Electron-phonon interaction on "shallow" donors in gallium phosphide

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Electron–phonon interaction with participation of the phonon states of the entire Brillouin zone has been observed for the first time for shallow impurity states in semiconductors.

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Shallow impurity states in semiconductors are formed by Bloch functions of a very slight region of k-space near an extremum of the corresponding band. As a result, an electron bound with a shallow center should in principle interact predominantly with long-wave lattice vibrations, and the interaction with short-wave vibrations should be greatly weakened.

We have observed in the photoexcitation spectra of the shallow donor centers S and Te in GaP a structure that shows clearly the interaction of the bound electron with the phonon states of the entire Brillouin zone. A similar interaction was observed earlier only for small-radius impurity centers.

The experiments were performed with an IKS-21 spectrometer with modified optical system and recording system, which made it possible to measure dependably optical transmission at the 1% level. The amount of light scattered in the instrument was strictly monitored. The measurements were made at temperatures 20 and 80 °K.

A typical spectrum is shown in the figure. The strongest line with a maximum at 97.0 meV for sulfur and 82.5 meV for tellurium corresponds to electron transitions from the donor ground state 1S to the excited state 2$P_{\pm}$.[1] The structure consisting of three complex-shape lines, observed in the short-wave region of the spectrum, lies higher than the corresponding photoionization thresholds and cannot be connected directly with the photoexcitation processes. We call attention to the similarity of the spectra in the case of sulfur and tellurium. At 86 °K, the spectra retain their general shape, but the details are less pronounced.

The spectral positions of the lines allow us to interpret the observed structure as being the single-phonon wing of the strongest zero-phonon line corresponding to the $1S \rightarrow 2P_{\pm}$ transition. This assumption is confirmed when the spectrum is compared with the GaP phonon state density function calculated from experiments on elastic neutron scattering and shown in the figure. It turns out therefore that the 1S and the 2$P_{\pm}$ states of shallow donors in GaP, which are made up in principle of the Bloch states of an insignificant region of k-space in the vicinity of the absolute minimum of the conduction band, interact with the phonon states in the entire Brillouin zone.

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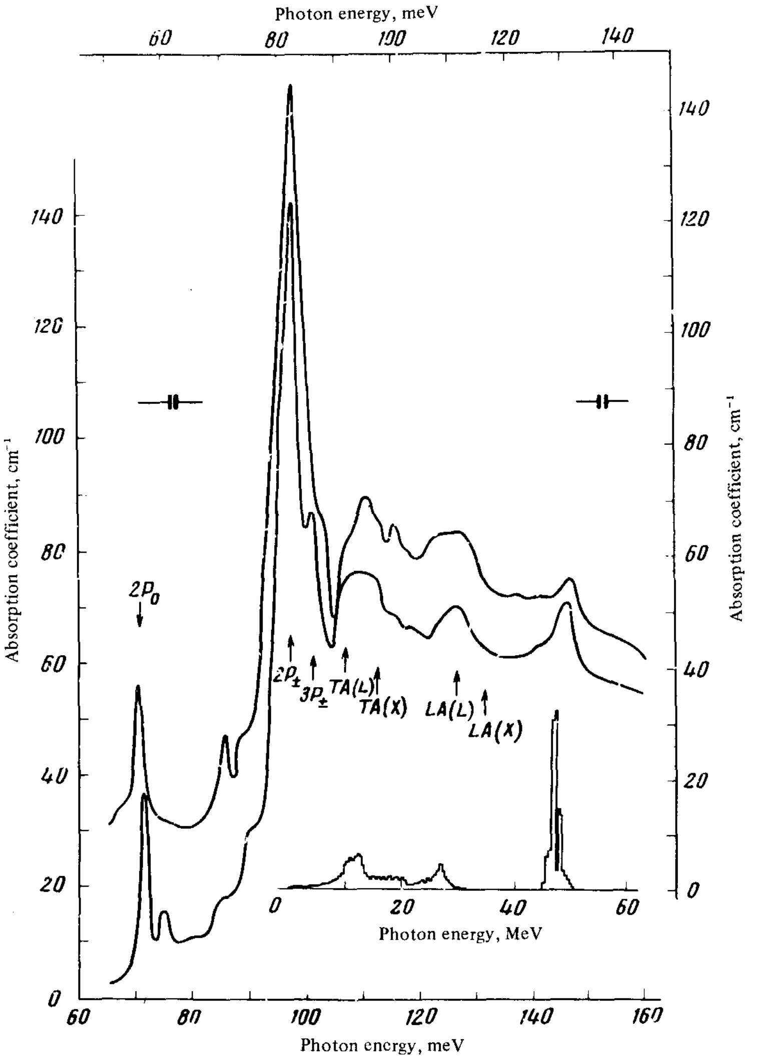

FIG. 1. Impurity absorption spectra of gallium phosphide: $T = 20$ °K. Lower curve—GaP :S (lower and left-hand scales), upper curve—GaP :Te (upper and right-hand scales). The absorption due to the lattice vibrations has been subtracted. The arrows mark the photoexcitation lines and the singularities in the singe-phonon wing corresponding to acoustic phonons at the X and L points of the Brillouin zone. The insert shows the phonon state density function of GaP.[2]

The observed enhancement of the electron-phonon interaction can be connected with the strong anisotropy of the effective mass of the free electrons. According to the results of the measurements of the cyclotron resonance, the transverse and longitudinal effective masses of the electrons in GaP amount to $m_t = 0.25m_0$ and $m_\lambda \approx 5m_0$, respectively.[3] It is known that the ionization energy of the donor ground state is determined by the transverse effective mass.[4] Let us estimate the corresponding characteristic radius of the ground state:

$$a_z \sim \frac{\hbar}{(2m_t E)^{1/2}} \approx 13 \text{Å}.$$

Here E is the binding energy of the ground state and amounts to 104 meV for S and 90 meV for Te.[1] By way of comparison we indicate that $a_t \approx 20$ Å for the donors in silicon. We can similarly estimate the characteristic radius of the ground state of an electron bound with a donor, which turns out to be $a_\lambda \approx 3$ Å for the direction of the longitudinal axis of the effective-mass ellipsoid ($a_\lambda \approx 10$ Å for donors in silicon). Thus, owing to the anomalously large longitudinal effective electron mass in GaP, the corresponding characteristic radius of the ground state of an electron bound to a donor is comparable in magnitude with the analogous parameters of the small-radius centers in ionic crystals; this is possibly the cause of the observed effect.

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