Capture processes at double donors in silicon

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The hole-capture processes at isolated double donors in chalcogen-doped silicon have been investigated. Different steady-state and transient-capacitance techniques were used. It is shown that the capture process at neutral centers is governed by an Auger-type capture process at a He-like center. The hole-capture cross sections for neutral centers are almost temperature independent and have values of about 10^{-16} cm^2. The processes for hole capture at singly ionized centers are best described as a multiphonon emission and/or a radiative process. At low temperatures the cross sections are about 10^{-24}–10^{-22} cm^2.

I. INTRODUCTION

Good insight into the recombination processes of free charge carriers has long been considered important in both applied and basic research. The free-carrier lifetime controls the properties of most semiconductor devices, and recombination processes are frequently used to study important parameters of semiconducting materials. Recombination is often discussed in terms of radiation, cascade, multiphonon-emission, or Auger processes. The particles involved are photons, phonons, or other charge carriers.[1] In moderately doped semiconductors with indirect band gaps the lifetime of free charge carriers is generally determined by recombination via energy levels in the forbidden energy gap. These energy levels may be due to either shallow or deep centers originating from both intrinsic and extrinsic defects. The defects known as EL2 in GaAs and gold in silicon are typical examples of lifetime-controlling defects in semiconductors.

The capture of electrons into the singly charged isolated sulfur and selenium centers in silicon has recently been studied in some detail.[2,3] It has been shown that electron capture into these centers is probably governed by a cascade or at least a two-stage capture process via excited states. The capture cross sections describing the electron capture into the doubly ionized sulfur and selenium centers in silicon have been found to be very large and hitherto no absolute values of these cross sections have been reported.

The purpose of this paper is to report on the capture of holes at the isolated sulfur, selenium, and tellurium centers in silicon. Reviews of these centers are given in Refs. 4–6. In this paper it is shown unambiguously that these centers are indeed double donors. The temperature dependence of the hole-capture cross section has been studied for both neutral and singly positively charged centers. However, a major part of our study has been devoted to the hole capture of neutral centers showing that this process is governed by an Auger-type capture process.

II. HOLE CAPTURE AT NEUTRAL AND REPULSIVE CENTERS

A double donor has three charge states: a neutral, a singly positively charged, and a doubly positively charged state. The three charge states will be denoted D^0, D^+, and D^{2+}, respectively. In the neutral state two electrons are bound to the double donor. There are two ways of changing the charge state of the center from a neutral to a singly charged state: either by exciting an electron from the center into the conduction band or by capturing a hole from the valence band as described by the following equations:

$$D^0 \rightarrow D^+ + e \quad \text{for electron emission}, \tag{1}$$

$$D^0 + h \rightarrow D^+ \quad \text{for hole capture}. \tag{2}$$

There is, however, a fundamental difference between these two processes. In the first case, electron emission, the center absorbs energy, whereas in the second case energy is released. The released energy must be carried away and may trigger other processes. If the hole capture is radiative and reabsorption of the emission is not important, the capture process, as described in Eq. (2), will result in a singly positively charged center. If, however, the hole capture is nonradiative and the released energy is carried away by another particle or particles a different final charge state may result. For example, the neutral chalcogen centers are located in the upper half of the band gap [Fig. 1(a)] and enough energy is released during the hole-capture process to excite the second electron of the double donors into the conduction band. The equation describing such a process is

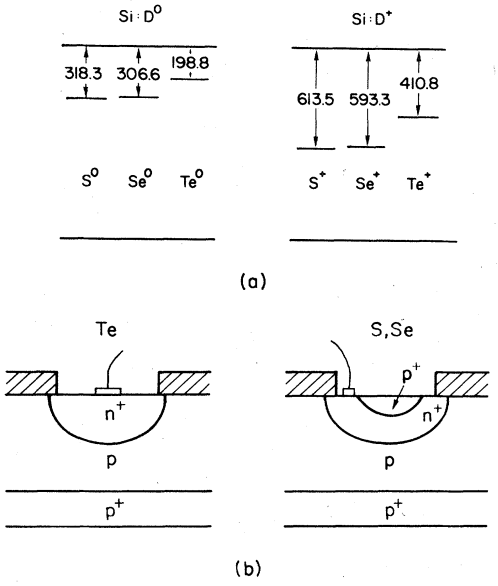

FIG. 1. (a) Optical binding energies for isolated D^0 and D^+ centers in chalcogen-doped Si (from Refs. 4 and 6). (b) n^+p and p^+n^+p sample structures used in this work.

$$D^0+h\rightarrow D^{2+}+e\ , \tag{3}$$

and the process is known as an Auger-type capture process for a He-like center. The final charge state is, therefore, in this case, a doubly positively charged center.

