New donor-related state of nonequilibrium charge carriers in germanium

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New luminescence bands, which appear in germanium doped with arsenic and phosphorus, are observed at helium temperatures. The origin of the bands is explained by the radiative decay of complexes containing the ionized donor, two electrons, and two holes.

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In a recently published paper,[1] the luminescence bands lying near the emission line of an exciton bound to an antimony atom in uniaxially deformed germanium were interpreted as α_2 and β_2 lines, which arise as a result of decay of a multiparticle exciton-impurity complex, formed due to the localization of two excitons on the antimony atom. We discovered analogous emission bands, displaced by approximately 1 meV toward low energies relative to the emission line of the bound excition α_1, more than one year ago in germanium, doped with arsenic and phosphorus and compressed along the (111) axis. These results were not published, since to date we have not seen a complete explanation of its origin.

It is convenient to observe the new radiation in uniaxially strained germanium crystals doped with arsenic with comparatively low levels of excitation, when electron-

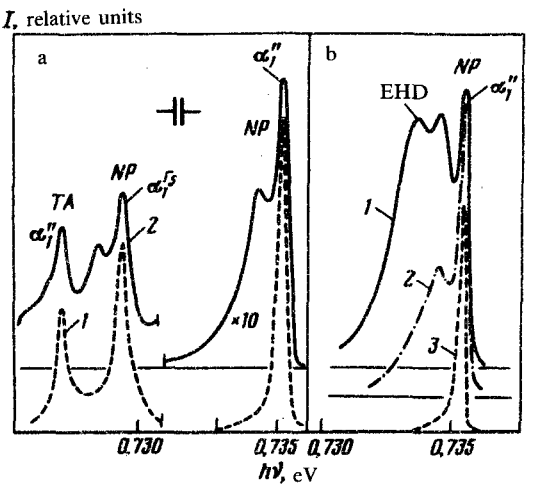

FIG. 1. The spectral distribution of the *NP* and *TA* components of photoluminescence of germanium doped with arsenic compressed along the (111) axis by a pressure $P = 740$ kg/cm^2. The new emission band is not labeled in the figure. (a) Low level of excitation: 1) 2 K; 2) 4.2 K. (b) High level of excitation: 1) 2 K; 2) 2.8 K; 3) 4.2 K.

hole drops (EHD) are not yet formed.[2] Figure 1 shows luminescence spectra of germanium doped with arsenic with a concentration 5×10^{15} cm^{-3}. It is evident from Fig. 1a that the new radiation is not observed at 4.2 K, but is clearly visible, when the temperature decreases to 2 K, in the phonon-free (*NP*) component of the spectrum, including near the $\alpha_1^{\Gamma_5}$ line corresponding to the decay of a bound exciton with the creation of a neutral donor in the excited Γ_5 state.[3] At high levels of excitation and low temperatures (Fig. 1b), the electron-hole drop radiation appears in the spectrum.[2] As the temperature is increased, the electron-hole drop band disappears first and only later does the new emission band disappear.

Figure 2 shows the dependence of the spectral position of different components in the emission spectrum of Ge doped with arsenic on pressure P applied along the (111) and (001) axes. Uniaxial compression along (111) removes the degeneracy of the conduction and valence bands. At the same time, the splitting of the states Γ_1–Γ_5 changes both in the neutral donor and in the bound exciton, which leads to the sublinear P dependence of the displacement of the α_1' and α_1'' radiation components of the bound exciton. The component $\alpha_1^{\Gamma_5}$ should be displaced with pressure according to the expression[4]

$$\Delta = \Delta_0\left(1 + \frac{\Delta_c}{\Delta_0} + \frac{\Delta_c^2}{\Delta_0^2}\right)^{1/2}, \qquad (1)$$

where Δ_c is the splitting of the conduction band, $\Delta_0 = 4.23$ meV for arsenic, i.e., the splitting of Γ_1–Γ_5 in the neutral donor at $P = 0$. The dependence computed according to (1) agrees well with experiment. The new emission band is displaced with increasing

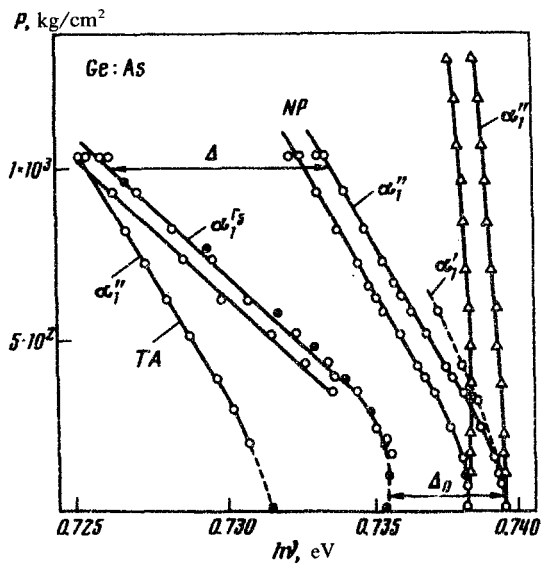

FIG. 2. The spectral position of the *NP* and *TA* photoluminescence bands of germanium doped with arsenic at 2 K as a function of the pressure P along the (111) (circles) and (001) (triangles) directions. The dark circles indicate a calculation using Eq. (1).

