Deep level transient spectroscopy investigation of a deep trap in float-zone Si

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By means of deep-level transient spectroscopy we have investigated defect states in float-zone, boron-doped Si material subjected to electron irradiation. Attention was mainly focused on the $Ev+0.34$ eV peak, the emergence of which in the spectra shows a delay with temperature in relation to the beginning of the decay of the $Ev+0.28$ eV peak of the carbon interstitial defect. In addition, the concentration of the $Ev+0.34$ eV level was found to increase with the boron content of the Si material. Our results point to a carbon-related, boron-dependent structure although the role of boron is not clear from the present data.

Carbon-related defects in silicon have been the subject of a large number of works. In particular, a level positioned at about 0.34 eV [herein to be referred as $H(0.34)$] above the top of the valence band in float-zone material has received much attention in recent years. However, the results of various researchers are in some respects controversial. An early assignment has correlated the $H(0.34)$ state with the C_i-C_s pair.[1] Recently, Song *et al.*[2] have raised serious doubts about this correlation. In a *p*-type material, it was proposed that the Ci-Cs pair is a bistable trap possessing two levels $H(0.05)$ and $H(0.09)$, each of them corresponding to the two configurations of the defect. It is worth noting that in some experiments, signals from the $H(0.34)$ defect were not observed,[3] although the level has also been reported in proton[4] irradiated Si.

Aluminum-silicon Schottky diodes with boron dopant concentrations in the range of $(0.8–9)\times10^{15}$ cm^{-3} were irradiated with 1.5 MeV electrons with a dose of 1.7×10^{16} e^-/cm^2. The irradiations were performed at 80 K (*in situ*) and at room temperature. The deep level trap spectra (DLTS) were recorded between 80 and 300 K. The trap energy level positions were determined from Arrhenius plots (ln en/T^2 vs $1/T$) and the capture cross sections were measured by applying the pulse width-variation method.[5]

Figure 1 depicts the DLTS spectra as received at the indicated annealing temperatures. From previous reports[6] peaks $H(0.19)$ and $H(0.28)$ arise from V_2 and C_i, respectively, whereas the two levels $H(0.32)$ and $H(0.37)$ have been associated with the one configuration of the B*s*-V pair. $H(0.34)$ peak is the main concern of this investigation. The findings of this work are succinctly summarized and discussed below.

(i) Delayed growth of H(0.34). A careful study of the spectra of Fig. 1 reveals that the emergence of $H(0.34)$ is not simultaneous with the onset of the migration of the C*i*'s, as indicated by the decay of the $H(0.28)$ peak. Thus a small, nevertheless characteristic, delay is observed between the beginning of the decay of the $H(0.28)$ peak and the appearance in the spectra of the $H(0.34)$ peak. In a reaction process one could envisage three stages: migration, quasichemical, and accommodation. In the second stage the defect partners attach each other to a more or less unstable configuration prior to the final arrangement of the defect when the stable configuration is established. Otherwise, one could think of an energy barrier that separates the second and third stage preventing the automatic formation of the defect complex. The probability of penetration or overcoming such a barrier depends among other factors on the charge state of the participants and the temperature. The higher the dynamical barrier the larger the necessary increase in temperature for the final structure to be achieved. This appears in the spectra as a delay with temperature between the first stage [migration of C*i*'s—decay of $H(0.28)$ peak] and the third stage [formation of the final defect structure—emergence of the $H(0.34)$ peak].

An alternative explanation could also be considered. The fact that part of the amplitude of the $H(0.28)$ peak disappears before the $H(0.34)$ peak appears suggests that more than one process is occurring during the annealing of C*i*'s. Such a process might be the neutralization of C*i*'s by primary defects which are always present in the lattice. Vacancies, for example, which are very mobile even below room temperature may encounter some of the C*i*'s leading to electrically inactive centers. This is in agreement with the observation discussed below that the decrease of the $H(0.28)$ peak is larger than the increase of $H(0.34)$. As the temperature increases and the mobility of C*i*'s increases the reaction process leading to the formation of the $H(0.34)$ defect prevails.

As is well known, C_s and O_i are the main traps for the migrating C*i*'s. In a float-zone material where the concentrations of C_s and O_i are of the same order ($\sim10^{16}$ cm^{-3}) the final product will depend upon the capture cross section σ of the impurities for the C*i*, which is larger for C_s[7] ($\sigma_{C_s}=3.25\sigma_{O_i}$). Thus, at first sight, C_i-C_s emerges as the main candidate for the $H(0.34)$ peak, a fact also consistent with photoluminescence studies,[8] but in disagreement with the work mentioned above.[2]

(ii) ($\Delta[H(0.34)<\Delta[H(0.28)]$. In this relation Δ stands for difference and the brackets denote concentration. A simple comparison of the spectra of Fig. 1 for $T=2.55$ °K and $T=400$ °K shows that the decrease of the amplitude of
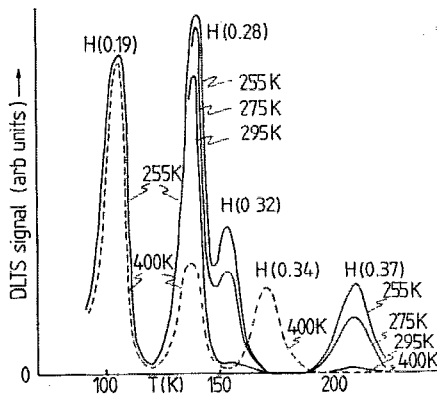
FIG. 1. DLTS spectra of float-zone, boron-doped Si material, electron irradiated at 80 K and subsequently undergone 40 min isochronal annealings at the indicating temperatures ($e_p = 5$ s^{-1}).

