yu.L. Ivánov, and A.E. Zhukov, Fiz. Tekhn. Polupr. **41**, 850 (2007).
11. Q.X. Zhao, P.O. Holtz, A.Pasquarello, B. Monemar, and M. Willander, Phys. Rev. B **50**, 2393 (1994).

Received 29.05.08.
Translated from Ukrainian by H.G. Kalyuzhna

АТОМАРНІ ТА МОЛЕКУЛЯРНІ СТАНИ $A(+)$-ЦЕНТРІВ В КВАНТОВИХ ЯМАХ GaAs/AlGaAs

Ю.Л. Іванов, П.В. Петров, Н.С. Аверкієв

Р е з ю м е

Розглянуто нетривіальні домішкові стани акцепторів, які захопили додаткову дірку, так звані $A(+)$-центри в квантових ямах GaAs/AlGaAs. Стаціонарна концентрація $A(+)$-центрів в квантових ямах практично будь-якої розумної величини досягається шляхом подвійного селективного легування ям і бар'єрів. Показано, що разом з одиночними, атомарними $A(+)$-центрами можуть утворюватися їх колективні, молекулярні стани, незважаючи на кулонівське відштовхування позитивно заряджених $A(+)$-центрів. Атомарні та молекулярні стани $A(+)$-центрів виявляються в різних піках спектра зв'язаної з ними фотолюмінесценції, яка є основним методом дослідження в цій роботі. Різним станам $A(+)$-центрів властиві також різні залежності величини циркулярної поляризації та зміщення піків фотолюмінесценції в магнітному полі.