This type of Auger capture has been suggested previously as a possible mechanism for the capture of free charge carriers into deep centers, but to the best of our knowledge it has never been studied experimentally. Theoretical considerations[7–10] show that the Auger-type capture process should result in weakly-temperature-dependent capture cross sections in the range 10^{-20}–10^{-14} cm^2, in agreement with our results.

The D^+ centers are singly positively charged and therefore repulsive to holes. Hole capture at these centers is therefore best described by different types of processes such as radiative capture processes and/or multiphonon-emission (MPE) processes. Our data indicate that different hole-capture processes may occur at singly charged sulfur, selenium, and tellurium donor centers in silicon.

III. EXPERIMENTAL DETAILS

The samples used in this paper were either n^+p diodes or n^+p diodes in p^+n^+p transistor structures employing a 1.5×10^{15}-cm^{-3} boron-doped epitaxial layer as the p region [Fig. 1(b)]. The n^+p and p^+n^+p structures were doped with chalcogens by ion implantation as the dopant source and, as in the case of Se, solid-state diffusion. In all cases the implantation depth was less than 2000 Å, i.e., much smaller than the depth of the n^+ region. The n^+p structures were used for diffused Se and implanted Te samples. In the case of Te the n^+ diffusion was done after in-diffusion of the implanted Te due to the high temperature needed for the latter process.

Varying implantation procedures were employed for different chalcogens. In the case of sulfur, a dose of 5×10^{14} cm^{-2} at 60 keV was used for implantation of a p^+n^+p transistor structure. After deposition of a 4000-Å-thick SiO_2 layer on top of the sample in a chemical-vapor-deposition (CVD) reactor at 420 °C, the diode was diffused in an open-tube furnace for 1 h at 1000 °C in a nitrogen atmosphere. Contact holes were then opened in the SiO_2 layer by means of a photolithographic process, and an aluminum layer was sputtered onto the surface, forming an Ohmic contact. The electrically active sulfur concentration (D^0 and D^+) was typically 4×10^{12} cm^{-3}, which was about 0.4% of the shallow-level concentration as deduced from deep-level transient-spectroscopy (DLTS) measurements. The net shallow-level concentration in the p region was 1×10^{15} cm^{-3}.

Selenium doping was performed at a dose of 10^{14} cm^{-2} at 100 keV. After diffusion in an oxygen atmosphere for 1 h at 900 °C, a selenium (Se^0 and Se^+) concentration of about 7% (5×10^{13} cm^{-3}) of the shallow-level concentration in the p region was generally detected. The net shallow-level concentration was found to be 7×10^{14} cm^{-3}. Se-doped samples were also made using a solid-state diffusion procedure. A small amount of Se together with some n^+p diodes and Si powder were put in a quartz ampoule. After evacuation, the sealed ampoule was put into an open furnace for 1 h at 930 °C. The shallow-level concentration was about the same in both implanted and diffused samples. The Se^0 and Se^+ concentration was about 9% (6×10^{13} cm^{-3}) of the shallow-level concentration in the p region.

Tellurium doping was achieved by ion implantation into a p-type epitaxial layer using a dose of 10^{13} cm^{-2} at 100 keV. The samples were then diffused in an open furnace at 1250 °C for 15 min in an oxygen atmosphere. In order to avoid overly thick oxide layers the diffusion continued for 45 min in a nitrogen atmosphere. The n^+p junction, 1.5 μm deep, was formed by phosphorous deposition at 920 °C for 20 min and diffusion in an oxygen atmosphere at 1000 °C for 30 min. The Te^0 and Te^+ concentration obtained using this procedure was typically 9% (6×10^{13} cm^{-3}) of the shallow-level concentration. The net shallow-level concentration in the p region was 7×10^{14} cm^{-3}.

Junction-space-charge techniques are particularly suitable for investigations such as the ones described in this paper since they allow for a distinction between minority- and majority-charge-carrier—transfer processes. Various forms of junction-space-charge techniques were therefore employed in our investigations, including both transient and steady-state methods.[11] Emission rates were measured using deep-level transient spectroscopy[12] and single-shot capacitance techniques, while capture rates were studied using both DLTS techniques and pulse-train methods.[3] The free-hole concentration was, in all cases, determined from C^{-2}-V plots.

IV. EXPERIMENTAL RESULTS

To make sure that the chalcogen-related centers studied in our ion-implanted samples are indeed the same centers

as investigated previously in diffused samples, the thermal emission rate of electrons was measured for both the D^0 and D^+ centers in our sulfur-, selenium-, and tellurium-doped samples. Comparing our results (Fig. 2) with those previously published[2,3,13] on chalcogen-doped silicon, it is quite evident that the same centers are formed in ion-implanted samples as in diffused samples.

