SHALLOW TRAPS CORRELATED WITH DEEP IMPURITIES IN SILICON AS OBTAINED BY PHONON INDUCED CONDUCTANCE

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At low temperatures shallow neutral donors and acceptors in silicon can bind an extra carrier to form the so-called D^- and A^+ centers. With the method of phonon-induced electrical conductivity (PIC) we find the same threshold energies for the detachment of these carriers associated with the shallow impurities P and B [1], as have been obtained previously by FIR measurements. This shows that the detachment is by a one-phonon process. We find that there is no central cell correction for the binding to the deeper acceptors Al and Ga, whereas for In^+ the binding energy is as large as 5.8 meV. We interprete this dependence on acceptor species as another example of the shallow-deep instability of the binding energy with the variation of the central cell potential [2].

In contrast to these hydrogen-like impurities the chalcogens Te, Se, and S in silicon are He-like deep double donors. In the effective mass approximation one would not expect that an extra electron can be trapped by these dopants, since the corresponding He^--state is not stable. However, the situation is complicated by the tendency of the chalcogens to form complexes. In this paper we show that we have found shallow electron traps associated with chalcogen doping in the case of Te and S.

The Te-doped samples consist of epitaxial layers (about 0.7 mm thick) grown from the vapour phase [3]) on a Si-substrate, which was about 0.7 mm thick (see inset in Fig. 1). During the growth not only single Te defects are formed but also Te complexes, which can be identified by IR-absorption [4].

Figure 1 shows the PIC signals of a Te-doped sample for different contact configurations. In curve A the PIC signal of only the n-doped

substrate is obtained. This signal shape is typical for P^- states of the residual doping [1]. The absorption structure at 3.6 meV might be due to interstitial oxygen. In curve B the conductivity change is measured through the sample. Thus the PIC signal of the epitaxial layer as well as of the substrate is obtained. In addition to curve A the signal increases at 4.5 meV and at 7.8 meV followed by structures up to 12 meV. These parts of the PIC signal are due to the Te-doping of the epitaxial layer. They are observed only when the two Al contacts are negatively biased. In this case electrons are extracted from the illuminated zone to the epitaxial layer and therefore the observed shallow Te states must be due to trapping of an electron and not a hole. Curve

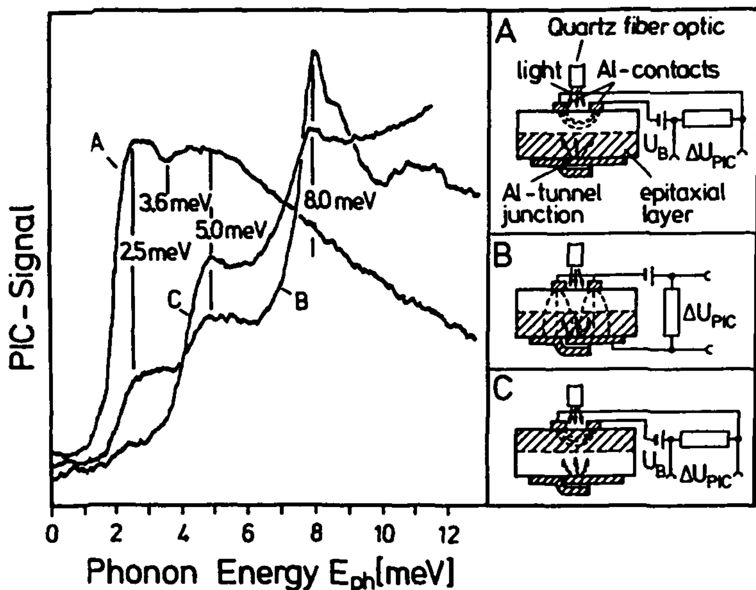

Fig. 1. PIC-signal of a sample with a Te-doped ($5x10^{16}$ cm^{-3}) epitaxial layer, T = 1.0 K. The inset shows the different contact configurations (the epitaxial layer is marked) of the measured PIC curves. The illumination of the sample with visible light is necessary to produce free electrons in the sample which can then be captured by neutral donors to form the shallow states

C results only from the epitaxial layer, no signal of the substrate is observed but the signal steps at 4.5 meV and 7.8 meV are still there.