FIG. 2. DLTS spectrum of float-zone, boron-doped Si material electron irradiated at room temperature ($e_p = 500$ s^{-1}).

the $H(0.28)$ peak of C_i's is larger than the increase of the $H(0.34)$ peak. This indicates that a number of C_i's are captured by other sinks (like divacancies[2] and/or interstitial loops[9]) most likely leading to the formation of electrically neutral structures, since no other peak appears in the spectra.

Two more observations worth noting at this point. At first, the thermal emission of the $H(0.34)$ peak was found practically independent of the bias in our studies. In general, the absence of the Poole–Frenkel effect indicates that the defect is in a neutral charge state after carrier emission. Carrier emission is negligibly affected by the applied external electric field because of the absence of a long range Coulombic potential. However, a polarization potential may be assigned to the center. A level with similar activation energy has been previously attributed to the donor state of the C_i-C_s pair.[1] Our results do not preclude the level being a donor state which is not expected to display any Poole–Frenkel effect after hole emission ($+/o$). Note, however, that lattice relaxation during emission can also mask the Poole–Frenkel effect as is well known from the literature. Thus, the absence of the Poole–Frenkel effect although is not, by itself, informative as regards the defect type, it does not contradict the previous surmise for the level being a donor state. Second, the capture cross section σ of the level was measured, and found to be $\sigma \sim 8.5 \times 10^{-17}$ cm^2. Such a value might be taken as an indication of a positive charged center. This center becomes neutral after hole emission in accord with the absence of the Poole–Frenkel effect. Furthermore, σ was found to be temperature-independent in the range of 160–220 °K. Solely from this result it is difficult to draw any certain conclusion for the carrier capture process.

(iii) Dependence of [H(0.34)] on the boron concentration. In Fig. 2 the whole spectrum of float-zone silicon immediately after room-temperature irradiation is presented. A level $H(0.09)$ was observed exhibiting charge dependent amplitudes in agreement with recent data[2] where the level was identified as the C_i-C_s pair. Peaks $H(0.19)$ and $H(0.27)$ arise from the V_2 and the C_i, re-
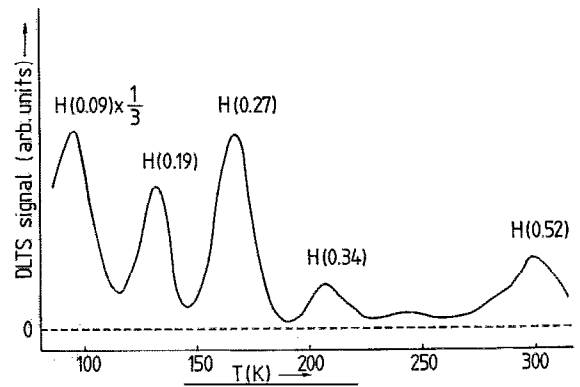
spectively, although the origin $H(0.52)$ peak is unknown. In the latter figure the concentrations of the $H(0.09)$ and $H(0.34)$ levels are not equal, an indication that either they do not arise from the same center or they originate from different configurations of the same defect. The lack of tracing of the $H(0.09)$ peak in 80 K irradiated Si, after the annealing of the C_i's is at present not understood. It may be the result of different reaction processes for C_i's between the two cases.

In the further experiments reported here we have measured the concentration of the $H(0.34)$ peak (Fig. 2) created after room-temperature irradiation of various float-zone samples with different boron concentrations (Table I). The concentration of the $E_v + 0.34$ eV increases with the boron concentration of Si. In a recent experiment[10] a level labeled $H(0.34)$ observed both in float-zone and Cz-grown material, has been attributed to the boron-carbon (B-C) pair. We have two remarks on that assignment. First, as it is generally accepted in the literature the level in Cz-Si arises from two energetically close defects one of which is surely C_i-O_i[11] and the other presumably the C-O-V complex.[12] Second, the $H(0.34)$ peak appears in Al[13] and Ga[14] doped Si as well. Significantly enough, a "new" carbon-related defect was reported in Ga-doped Si,[14] with the same activation energy, the concentration of which increases with the Ga concentration. However any delayed growth has not been reported in Ga-doped Si.

Concerning the identity of the defect our results point to a carbon-related, boron-dependent structure. The observed delayed growth is in agreement with the reports about the photoluminescence G-line in Si attributed to the C_i-C_s pair. However this defect has different levels in the

TABLE I. $H(0.34)$ concentrations of float-zone material with different boron content immediately after room temperature electron irradiation.

ρ (Ω cm)	Boron content (cm^{-3})	$N_{H(0.34)}$ (cm^{-3})
9	1.8×10^{15}	traces
6.4–7.4	3.5×10^{15}	4.8×10^{12}
1.45	1.5×10^{16}	1.9×10^{13}

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energy gap. The defect might arise from a different configuration of the di-carbon structure which theoretically cannot be excluded.[15] Boron seems somehow to prevent a number of C_i's from going to the unknown sinks,[2,9] thus helping the formation of additional $H(0.34)$ defects. Clearly more work needs to be performed in Si doped with various acceptors (e.g., B, Al, Ga, In.) before a final conclusion can be reached.

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