Energy-Resolved Measurements of the Phonon-Ionization of D^- and A^+ Centers in Silicon with Superconducting-Al Tunnel Junctions

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By means of phonon spectroscopy with superconducting-Al tunnel junctions as tunable phonon generators we show that the threshold energy of the phonon-induced conductivity for Si:B^+ and Si:P^- agrees well with far-infrared data, proving that the ionization is mainly a one-phonon process. This ionization mechanism allows a sensitive detection of very-high-frequency phonons.

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The electrical conductivity in semiconductors at low temperatures may be assisted by acoustic phonons in two ways: The phonons create mobile carriers through ionization of shallow bound states or provide the necessary energy differences for hopping processes. The techniques of acoustic-phonon spectroscopy with superconducting tunnel junctions, now well developed,[1,2] allow the investigation of these processes in the interesting frequency range. Thus a direct access is possible to topics such as the elementary processes in carrier recombination to shallow impurity states or the energetic and spatial density of states in the hopping situation. We report here results of the first spectral analysis of the phonon-ionization of D^- and A^+ centers in silicon with superconducting Al junctions as tunable phonon generators. The induced change in electrical conductivity is used as the detecting mechanism; we abbreviate this phonon-induced conductivity as PIC in the following.

Thin (30 nm total) Al junctions as phonon generators were evaporated on one side of the crystal samples which were about 3 mm thick. For the measurement of PIC two or four stripes were either alloyed or simply evaporated on the opposite face of the crystal. There is no difference in the spectral results though the contact resistance varies appreciably. For generating a sufficiently large number of carriers, necessary for the production of D^- or A^+ centers, the area between the stripes (distance 1 mm, length 5 mm) could be illuminated with visible light from the top of the cryostat through a fiber optic blocking room-temperature radiation (see inset of Fig. 1). The sample was enclosed in an aluminum can. It was also possible to illuminate the crystal with room-temperature radiation.

Depending on tunneling resistance the different aluminum junctions could be driven by modulated dc currents up to 30 mA corresponding to maximum bias voltages of about 1 meV to more than 20 meV. The modulation frequency was 140 Hz.

The change in conductivity was measured by a lock-in technique. A bias of up to 9 V was applied to the PIC contacts and the current change was measured by a load resistor (2 MΩ) with use of a PAR 124A lock-in amplifier with a PAR 117 preamplifier.

All silicon samples are bulk-doped floating-zone material obtained from Wacker-Chemitronic, Burghausen, West Germany. The crystal orientation is (110) or (112).

Figure 1 shows the measured signal at small intensities of light and for two concentrations of phosphorus in Si. The lock-in signal is plotted as a function of the phonon energy E, which is related to the junction bias U by $E = eU - 2\Delta_{Al}$, where $2\Delta_{Al}$ is the superconducting aluminum gap. At low phosphorus concentration a sharp signal rise appears at a threshold of 2.0 meV which shifts somewhat to higher energies and becomes less sharp at

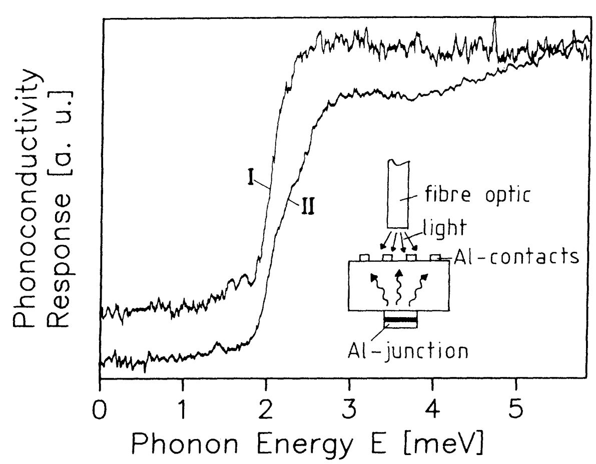

FIG. 1. PIC response signal for two different phosphorus-doped silicon samples at $T = 1.0$ K. (I) $[P] = 6 \times 10^{14}$ cm^{-3}, (II) $[P] = 6 \times 10^{15}$ cm^{-3}.

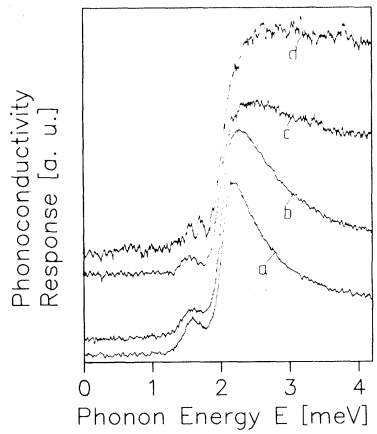

FIG. 2. PIC response signal for various illuminations, same sample as sample I of Fig. 1, and $T = 1.0$ K. Curve *a*, room-temperature radiation through a stainless-steel tube held at 300 K at the top of the cryostat; curve *b*, additional illumination by the fiber optic (room light); curve *c*, additional illumination by a bulb through the fiber optic; curve *d*, higher light intensity from the bulb, same curve as curve I of Fig. 1.

