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Dependence of the Phonoionization of A^+-States in Si on Uniaxial Pressure

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By the new technique of phonon induced conductance we have investigated the dependence on pressure of the phonoionization response of shallow A^+ - states in Si with superconducting Al-junctions as monochromatic phonon generators. In the case of B^+ and Al^+ we obtain a much more complicated behaviour than previously found for B^+ with FIR-photoconductivity which may be connected with differences in coupling for short wavelength phonons. In the case of In^+ on the other hand a shift to lower energies is observed for uniaxial pressure in [100]-direction whereas for pressure in [111]-direction only the signal intensity varies but not the position of the threshold.

It is well established from thresholds in FIR photoconductivity response that shallow impurities in semiconductors at low enough temperatures can bind a second carrier to form a metastable state analogous to the H^- -Ion. It has been shown recently [1] that phonon spectroscopy with superconducting Al-junctions gives the same threshold energies of phonoionization e.g. in the case of B^+ or P^- in Si, however, with much steeper and narrower signal forms. This is due to the fact that the wavelength of the interacting phonons is comparable to the extent of the A^+- state. Increasing phonon energy means shortening of the wavelength and thus a reduction of the interaction. Phonon spectroscopy turned out to be a rather sensitive and relatively simple means to determine binding energies of A^+-states. In the case of acceptors in Si it has been found by this technique [2], that there is a shallow-to-deep instability of the binding energies, with about 1.8 meV for B^+ , Al^+, and Ga^+ and 5.9 meV for In^+ . No indication for a split multiplet character from hole-hole-coupling has been found in these experiments as might be inferred from the interpretation of the luminescence multiplet of acceptor-bound excitons [3,4]. However, since the working temperature with superconducting Al-junctions, namely 1 K, is rather low it is only for favourable values of the splitting to be registered in such phonoionization experiments. In principle information on zerofield splitting δ might be expected from the nonlinear dependence of threshold energy on uniaxial pressure, since the levels split by strain ε as

$$E_\pm = \left[(D\varepsilon)^2+(\delta/2)^2\right]^{1/2} \pm \delta/2$$

if the formalism developped for neutral double acceptors [5] is applicable to A^+ - states.
Here D is the appropriate deformation potential constant of the A^+ - state expected to have a value between the values of the valence band and the neutral acceptor A^0 .

A somewhat different interpretation for large pressure has been given qualitatively in [6], where the shift of the threshold to smaller energies under uniaxial pressure has been measured with FIR-photoconductivity: beyond a critical value of pressure the threshold does not move any more since it is pinned to the heavy hole valence band together with the A^0 - binding energy. No analysis of the change of threshold in the low pressure regime has been given.

Here we present analogous phonoconductivity measurements for B^+ and also for the deeper acceptors Al^+ and In^+. Fig. 1 shows the complicated stress dependence for B^+ : Instead of a gradual decrease of the threshold energy as found with photoconductivity [6] there is first a flattening of the threshold (Fig. 1a) and then a sharp line emerging at lower energies (Fig.1b; the precursor peak is a well established feature of the Al-junction phonon spectrum at a distance of the superconductor gap in front of the main phonon line). This threshold then shifts and flattens towards higher values and finally disappears in a very small pressure range (Fig. 1c).

In Fig. 2 we have given the threshold values at half height (because they are easier to determine than the back extrapolation to the starting point). Taking only the values of the sharp line we can formally fit them to the above mentioned square root dependence, however, the values obtained (δ=12 meV, D=22 eV) are much too large to be reasonable.

A clue to the understanding may be found in first calculations of R. Haug and E. Sigmund, Univ. Stuttgart: To describe the phonon coupling they used the variational results of [7] for the s- and d-like parts of the acceptor ground state envelope function. Since their relative contribution to the lowest state varies with pressure the phonon coupling is determined to a varying degree by one or the other component. Because of the different Bohr-radii associated with these envelopes and since the ratio of phonon wavelength to the extent of the wavefunction is important for the coupling the steepness and position of threshold varies with pressure which has been shown by model calculations. Though this interpretation has to be verified by a more detailed theory including hole-hole-interaction it appears that these measurements demonstrate a rather direct example of probing extended wavefunctions by short wavelength phonons.

Our results for Al^+ are quite similar to these of B^+ again indicating that there is no large central cell effect in contrast to the neutral acceptors.

For In^+ , however, our results appear to be qualitatively different (Fig. 3): Quite similar to the FIR-photoconductivity results for B^+ [6] we find for [100]-pressure a gradual decrease of the threshold position remaining constant at the highest pressures. Again, formally we can fit this dependence with a δ of 4.5 meV and a D equal to the band value. Though the value of δ is not to far from values deduced from luminescence results [4], the D-value appears rather large. And also our result for [111]-pressure is contradictory: Here we get no shift but only flattening and then a steepening of the threshold. Again it appears that the signal is determined by details of the wavefunction and the phonon coupling.

