Neutralization of D^- centers in Si:P by ballistic phonons of various polarizations

B. A. Danil'chenko and S. I. Komirenko
Institute of Physics, Academy of Sciences of the Ukrainian SSR, 252650, Kiev-28

(Submitted 25 July 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **54**, No. 7, 384–387 (10 October 1991)

Longitudinally polarized phonons interact with D^- centers at an intensity an order of magnitude higher than that for phonons of transverse modes. An upper limit is estimated on the time scale for the restoration of the density of D^- states after their neutralization by nonequilibrium phonons.

Impurity atoms in semiconductors at liquid-helium temperatures can capture an excess electron or hole to an outer shell, thereby forming D^- (or A^+) centers. Most of the research which has been carried out on these states has used the method of submillimeter photoconductivity.[1] A recently developed method of photoinduced conductivity[2] (PIC) has made it possible to study these centers with the help of nonequilibrium phonons. It has been shown[2] that D^- centers are neutralized by one-phonon transitions from a bound state into the conduction band. However, all studies in this area have been of an "energy" nature, by which we mean that the binding energies in various materials, and the changes in these binding energies upon the application of an external pressure or magnetic field to the sample, have been determined. It is thus clearly of interest to determine the properties of the interaction of phonons of various polarizations with D^- centers. The absorption of longitudinal and transverse ballistic phonons by free carriers was studied in Ref. 3. Their scattering by "in-center" transitions was studied in Ref. 4. There has been no study of the role played by the polarization of the phonons involved in the impurity-band transitions or in the processes of phonon neutralization of D^- centers.

In this letter we are reporting a study of the D^- states in Si:P crystals with $N_d - N_a = 8\times10^{14}$ cm^{-3} and $N_a = 2\times10^{13}$ cm^{-3} by means of a heat-pulse method and also by means of the PIC method. The test samples were cut as parallelepipeds with dimensions of $0.5\times0.5\times1$ cm, faceted by (111), (211), and (110) planes, respectively. Our first step was to record a time-of-flight spectrum of the nonequilibrium phonons which were injected by a thin-film metal generator with the help of a superconducting indium bolometer (Fig. 1). Ohmic contacts were then fused to the sample in place of the bolometer. An electric field was applied to the sample, and a "cold" preamplifier measured the change in the current in the circuit due to the arriving ballistic phonons. The phonon-conductivity signal was recorded as the sample was excited by room-temperature IR light, supplied along a metal waveguide (Fig. 2a), and also in darkness. In the latter case, the IR light was deflected by a "cold" mirror (Fig. 2b).

The phonon-conductivity signal is the change in the conductivity of the sample caused by nonequilibrium phonons in a static field; i.e., this signal is $\Delta\sigma = e\mu\Delta n$ [$\Delta\mu = O(1)$], where $\Delta n \sim \beta W N_{d-}$, and β and W are the ionization cross section of a

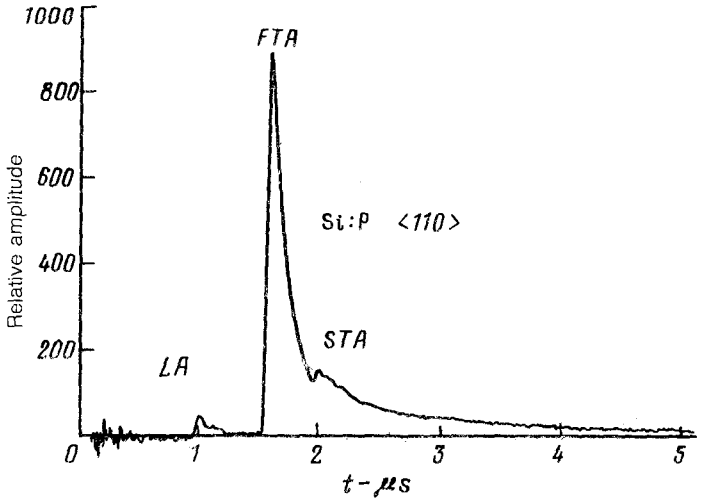

FIG. 1.