P analogously to the displacement of the α_1'' and $\alpha_1^{\Gamma_5}$ lines. It follows from this that the neutral donor, which can make a transition to the excited state, participates in the recombination responsible for the origin of the new band. We note that with the decay of the multiparticle exciton-impurity complex which contains two excitons the final state is a bound exciton, rather than a neutral donor, which excludes the possibility of interpreting the new line as a α_2 line, as proposed in Ref. 1. It is evident from Fig. 1 that the new band has a tail that extends into the low-energy region. Such inhomogeneous band broadening contradicts the suggestion made in Ref. 1 that the excited state of the bound exciton is unstable.

The spectrum of the phonon *LA* component of the radiation of germanium doped with arsenic compressed along the (111) and (001) axes is completely analogous to the spectrum of the *NP* component. We were not able to observe the bands analogous to the "β_2" band in Ref. 1. The intensity of the new band in the *TA* component was much lower, as compared with the intensity of the α_1 line, than in the remaining components. We also investigated a germanium specimen doped with antimony up to concentration of 3×10^{15} cm^{-3}. Under compression along the (111) and (001) axes and pressures $P\lesssim 2000$ kG/cm^2, the *LA* component of the spectrum of this specimen was analogous to the spectrum with arsenic doping, but the distance between the line α_1 and the maximum of the new band was slightly smaller ($\sim$0.5 meV). We could not observe the "β_2" band. The intensity of the *NP* component of the radiation from germanium doped with antimony is at least 60 times lower than the intensity of the *AA* component, which did not allow us to study its structure.

The results presented above can be explained on the basis of the following scheme. According to the shell model,[5] the most complicated complex, when the degeneracy is removed as a result of uniaxial compression, for example, along the (111) axis, can contain a positively charged impurity donor, two electrons, and two holes. We shall introduce the following notation for the binding energies: E_{D_0} and $E_{D_0^x}$ for the donor in the ground and excited states; E_{ex} for the exciton; E_{D_1} for the bound exciton; E_{D_1+h} for the hole on the bound excition; E_{D_0+h} for the hole on the neutral donor. Recombination in such a four-particle complex can be accompanied by ejection of a hole into the valence band, so that the final state will turn out to be the neutral donor. The energy of the emitted photon in this case is $h\nu_1 = E_g - (E_{D_0} - E_{D_0^x}) - E_{ex} - E_{D_1+h} - (m^x v^2)/2$, where $m^x v^2/2$ is the kinetic energy of the ejected hole. The recombination radiation must occupy a band, which was displaced toward low energies relative to the line α_1 by an amount $E_{D_1+h} + (m^x v^2/2)$; in addition, the velocity of the hole v can vary over a rather broad range. If the hole is not ejected, then a neutral donor with a hole bound to it must be the final state. Such a complex is stable.[6] The energy of the emitted photon in this case is $h\nu_2 = E_g - (E_{D_0} - E_{D_0^x}) - E_{ex} - E_{D_0+h}$; i.e., a narrow line must be emitted. However, this line must be very close to α_1, since E_{D_1} and E_{D_0+h} differ insignificantly.[6] We note that our interpretation assumes the existence of a new type of impurity complexes.

[1]V. D. Kulakovskiĭ and I. V. Kukushkin, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 323 (1982) [JETP Lett. **35**, 396 (1982)].

[2]T. Rice, J. Hensel, T. Phillips, and G. Thomas, Electron-Hole Liquid in Semiconductors [Russian translation], Mir, Moscow, 1980.
[3]A. Mayer and Lightowlers, J. Phys. C. **12**, 945 (1979).
[4]G. L. Bir and G. E. Pikus, Simmetriya i deformatsionnye éffekty v poluprovodnikakh [Symmetry and Deformation Effects in Semiconductors], Nauka, Moscow, 1972.
[5]G. Lirczenow, Can. J. Phys. **55**, 1787 (1977).
[6]M. Lampert, Phys. Rev. Lett. **1**, 450 (1958).

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