The capture rates for holes were measured in n^+p diodes by first occupying the D^0 and D^+ centers with electrons using a minority-carrier—filling pulse and then monitoring the decrease in the capacitance due to a majority-carrier pulse train of constant pulse length. The measurements were first performed on the D^+ centers after thermal excitation of the first electron of the D^0 centers. The hole-capture cross section σ_p was then calculated from the hole-capture rate $\sigma_p v_{\rm th} p$; where $v_{\rm th}$ is the thermal velocity and p is the hole concentration. $v_{\rm th}$ is defined by

$$v_{\rm th}=(3k_BT/m_p^*)^{1/2}\ ,$$

where k_B is the Boltzmann constant, T is the temperature, and $m_p^*=0.70m_e$ is the effective mass of the holes. The hole-capture cross sections calculated from the measured capture rates are presented in Fig. 3. At low temperatures the cross sections for the capture of holes into the singly positively charged chalcogen centers are of the order of 10^{-24}—10^{-22} cm^2. The largest cross section was found for the S^+ center and the smallest value was measured for the Te^+ center. Whereas the cross section for the S^+ center showed a pronounced temperature dependence, the hole capture into the Se^+ and Te^+ centers was almost independent of temperature in the temperature region studied. In order to increase the temperature region for the sulfur-doped samples, similar measurements were performed using DLTS.

Investigations performed on neutral chalcogen centers gave values for the hole-capture cross sections in the region 10^{-17}—10^{-16} cm^2 for all three chalcogens (Fig. 4). The largest capture cross section was again obtained for the sulfur center, while the smallest cross section was measured for the tellurium center. In all three cases only a weak temperature dependence was observed. Since the capture cross sections of holes for the D^+ centers were at least 3 orders of magnitude smaller than those for the D^0 centers, the hole capture into the D^0 centers could readily be measured without any disturbance from the D^+ centers. Owing to the small S concentration in the n^+p diodes, it was not possible to measure σ_{pD^0} using the pulse-train method.

The pulse-train method gave, in all cases, a single-exponential dependence of the diode capacitance on the number of pulses. To demonstrate this, the time dependence of the capacitance due to the capture of holes into the Se^0 and Se^+ centers is shown in Fig. 5 for a measure-

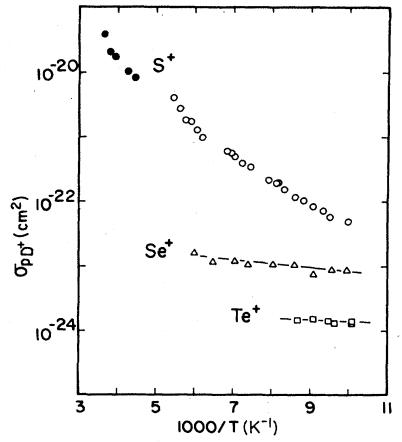

FIG. 3. Hole-capture cross sections for D^+ centers deduced from pulse-train and DLTS (solid circles) measurements.

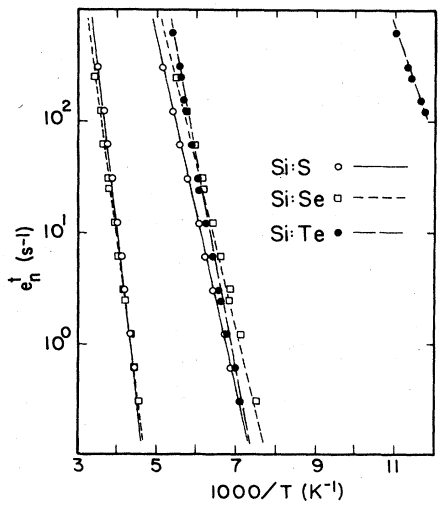

FIG. 2. Comparison of thermal emission rates of electrons obtained in implanted samples (this work) and diffused samples (from Refs. 2, 3, and 13) (straight lines). The straight lines for neutral Se and Te have been extrapolated.

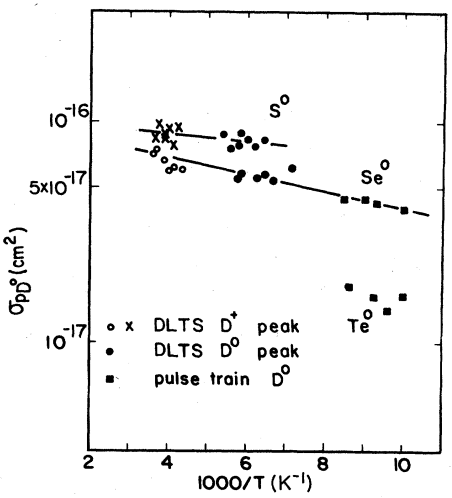

FIG. 4. Hole-capture cross sections for D^0 centers. Three different measurement techniques have been used: pulse train, DLTS on the D^0 peak, and DLTS on the D^+ peak. See text for details.