D^- center and the phonon flux density, respectively, both averaged over frequency. We should point out that our estimates put the steady-state electron density in the conduction band at $n \sim 10^9$ cm^{-3} for the case of IR illumination, and Δn does not exceed this density by more than an order of magnitude at the maximum power supplied to the thin-film generator.

The result of greatest interest is the difference between the shape of the phonon-conductivity signal and that of the time-of-flight spectrum of the phonons recorded with the help of the bolometer. Specifically, the ratio of phonon amplitudes FTA/LA

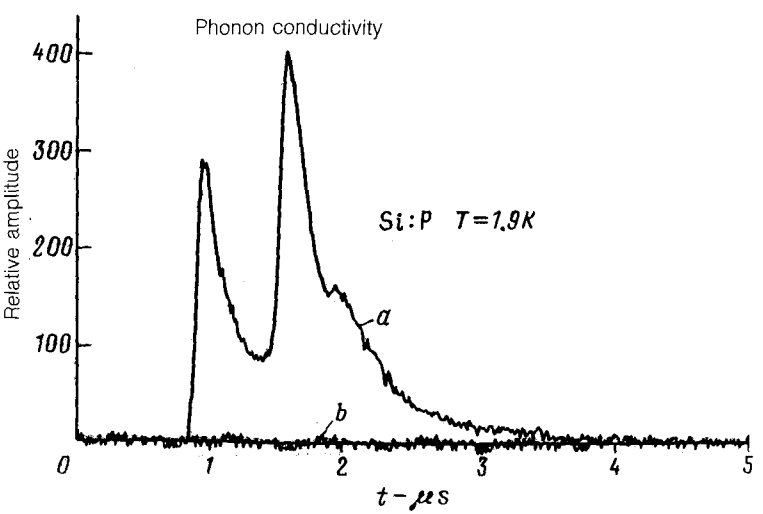

FIG. 2

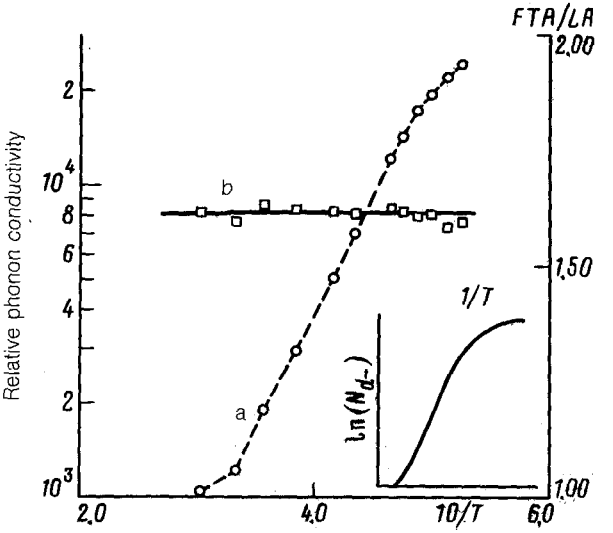

FIG. 3.

in the two cases differed by more than an order of magnitude. Such a difference might be explained on the basis that the time delay between the arrival of the LA and the FTA phonons is about 5×10^{-7} s—too short for a restoration of the original population of D^- states. The ratio FTA/LA of the phonon-conductivity signal does not depend on the temperature (Fig. 3b). However, at a constant level of the power applied to the phonon generator, under conditions such that the density of D^- centers changes by two orders of magnitude as the temperature is varied (Fig. 3a), the ratio FTA/LA would necessarily change if this difference were due to a long time scale for the capture to D^- states. The time scale for the restoration of the original population of D^- centers thus does not exceed 5×10^{-7} s under these conditions. There are two possible explanations for the observed difference in the ratios LTA/LA: (1) The first is a difference between the energy spectra of the longitudinal and transverse phonons which have traversed a distance of 1 cm. The maximum frequency of the ballistic phonons of the LA mode is $\hbar\omega_{\max}/k\approx27$ K, while $\hbar\omega_{\max}/k$ for the transverse modes does not exceed 18 K. As a result, there should be a difference between the absorption coefficients for the different modes as they interact with a state with a binding energy E_i. (2) Second, even if the phonons of the different polarizations had identical energy spectra, it would be difficult to expect the absorption coefficients to be equal, since the transition matrix elements, which determine the size of the absorption coefficient, are different for different modes (by analogy with in-center transitions[4]).

