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Formation of a Bistable Interstitial Complex in Irradiated p-Type Silicon

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The influence of the injection of minority charge carriers on the formation of a divalent bistable defect (DBH) having two energy levels of $E_v + 0.44$ eV and $E_v + 0.53$ eV in its metastable configuration is investigated. Using forward current injection, the formation temperature of this defect in p-type silicon can be lowered by about 50 °C. The production of such bistable defect is enhanced in materials with a high ratio of boron to carbon concentrations. This allows one to conclude that the boron atom is one of the constituents of the defect under study. There is also a correlation between the behavior of the bistable hole traps and a metastable electron trap observed earlier. It is concluded that these traps are related to metastable and stable configurations of the DBH defect, which has inverse occupancy level ordering in its stable configuration.

1. Introduction

Defects with deep levels have a significant impact on the characteristics of semiconductor devices. Special classes of such defects are the bistable and the metastable defects,[1–3] whose presence may have an effect on the stability of electronic devices. An example of such an effect is a bistable defect found in the study by Fleming et al.[4], later on identified as a tri-vacancy.[5,6] The bistability of the tri-vacancy significantly affects the characteristics of irradiated silicon bipolar transistors[4] and radiation detectors.[7,8]

A large number of bistable defects have been discovered and investigated previously.[1–3] Recently, interest in such defects arose after it was shown in the study by Fleming et al.[4] that using the injection of minority charge carriers through a collector or emitter junctions of silicon transistor structures, one can detect the bistability of a number of important radiation defects. In n-type silicon, they are the trivacancy,[5,6] a thermal double donor[9,10] and the cluster-related hole traps H (116 K), H (140 K) and H (152 K).[11] In p-type silicon irradiated with neutrons, the use of this method allowed to detect another new bistable defect, with two energy levels discharging around 250 K according to the study by Fleming et al.[12]. The properties and nature of this defect, labeled here as divalent bistable defect (DBH) center, were afterward investigated in n^+–p silicon structures irradiated with electrons and α-particles by deep-level transient spectroscopy (DLTS).[13–15]

In those works, it was established that the DBH defect in its metastable configuration (BH-configuration) acts as a divalent hole trap with levels of $E_v + 0.44$ eV and $E_v + 0.53$ eV, and it is thermally stable up to 450 K.[13] A partial correlation between its appearance and the annealing of the self-diinterstitial-oxygen complex (I_2O) was established.[14] It was also shown that another metastable electron trap previously found as ME1 in the study by Makarenko et al.[16] corresponds to the stable configuration (ME-configuration) of the DBH defect in p-Si, a center that can be effectively formed under minority carrier injection.[15]

However, many other characteristics of the DBH center have not yet been determined. Thus, an important issue that needs to be solved to understand the nature of the DBH center is to determine its composition. Based on the data regarding the annealing temperature in the study by Lastovskii et al.,[13] it was suggested that this center is a complex of self-interstitial–interstitial carbon atoms (IC_i). However, subsequent studies,[14] carried out using the IR absorption method, did not confirm this hypothesis. Therefore, new experimental evidences are required to establish the nature of the DBH complex under study.

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2. Experimental Section

Three sets of silicon diode structures were investigated. Two of them (set 1 and set 2) consist of 50 μm thick epitaxial silicon layers grown on a boron-doped silicon substrate of 525 μm thickness and 0.006 Ω cm resistivity. These two sets have different contents of boron impurity in the epitaxial layer. Base regions of set 1 and set 2 diodes have resistivities of 10 Ω cm and 50 Ω cm, respectively. The third type of diodes are processed on silicon crystals of 10 Ω cm (set 3), grown by the Czochralski method. All the three sets of diodes were similarly processed.

Irradiations with alpha-particles with energies of about 5 MeV have been performed from a surface source described in the study by Makarenko et al.[15]. The irradiation time was between 40 and 150 min. The damage distribution for this kind of irradiation source is described in the study by Makarenko et al.[17]

Irradiation with 5.5 MeV electrons was carried out at a linear electron accelerator at room temperature with fluences in the range of $\phi = (2\text{–}20) \times 10^{14}\ \text{cm}^{-2}$. The electron flux density was about $2 \times 10^{12}\ \text{cm}^{-2}\ \text{s}^{-1}$.