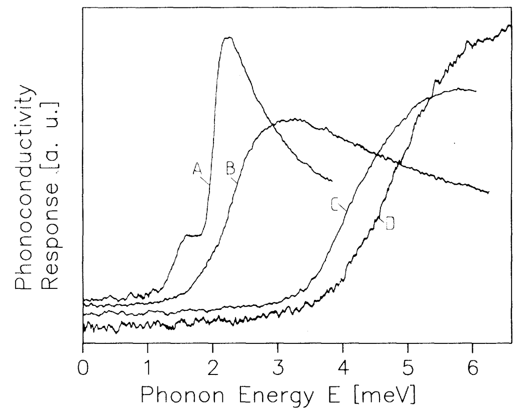

FIG. 3. PIC response signal for boron-doped silicon, all samples illuminated with the same light intensity, and $T = 1.0$ K. Curve *A*, $[B] = 5\times10^{13}$ cm^{-3}; curve *B*, $[B] = 9.5\times10^{14}$ cm^{-3}; curve *C*, $[B] = 5.4\times10^{15}$ cm^{-3}; curve *D*, $[B] = 9.0\times10^{15}$ cm^{-3}.

the higher concentration. This threshold is in good agreement with far-infrared (FIR) measurements[3-5] which indicate 2 meV for the binding energy of the isolated P^- center.

The dependence of the signal on phonon energy is shown in Fig. 2 for illumination with room-temperature radiation and small intensities of visible light. No change in conductivity could be detected below the threshold. Especially, no structure could be detected at half of the threshold energy corresponding to two-phonon processes.[6] The additional signal contribution at about 1.5 meV, which appears also in Fig. 3 (curve *A*), is due to the relaxation and recombination of tunnel-injected thermal quasiparticles in the aluminum junction.[1,2] At the smallest intensity the signal in Fig. 2 decreases faster above the threshold than expected from FIR results for this phosphorus concentration.[4] This is mainly because the spectral density of the phonons emitted from the Al junctions decreases with energy.[1,2] With increasing intensity the signal above the threshold begins to grow. At high light intensities (not shown in Fig. 2) we observe a bolometric detection below and a growing ramp beyond the signal threshold. This dependence on light intensity is not yet understood.

Figure 3 shows results for different boron concentrations. Curve *A* is almost identical to curve I in Fig. 2 in accordance with the fact that the binding energy of the corresponding neutral centers is the same. Also, the threshold shift with increasing concentration (curves *B*, *C*, and *D* in Fig. 3) is quite similar to corresponding curves in FIR measurements[7-9] for $Si{:}B^+$, indicating the formation of an A^+ band.

Measurements of D^- centers in Ge:Sb, which we have made, are also in good agreement with FIR data at 1.0 K.[10]

Although a detailed theory of the phonon coupling to these centers is not yet available, one important conclusion can be drawn already from these results: The phonon-ionization is mainly due to a one-phonon process even though the phonon wavelength at the threshold energy (10 to 20 nm for Si:B) is smaller than the supposed Bohr radius of these centers (~ 30 nm),[3,11] which should reduce the interaction strength. An estimate of the quantum efficiency of the process cannot yet be given since neither the physical time constants nor the number of centers generated could be determined.

We have also tried to phonon-ionize shallow neutral donors in epitaxial layers of InP and GaAs. Up to now we have no clear-cut indication for a threshold corresponding to the ionization energy in contrast to the conclusions of Crandall.[12] Instead, we find PIC with some structure over the whole energy range. These signals are possibly due to hopping processes because of the compensation ($\sim 5\%$) of the available epitaxial layers used for detection. This indicates that the new experimental method described in this Letter can also be a powerful tool to investigate hopping conductivity.

In this Letter we have shown for the first time by means of phonon spectroscopy that the phonon-ionization of D^- and A^+ centers in silicon is mainly a one-phonon process. The ionization energy of about 2.0 meV is in good agreement with the theory and with FIR measurements for Si:P$^-$. For Si:B$^+$ we obtain the same ionization energy for a concentration $[B] = 5 \times 10^{13}$ cm^{-3} and observe a shift of the energy threshold of more than a factor of 2 at higher concentrations. The described phonon-ionization mechanism, called phonon-induced conductivity, is an effective detector with a sharp threshold for high-frequency acoustic phonons.

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