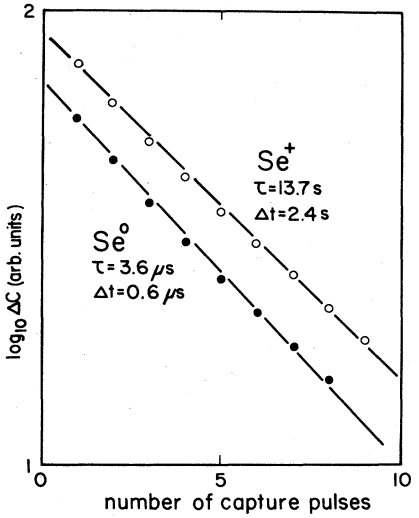

FIG. 5. Transients obtained from the pulse-train technique for the Se^0 and Se^+ centers at about 120 K. The transients are single exponential and the time constants differ by about 7 orders of magnitude. Δt is the constant majority-carrier pulse length.

ment performed at about 120 K. In both cases a single time constant was found. In order to increase the temperature range of our study the pulse-train method was followed up by DLTS measurements.

V. AUGER-TYPE CAPTURE PROCESSES

To demonstrate the different types of capture processes for holes at the D^0 and D^+ centers, we will now describe the DLTS measurements in more detail using selenium-doped n^+p diodes as an example. The capture of holes at Se^0 and Se^+ centers was studied by first applying a minority-carrier pulse to establish a certain electron occupancy of the centers, followed by a majority-carrier pulse. The length of the majority-carrier pulse was increased in subsequent DLTS runs (Fig. 6). For a majority pulse length of 2 ms, the electron occupancy of the Se^0 center was almost negligible, while the occupancy of the Se^+ center was about 50%. Plotting the logarithm of the height of the two DLTS peaks obtained for a particular rate window as a function of the majority-carrier pulse length gives similar time constants for both the Se^0 and Se^+ peaks (Fig. 7). Furthermore, these time constants were very close to the time constant obtained for Se^0 using the pulse-train method (Fig. 5), whereas the time constants obtained for the Se^+ center shown in Figs. 5 and 7 differ by about 7 orders of magnitude. It should be noted that the Se^0 and Se^+ peaks appear at different temperatures. Owing to experimental difficulties it was not possible to decrease the Se^+ peak (Fig. 6) further by increasing the length of the majority pulse. Not even the largest majority pulse length (2.5s) changed the Se^+ peak height. Since the chalcogens form double donors, two DLTS peaks of similar heights are expected if the injection pulses completely fill the D^0 centers with electrons. However, owing to similar capture rates for electrons and holes for the D^0 centers, the highest concentration of D^0

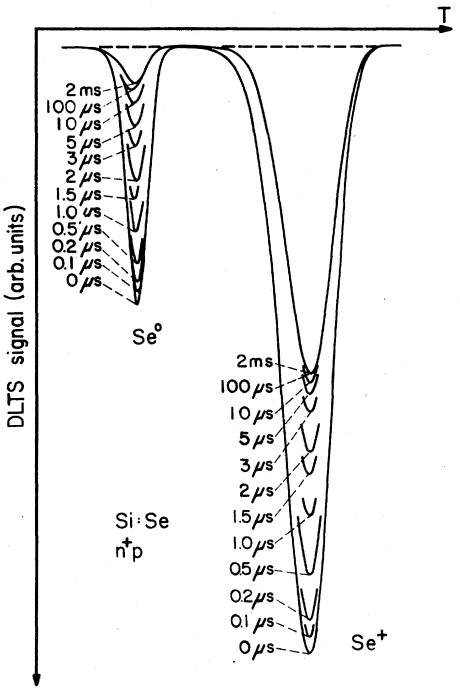

FIG. 6. Hole-capture measurements on a Se-doped n^+p diode showing the decrease in the DLTS peak heights with increasing majority-carrier pulse length. Note that there is no significant decrease in the Se^+ peak when the pulse length is increased from 100 μs to 2 ms.

centers which can be obtained in an n^+p diode after applying a long minority pulse is about one-half the concentration of the D^+ centers. It should be noted that electron capture into the D^{2+} centers is much faster than it is into the D^+ centers, and, hence, D^+ centers could be generated with short minority-charge-carrier pulses without generating any D^0 centers at all.