The electrically active defects induced by irradiation with alpha-particles or high-energy electrons were investigated by means of the DLTS technique. In addition, we use two notations for the recorded spectra: DLTS, when filling pulses are performed with majority carriers (0 V or reverse bias filling pulses) and MC-DLTS when also minority carriers are injected during the pulses (forward bias filling pulses).

To register DLTS spectra, two setups were used. Measurements in the temperature range of 30–270 K were carried out using a HERA-DLTS FT-1300 spectrometer[18] and in the temperature range of 79–270 K using the "Svitanak" spectrometer designed at the Scientific Research Institute of Applied Physical Problems of the Belarusian State University. The "Svitanak" setup also makes it possible to realize higher values of the forward current during the filling pulse when measuring MC-DLTS.

Conventional thermal annealing of the diodes above 100 °C was performed in air using a temperature-regulated tube oven. Below 100 °C, the samples were annealed in situ in the DLTS apparatus.

3. Experimental Results

3.1. Evaluation of Oxygen and Carbon Content

Evidently, when interpreting data on the kinetics of the formation and annealing of impurity-defect complexes in semiconductors, the information on concentrations of doping and background impurities is one of the main requirements. However, this demand cannot not always be fulfilled if device structures are envisaged. Usually, silicon devices are produced by high-temperature technological processes. This is definitely the case for diffused silicon diodes. The processes of oxidation and diffusion of doping impurities lead to a change in the concentration and distribution of impurities in the produced structures as compared with initial crystals. Therefore, to obtain unambiguous results, it is always necessary to monitor the content of doping and background impurities in the used structures.

A direct method of such control can be secondary ion mass spectroscopy (SIMS).[19,20] However, if the concentrations of oxygen and carbon are relatively small, then there are some difficulties with the effective application of this method. In addition, in structures with high resistivity base regions, it is required to study the impurity distribution at a greater depth, which may be an additional factor complicating the task.[20]

Alternatives to SIMS are indirect methods based on the already known data on formation and annealing of electrically active radiation defect-impurity complexes. Most often, methods of this type are used to determine the oxygen content.[17]

It is known (refer the study by Kimerling et al.[21] and references therein) that in irradiated silicon of n- and p-type conductivity, a reaction of interstitial carbon (C_i) with oxygen (O_i) takes place at $T \approx 300$ K

$$C_i + O_i \xrightarrow{k_{CO}} C_iO_i \tag{1}$$

The rate of this reaction (τ_{CO}^{-1}) depends on the oxygen content as

$$\tau_{CO}^{-1} = k_{CO}[O_i] = 4\pi R_{CO} D_{C_i}[O_i] \tag{2}$$

The C_i and C_iO_i centers are reliably registered by the DLTS method in n- and p-Si, thus making it possible to determine k_{CO} in materials doped with both, phosphorus and boron.

In parallel with reaction (1), C_i interctions with substitutional boron (B_s) and carbon (C_s) atoms can occur (see refer the study by Kimerling et al.[21])

$$C_i + B_i \xrightarrow{k_{CB}} B_iC_i \tag{3}$$

$$C_i + C_s \xrightarrow{k_{CC}} C_iC_s \tag{4}$$

If the concentrations of B_s and C_s are small compared with the concentration of O_i, then reactions (3) and (4) can be neglected. However, if the concentrations of C_s and O_i are comparable, then, evidently, the carbon content can also be determined from the kinetics of annealing of C_i, as it was done in the study by Makarenko et al.[17]

The main problem in determining the absolute value of oxygen concentration is related to the calibration of the k_{CO} value. Such a calibration was performed, for example, in the study by Markevich and Murin[22] and was used by us in a previous work.[17] Based on this calibration and using the experimental data of isochronal annealing (**Figure 1**), we determined the oxygen impurity content in all the three types of samples under study as $[O_i] \approx 1.5 \times 10^{17}\ \text{cm}^{-3}$. For comparison, a plot of Ci annealing in 4.5 Ω cm Czochralski-grown diode is added. This diode was processed similar to the sets under study. That is, there are practically no differences between the oxygen content in the epitaxial silicon layers and in the silicon grown by the Czochralski method. There are also no differences in the behavior of C_i annealing in boron-doped materials with resistivities in the range of 4.5–50 Ω cm (see data in Figure 1). In all the samples studied, the value of oxygen concentration is determined by the