The experimental temperature dependence $\Delta\sigma(T)$ (Fig. 3a) is exponential with an activation energy $E_i = 1.74\pm0.05\times10^{-3}$ eV. It can be seen from this figure that at $T<1.9$ K, and also at $T>3$ K, there is a deviation from this exponential behavior. This behavior of $\Delta\sigma$ can be understood by examining the temperature dependence of the density of D^- centers. To do this, we write a system of balance equations, taking the following processes into account: (1) the ionization of neutral phosphorus atoms by IR light, $\sigma_0 I N_{d0}$; (2) the capture of free carriers by neutral donors, accompanied

by the formation of a D^- center, $\gamma_- nN_{d0}$; (3) the capture of free carriers by positively charged donors, $\gamma_+ nN_{d+}$; (4) the photodecay of D^- centers because of the background light, $\sigma_- IN_{d-}$; and (5) the thermal neutralization of D^- centers, $\alpha_T N_{d-}$. Here σ_0 and σ_- are the cross sections for the photodetachment of an electron from a neutral center and from a D^- center, respectively; γ_- and γ_+ are the coefficients for the capture by neutral and positively charged donors; I is the intensity of the background light; and $\alpha_T = \gamma_- N_c \exp(E_i/kT)$ is the rate of thermal neutralization, where N_c is the effective density of states in the conduction band:

$$\frac{dn}{dt} = \sigma_0 I N_{d0} - \gamma_- n N_{d0} - \gamma_+ n N_{d+} + \alpha_T N_{d-} + \sigma_- I N_{d-}; \tag{2}$$

$$\frac{dN_{d-}}{dt} = \gamma_- n N_{d-} - (\alpha_T + \sigma_- I) N_{d-}; \tag{3}$$

$$N_{d0} = N_d - N_{d+}; \tag{4}$$

$$N_{d+} = N_a + n + N_{d-}. \tag{5}$$

The experimental temperature was assumed low enough that thermal ionization of neutral donors could be ignored. The electric field applied to the sample was too weak ($\leqslant 5$ V/cm) to cause impact neutralization of the D^- centers.[5] A solution of this system of equations for steady-state conditions under the assumptions

$$N_a \gg n, \quad N_{d-} \tag{6}$$

is

$$N_{d-} = \frac{\gamma_- (N_d - N_a)^2 \sigma_0 I}{(\alpha_T + \sigma_- I)\gamma_+ N_a}. \tag{7}$$

The inset in Fig. 3 shows the temperature dependence $N_{d-}(T)$ calculated from (7). The saturation at low temperatures is due to the predominant photodetachment. The deviation at high temperatures ($\sim T^{3/2}$) is attributed to the small value of the argument of the exponential function.

We should point out in conclusion that a completely clear picture of the interaction of LA and TA phonons with D^- centers might emerge from experiments using monochromatic sources of ballistic phonons.

We wish to thank O. G. Sarbeĭ for useful discussions and for support in the course of this work.

[1]E. M. Gershenzon, A. P. Mel'nikov *et al.*, Usp. Fiz. Nauk **132**, 353 (1980) [Sov. Phys. Usp. **23**, 684 (1980)].
[2]W. Burger and K. Lassmann, Phys. Rev. Lett. **53**, 2035 (1984).
[3]A. Zylberstejn, J. Phys. (Paris) **33**, Suppl. C4, 85 (1972).
[4]P. C. Kwok, Phys. Rev. **149**, 666 (1966).
[5]V. N. Aleksandrov *et al.*, Fiz. Tekh. Poluprovodn. **11**, 79 (1977) [Sov. Phys. Semicond. **11**, 44 (1977)].

Translated by D. Parsons