Very similar results were obtained in sulfur-doped sam-

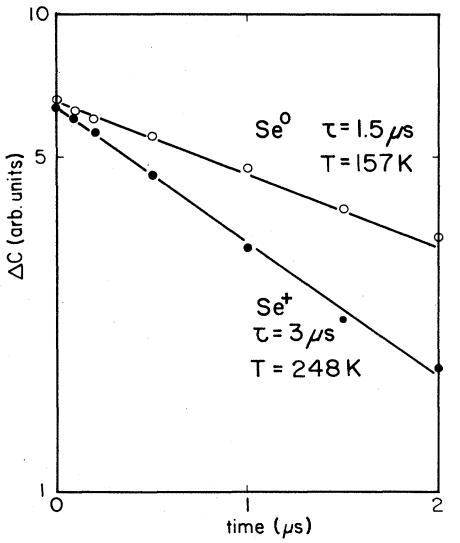

FIG. 7. Plot of the Se^0 and Se^+ DLTS peak heights (Fig. 6) vs the majority-carrier pulse length Δt.

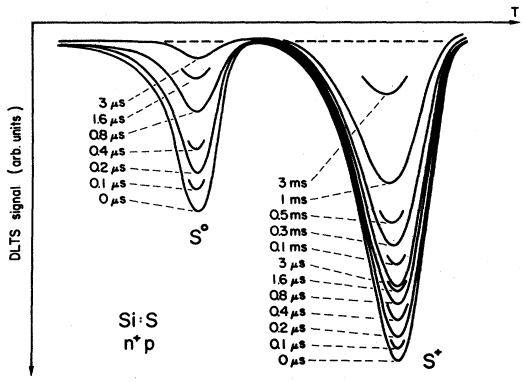

FIG. 8. Hole-capture measurement on a S-doped n^+p diode. Note the "break point" for the S^+ peak for a 3-μs majority-carrier pulse length.

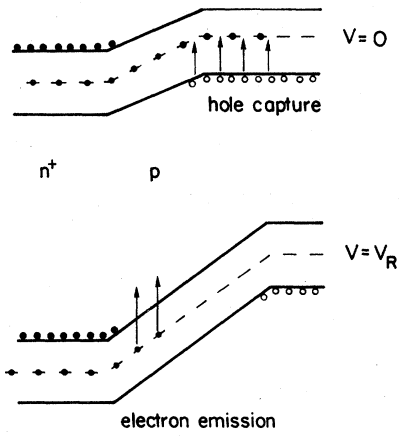

FIG. 10. Simplified figure showing the origin of the residual D^0 DLTS peak (Figs. 6 and 8) still seen for a very long majority-carrier pulse length.

ples, as can be seen by the data presented in Fig. 8 showing the DLTS spectrum of a Si:S sample. The spectrum is almost identical to the Se spectrum, except that the S^+ peak becomes very small for long majority pulses. Whereas the decrease in the S^0 peak is described by one time constant [squares in Fig. 9(b)], the data for the S^+ peak resulted in two time constants [Fig. 9(a)]. The first time constant of Fig. 9(a) was obtained by subtracting the slower part of the decay from the rest of the curve [Fig. 9(b)]. The time constant of the transient obtained [solid circles in Fig. 9(b)] was very close to the time constant of the transient obtained for the S^0 peak [squares in Fig. 9(b)], and the corresponding capture cross sections were almost identical, considering the different temperatures at which the peaks occurred. The second time constant derived from the data presented in Fig. 9(a) was about 3 orders of magnitude larger than the fast time constant and similar to the time constant obtained for S^+ by the pulse-train method.

It should be noted that the D^0 centers were obtained by filling the donors with electrons during the minority-carrier pulse. The capture of holes was then initiated by a majority-carrier pulse. Since minority-carrier injection had to be avoided during the application of the majority-carrier pulse it was not possible to increase the concentration of holes during the application of the majority-carrier pulse in that region of the space-charge region which was closest to the n region (Fig. 10). Since the D^0 centers in this region could not be emptied due to the capture of holes, they always contributed to the DLTS signal irrespective of the length of the majority-carrier pulse. This is the reason why a small D^0 signal in the DLTS spectrum of Figs. 6 and 8 was observed even for very large majority-carrier pulse lengths.

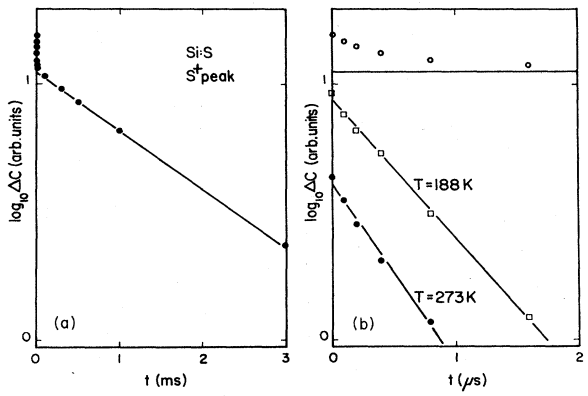

FIG. 9. (a) Biexponential behavior of the S^+ peak (Fig. 8) due to the hole capture at the neutral sulfur center at the temperature given by the S^+ peak (see text). (b) Comparison between the transient of S^0 (squares) and the first part of S^+ (solid circles).