The different heights of the PIC steps at 4.5 meV and 7.8 meV in curves B and C result from the different distances of the epitaxial layer to the phonon generator (Al tunnel junction). In B the conductivity change is probed directly under the generator whereas in C the phonons have to cross the substrate before they can ionise the shallow Te traps. Because of the strong energy dependence of the anharmonic phonon decay ($\propto E^5$) the phonon mean free path at 4.5 meV is larger by a factor of 15 than that at 7.8 meV leading to the observed dependence of the ratio of the step heights on probing distance and also to the fact that no structures at higher energies are observed in C. Neglecting the effect of elastic scattering one can estimate from the different step heights in curve B and C the constant A for the anharmonic decay ($\tau^{-1} = A\cdot\nu^5$) as 5.4×10^{-55} sec^{-4}, which gives a phonon mean free path of 0.4 mm at 8 meV), in reasonable agreement with calculations for the anharmonic decay in silicon [5]).

As shown in Fig. 2 the PIC-signals depend on light intensity i.e.

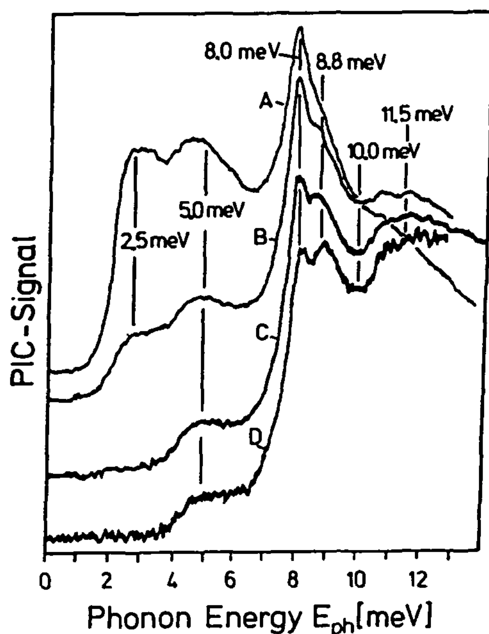

Fig. 2. Dependence of the PIC signal on the intensity of the sample illumination, T = 1.0 K, contact configuration B in Fig. 1, same sample. The light intensity is increasing from A to D

on the free carrier concentration produced in the sample. At small light intensities most carriers are trapped within the substrate and only a few reach the epitaxial layer. With increasing light intensity the high energy structures at 8.8 meV and 11.5 meV increase, because more carriers diffuse to the zone directly underneath the junction to be trapped there, increasing the signal due to the higher energy phonons with shorter mean free path. At the same time the low energy threshold due to the substrate disappears because the high carrier concentration shortens this part of the resistances in series.

The results reported so far were obtained with two samples containing a large variety of Te-associated complexes. These complexes can be dissolved by annealing and quench-cooling and formed again by slow cooling. Dissolving the complexes by a baking-quench-cooling cycle the signal completely disappears apart from the low energy threshold of the substrate. The relative concentrations of isolated, pair, and X_1-, X_2-, X_3-, X_4-, X_5-complexes were respectively 33, 1, 0.04, -, 0.14, 0.41, 1.33 in the first sample and 15.6, 1, 0.18, 0.05, 0.10, 0.18, 1.00 in the second sample. So, pairs and X_5 were the most concentrated complexes. To sort out the Te-complexes corresponding to the signal thresholds one might try appropriate annealing cycles to shift the relative concentrations.

Sulfur doping was obtained by diffusion. From IR-absorption [4]) it was found that the sample contains no single sulfur, but only pairs, X_1-, and X_3-complexes (relative concentrations 1, 0.82, 0.18). In this case we find small steps at 4.0 meV and 6.0 meV. Here it was not tried to produce predominant single sulfur by a temperature cycle.

Thus from our measurements so far it appears possible that He^--like traps may be associated with double donors formed by chalcogen complexes whereas with isolated Te donors we did not find such traps.

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