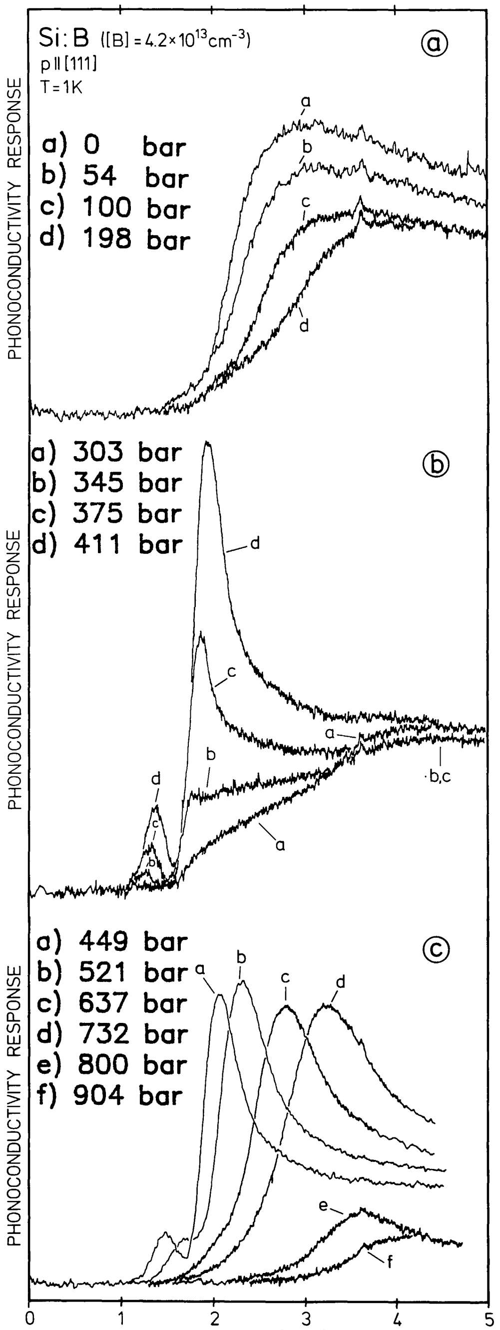

Fig.1. Pressure dependence of the phonoconductivity signal of Si:B$^+$ (the peak at 3.63 meV is due to phonon scattering by the resonance of interstitial oxygen well known from FIR measurements).

It is to be expected, therefore, that intrinsically new information on properties of shallow traps may be obtained from phonon spectroscopy.

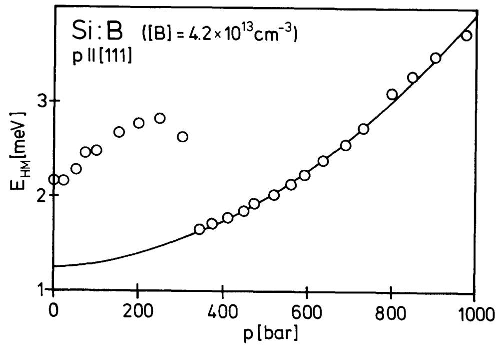

Fig.2. Pressure dependence of the threshold values at half height for Si:B$^+$

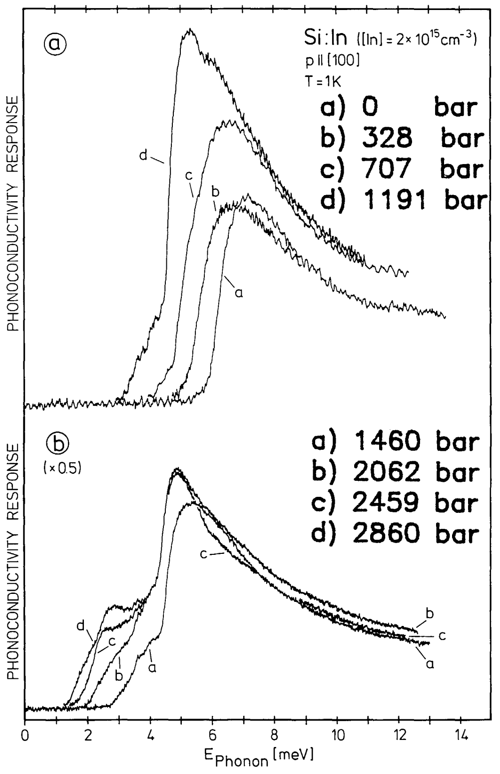

Fig.3. Pressure dependence of the phonoconductivity signal of Si:In$^+$

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