The results presented so far are best understood if it is assumed that the hole capture at a D^0 center results in an annihilation of the associated D^+ center, i.e., that the capture of a hole into a D^0 center simultaneously causes the excitation of the second electron into the conduction band, transforming a D^0 center directly into a D^{2+} center [Eq. (3)]. This type of hole capture is considered an Auger-type hole-capture process,[7–10] which is possible if the energy released by the hole-capture process exceeds the energy needed to excite the second electron into the conduction band. This Auger-type process does *not* depend on the free-carrier concentration.

In order to obtain further evidence for the Auger-type hole-capture process, additional experiments were performed. The total capacitance C of the diode was studied as a function of temperature T (Fig. 11). The diode was first cooled from room temperature to 77 K under constant reverse bias. After applying a minority-carrier pulse (min. pulse; see Fig. 11) which generated a certain number of D^0 and D^+ centers, the diode was warmed up to room temperature in the first experiment. At temperatures T_1 and T_2 the C-T curve (1) showed two steps owing to the thermal ionization of the D^0 and D^+ centers, respectively. In the second experiment (curve 2) the diode was cooled again to 77 K, but this time a majority-carrier pulse (maj. pulse) was applied at a temperature T_3 directly after the application of the minority-carrier pulse. The pulse length Δt of the majority-carrier pulse was chosen to

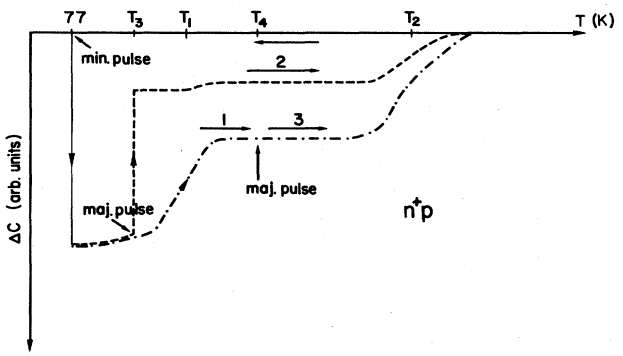

FIG. 11. Junction capacitance vs temperature (see text).

be about ten time constants of the hole capture at D^0 centers in order to ensure that any electron occupancy of D^0 centers could be neglected after the application of the majority-carrier pulse. It should be noted that, owing to the results presented in Figs. 3 and 4, such a majority-carrier pulse is not expected to change the electron occupancy of the D^+ centers. When the temperature was raised, the C-T curve showed only one step at T_2 owing to the ionization of those D^+ centers which were generated by the minority-carrier pulse in excess of the D^0 centers. Some D^0 centers close to the n region (Fig. 10) remain occupied by electrons after the majority-carrier pulse and give rise to a small step in the C-T curve (Fig. 11, curve 2). The experiment clearly showed that owing to the majority-carrier pulse the diode capacitance decreased by almost twice as much as in the first experiment due to the thermal ionization of the D^0 centers.

In order to show that this decrease in capacitance was not caused by hole captures into D^+ centers, a third experiment was performed (curve 3). After cooling the diode to 77 K and applying a minority-carrier pulse, the majority-carrier pulse was first applied at temperature T_4 after the D^0 centers were already completely ionized. No change in the C-T curve was observed compared with the first experiment, showing that the majority-carrier pulse length Δt was sufficiently short to not significantly change the occupancy of the D^+ centers. This sequence of experiments clearly demonstrates the Auger-type capture process, since in the absence of the Auger process the capacitance is expected to decrease due to the majority-carrier pulse in the second experiment by the same amount as in the first experiment. Furthermore, the experiments clearly show that the centers studied are double donors, i.e., that the D^0, D^+, and D^{2+} centers are three different charge states of the same defect.

These experiments could be performed in both sulfur- and selenium-doped silicon diodes, but not in tellurium-doped samples because of the high electron-emission rate of the Te^0 centers at 77 K and the freeze-out of the shallow-acceptor levels in the p region below 77 K.

Since our experiments unambiguously demonstrated that the D^0, D^+, and D^{2+} centers are different charge states of the same defect it should be possible to obtain information on one of these centers by measuring certain properties of the other center. It has already been shown that hole capture into D^0 centers resulted in the annihila-

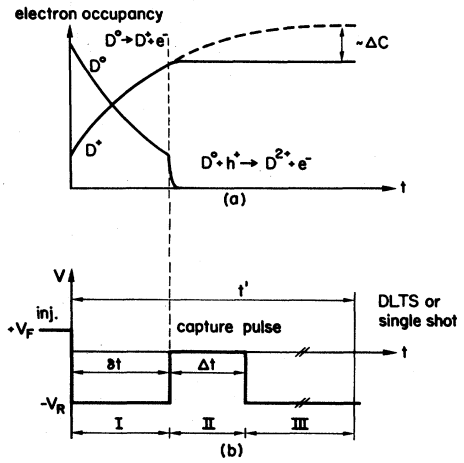

FIG. 12. Time dependence of the occupancies of the D^0 and D^+ centers owing to the pulse sequence shown in (b). Because of different final charge states obtained by electron emission and Auger hole capture at D^0 different occupancies of D^+ are obtained for varying time delays δt.

