DEPOPULATION EFFECTS IN THE PHONOCONDUCTION RESPONSE OF A+- STATES IN SILICON AND GERMANIUM

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It is well known from FIR photoconductivity thresholds that shallow neutral impurities in semiconductors at low temperatures can bind an additional carrier to form an A^+– or D^-–state analogous to the H^-–ion. Phonoconductivity measurements with superconducting Al-tunnel junctions (STJ) as phonon sources have been shown to be a sensitive means to investigate these states [1, 2]. The same thresholds as with FIR photoconductivity were found, but the threshold is steeper and the signal shape beyond the threshold depends strongly on the intensity of illumination which is necessary to produce the charged states (Fig. 1a). Also the stress dependence of the A^+–conductivity threshold appears to be quite different for either FIR or phonon spectroscopy on the other hand [3, 4]. Haug et al [5] calculated the phonoconduction response for the cases of Si : B^+ and Si : In^+ and found good qualitative agreement with our experimental results. The point is that the short wavelength phonons are very sensitive to changes in the spatial extent of the A^+–wavefunction and that deviations from the parabolic form of the valence band near $k = 0$ are important. For these calculations it was assumed that the spectrum emitted by the STJ is monochromatic and that only a small part of the A^+–centers is depopulated by the phonons.

We show here that deviations from these assumptions are effective in the experiment and responsible in particular for the observed illumination dependence of the phonoconduction signal. The phonon spectrum of an Al – STJ at bias $V = eU > 2\Delta_{Al}$ consists of a continuum with a sharp threshold at $\Omega_m = V - 2\Delta_{Al}$ (Fig. 2a). In the differentiated spectrum (Fig. 2b) Ω_m becomes the most prominent bias-tunable feature, namely the quasimonochromatic line of phonon spectroscopy used for the approximate analysis of sharp phonon scattering resonances such as the O_I line of Fig. 1a (which shows inversion of the center due to strong scattering). Since the calculated A^+–response to phonons has a width of several meV (Fig. 1bα) the complete differentiated spectrum has to be taken into account for comparison with theory. The low-frequency part of the differentiated spectrum may contribute to the signal at some bias $V - 2\Delta_{Al}$ even if the quasimonochromatic phonons at

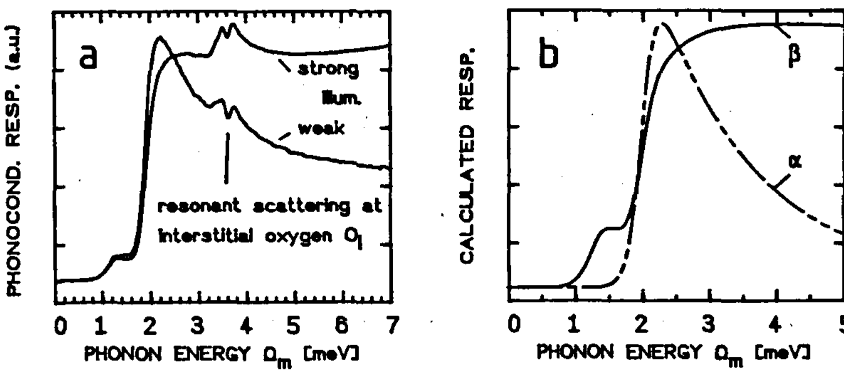

Figure 1: phonoconduction response a) of Ga^+ in Si at different illumination intensities b) calculated for α) monochromatic β) complete emission spectrum of the STJ for high illumination intensity (i.e. without depopulation effects)

$\Omega_m = V - 2\Delta_{Al}$ no more contribute to the signal because of the reduced interaction of high-frequency phonons with the A^+-state (Fig. 1bβ).

However, we have to keep in mind that with increasing $\Omega_m > E(A^+)$ there is an increasing amount of phonons with frequencies at $\Omega_m \gtrsim E(A^+)$ (Fig. 2a). This leads to a substantial depopulation of the A^+-centers if the illumination intensity (i.e. the A^+-concentration) is small and the A^+-phonon interaction is strong which is the case at the maximum of Fig. 1aβ. By such a reduction of the A^+-concentration the signal corresponding to strong illumination is more and more reduced beyond the threshold for weak illumination as shown in Fig. 1a.

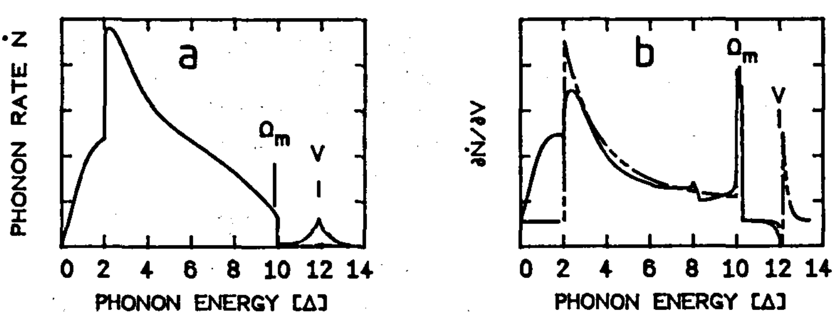

Figure 2: a) phonon emission spectrum [6] of an Al-STJ at bias $U = V/e > 2\Delta_{Al}$ ($2\Delta_{Al}$ = superconductor gap) b) differentiated spectrum (dashed line normal conductor approximation used for calculations)

We can roughly estimate the A^+-concentration from the measurement of the sample resistance to be at maximum $10^7 \ldots 10^9 \text{cm}^{-3}$. In the case of depopulation there is a change of the A^+-concentration by phonons in the same order of magnitude.

The depopulation effect can also be shown by irradiating phonons from a second STJ (Fig. 3). In this experiment, the first STJ is used for spectroscopy, while the second STJ is operated as a pump at constant bias. If the pump bias exceeds the A^+-threshold we get an increasing depopulation of A^+-centers with increasing pump bias. The effect of the pump STJ is comparable to that of the nonmonochromatic part of the emission spectrum of the spectroscopy STJ, namely a signal reduction increasing with pump bias. If we use a higher power phonon source as a pump (for example a NbAl-STJ), we can depopulate the A^+-states to such a degree that the conductivity threshold nearly disappears.

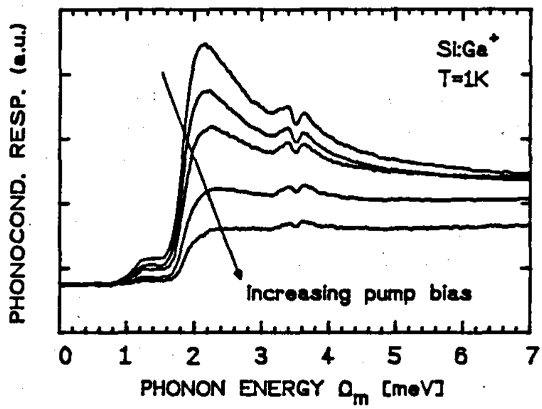

Figure 3: phonoconduction response of $Si:Ga^+$ at various biases of the second (pump) STJ

In principle such a combined irradiation could lead to non-thermal occupation by the pump STJ of possibly existing higher A^+-levels and a corresponding phonoconduction signal from the analyzing STJ. So far no population of excited bound states (as one might infer from the luminescence multiplet of acceptor bound excitons [7]) was found.

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