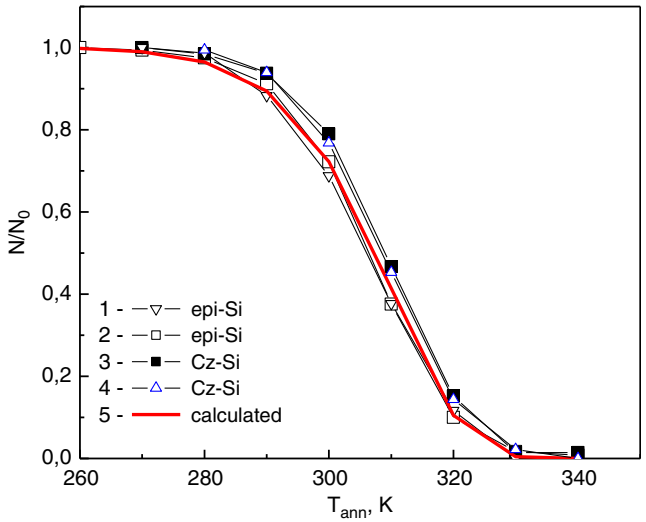

Figure 1. Thermal annealing behavior of interstitial carbon in diffused diodes made of epitaxial (1,2) and Czochralski-grown (3,4) silicon. Curve 1 is related to 50 Ω cm silicon; curves 2 and 3 are related to 10 Ω cm silicon, and curve 4 is related to 4.5 Ω cm silicon. The annealing time was 15 min. Curve 5 presents fitting results with the activation energy of 0.77 eV and $[O] = 1.5 \times 10^{17}$ m^{-3} calculated according to the study by Makarenko et al.[17]

temperature of phosphorus diffusion ($T \approx 1050\,^{\circ}C$) when producing the n^+-layers of the diodes.

Information about the content of carbon impurity when its concentration is relatively low and reaction (4) is ineffective, one can be obtained using a different approach. It is known that the interstitial silicon atoms ($Si_i \equiv I$) formed during irradiation in boron-doped silicon effectively replace substitutional carbon and boron atoms

$$Si_i + C_s \xrightarrow{k_{IC}} C_i \tag{5}$$

$$Si_i + B_s \xrightarrow{k_{IB}} B_i \tag{6}$$

If we determine experimentally the ratio between the rates of reactions (5)–(6) or, similarly, between the concentrations of C_i and B_i defects

$$\eta_{BC} = \frac{[C_i]}{[B_i]} = \frac{k_{IC}[C_s]}{k_{IB}[B_s]} \tag{7}$$

then, provided that the relation k_{IC}/k_{IB} is already known, we can determine the ratio $[C_s]/[B_s]$.

The boron dopant concentration in diode structures is easily determined from the capacitance-voltage characteristics. Therefore, if we determine experimentally the value η_{BC}, we can determine the carbon concentration.

Since reactions (5)–(6) often occur already in the course of irradiation at room temperatures, we cannot use them directly. Therefore, in practice, we can estimate the ratio between the concentrations of complexes of interstitial boron-interstitial oxygen (B_iO_i) and interstitial carbon-interstitial oxygen (C_iO_i)

$$\eta^*_{BC} = \frac{[C_iO_i]}{[B_iO_i]} \tag{8}$$

If the concentrations of boron and carbon impurities are small compared with the concentration of oxygen, then we can assume that $\eta^*_{BC} \approx \eta_{BC}$.