tion of a similar number of D^+ centers. This gives us the possibility of measuring the hole-capture process for D^0 by studying the D^+ DLTS peak. Furthermore, the decrease in the D^+ signal of the DLTS measurements due to the majority-carrier pulse, i.e., hole capture into D^0, can therefore be considered as a measure of the concentration of D^0 centers at this particular temperature and time, δt. After applying the minority-carrier pulse the occupancy of D^0 centers at a particular temperature is, however, time dependent owing to the thermal ionization of D^0 centers. The time dependence of the occupancy of D^0 centers at a particular temperature can therefore be measured in different DLTS experiments by using constant rate windows but varying the time delay, δt, between the minority-carrier pulse and the majority-carrier pulse of constant length Δt (Fig. 12). The pulse length (Δt) was chosen to be sufficiently short to ensure that no holes were captured into the D^+ center during the majority-carrier pulse. Hence, plotting the decrease in the DLTS signal of the D^+ peak (Fig. 13) logarithmically against the time delay δt should result in a straight line (Fig. 14),

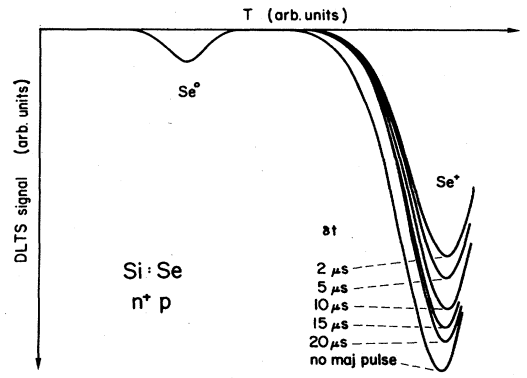

FIG. 13. DLTS spectra obtained for different time delays δt.

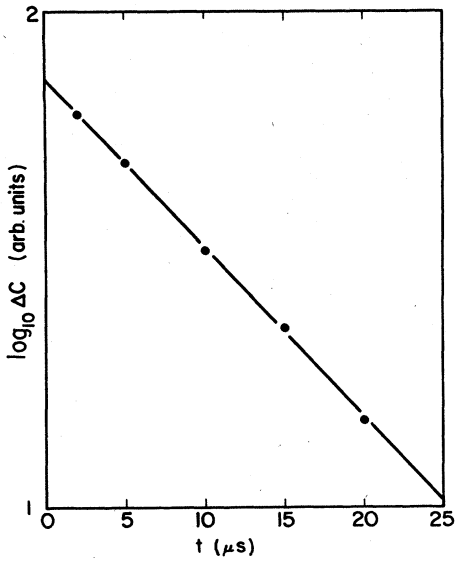

FIG. 14. Plot of D^+ peak in Fig. 13 vs time delay δt.

the slope of which corresponds to the thermal emission rate for electrons of the D^0 center at the temperature given by the DLTS peak of the D^+ signal. By varying the rate windows and, hence, shifting the peak temperature of the D^+ signal, the thermal emission rate for electrons, e_n^t, of the D^0 centers, can be measured as a function of temperature and can be compared with previous measurements (Fig. 2) of $e_n^t(D^0)$ obtained with conventional techniques. Similar measurements were performed using a single-shot capacitance method. The thermal emission rates of electrons obtained for the S^0, Se^0, and Te^0 centers, by studying the D^+ peaks at different temperatures, are plotted in Fig. 15, together with our data previously presented in Fig. 2. The results clearly show that the indirect measurements give the same activation energies as

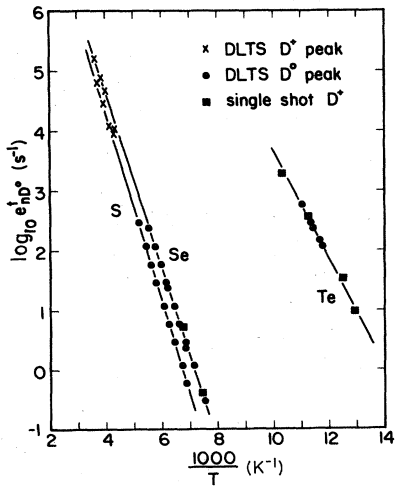

FIG. 15. Comparison of thermal emission data obtained with conventional methods (solid circles) and with the method explained in Fig. 12 (crosses and squares).

already obtained by more conventional techniques. The experiments once more confirm the different charge states of a double donor and the existence of the Auger-type hole-capture process. Without any of these properties, the above results could not have been obtained.

VI. DISCUSSION

Auger capture processes at He-like centers have been discussed previously in the literature[7–10] and are expected to be the dominant capture process for such types of centers. However, to the best of our knowledge only very few cases are described in the literature in which this type of capture process has been studied experimentally. Nonradiative capture processes are generally explained by either multiphonon emission or cascade processes. In both cases the capture cross section shows a typical temperature dependence. The capture cross sections obtained for MPE processes are often rather small and increase with temperature, whereas those observed for cascade processes can be large and decrease with temperature. The results presented in this paper show that Auger-type capture processes may, in principle, result in rather large or at least—as in our case—moderately large capture cross sections which exhibit a weak temperature dependence. Similar chemical trends are observed for both σ_{pD^0} and σ_{pD^+}, implying that the sulfur center has the largest capture cross section for holes and the tellurium center the smallest. This result is in agreement with previous theoretical considerations[7–10] of Auger-type capture processes, showing that σ_{pD^0} should increase with increasing binding energy of the centers if effective-mass-like wave functions are used. It has also been predicted that the capture cross section should only be weakly temperature dependent, in agreement with the results obtained for σ_{pD^0} and presented in Fig. 4.

Since double donors (and acceptors) exist not only in silicon but probably also in other materials such as III-V compounds, it may be possible that such centers contribute to nonradiative recombination processes to a much greater extent than hitherto appreciated.

In contrast to σ_{pS^0}, the hole-capture cross section of S^+ showed a rather pronounced temperature dependence and increased with increasing temperature. This may suggest that the hole-capture process at S^+ centers is governed by a kind of MPE process. MPE-governed capture processes have two temperature limits. At high temperatures the capture cross section approaches an exponential behavior, whereas at low temperatures the cross section is almost temperature independent. A theoretical model has been developed previously,[14] describing the temperature dependence of MPE-governed capture processes. The model includes two adjusting parameters, the capture barrier height and the dominant phonon energy. Fitting the experimental results obtained for σ_{pS^+} to this model (Fig. 16), a barrier height of about 147 meV and a phonon energy of 18.4 meV are deduced. This implies a large Franck-Condon shift of about 0.2 eV. Considering that the model is very sensitive to the value of the fitting parameters and that previous optical spectra[15] did not show

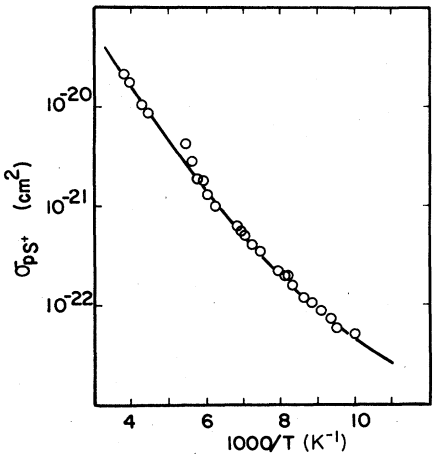

FIG. 16. Hole-capture cross section of S^+ (circles) fitted to the MPE model of Ref. 11 (solid line).

any indication of such a large Franck-Condon shift, further work is needed for better insight into the hole-capture processes of charged sulfur centers. Fitting our σ_{pSe^+} and σ_{pTe^+} data to the same model required a phonon energy of about 60 meV.

It is worth mentioning that the low-temperature values of all σ_{pD^+} cross sections are of the same order of magnitude as the radiative capture cross sections $\sigma^r_{pD^+}$ obtained from the photoionization cross section $\sigma^0_{pD^+}$ using the principle of detailed balance.[16] $\sigma^r_{pD^+}$ is expected to be proportional to $\sigma^0_{pD^+}$ when neglecting the small difference in the binding energies of S^+ and Se^+. It is interesting to note that previously published values of $\sigma^0_{pD^+}$ (Ref. 15) for S and Se indeed show a similar trend as the corresponding hole-capture cross sections. We have no further information on whether the hole-capture process at neutral chalcogen centers is indeed radiative. The properties of chalcogen-doped silicon devices will be discussed in a forthcoming paper.[17]

VII. SUMMARY

We have presented experimental evidence for Auger-type capture processes at He-like defects in semiconductors. The temperature dependence and the absolute values of the Auger capture cross sections are in agreement with theoretical estimates. Our results clearly show that the D^0 and D^+ centers are neutral and singly positively charged versions of a double donor. The hole capture at S^+ has been discussed in terms of MPE processes and a combination of MPE and radiative capture processes. The results obtained for the hole-capture process at Se^+ and Te^+ centers are (in the temperature region studied) close to values expected for radiative capture process.

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