Next, we again encounter the problem of how to calibrate the ratio k_{IC}/k_{IB}. Such a calibration is more complicated than in the previous case. The main difficulty lies in the fact that the k_{IC}/k_{IB} value depends on the type of particle used for irradiation. For example, if we would compare electron irradiation and alpha particle irradiation, in the latter case, irradiation intensity and post-radiation treatment can also be important.[24]

Consequently, it seems that no universal calibration can be obtained with this method. However, its use allows us to compare different types of diode structures only when they are irradiated with the same source of electrons. In the case of using different sources of electron radiation, the ratio between the amplitudes of the peaks of boron- and carbon-containing defects can be somewhat different. This difference can be seen by comparing the MC-DLTS spectra obtained on the same material irradiated with electrons of different energies (**Figure 2**). As seen from the DLTS and MC-DLTS spectra shown in Figure 2, the contribution of the divacancy signal (H3 peak) should be taken into account in the analysis of the shape and amplitude of the B_iO_i (E1) peak. Thus, for a diode irradiated with 0.9 MeV electrons, the concentration of the divacancy is negligibly small, and MC-DLTS spectrum for E1 trap looks practically undistorted (Figure 2). When the introduction rate of the divacancy is large, to determine the actual amplitude of the E1 trap one has to use the difference between DLTS and MC-DLTS spectra.

Although some differences between irradiations with different electron energies exist, they are relatively small and allows us to use the data from the study by Kimerling et al.[21] to determine the carbon concentration in our samples by comparing the amplitudes of B_iO_i and C_iO_i peaks (**Figure 3**). If the calibration

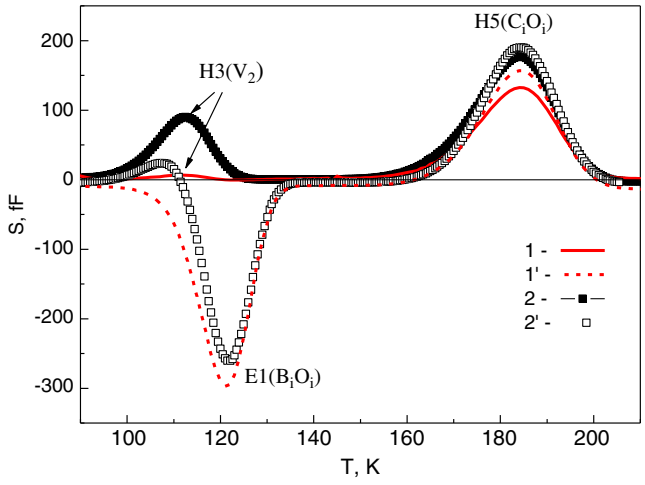

Figure 2. DLTS and MC-DLTS spectra of similar epitaxial p-Si diodes irradiated with electrons and annealed at 400 K during 20 min. Lines 1 and 1′ show DLTS and MC-DLTS spectra for diodes irradiated with 0.9 Mev electrons ($F = 2 \times 10^{15}$ cm^{-2}) and curves 2 and 2′ show DLTS and MC-DLTS spectra for diodes irradiated with 3.5 Mev electrons ($\Phi = 4 \times 10^{14}$ cm^{-2}).

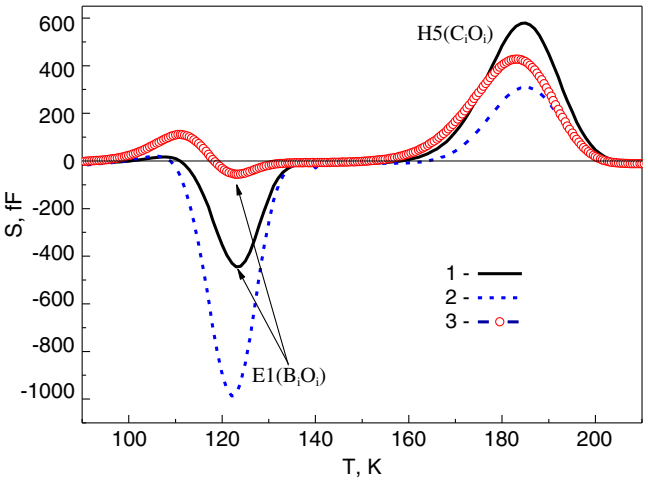

Figure 3. MC-DLTS spectra of different p-Si diodes irradiated with electrons and annealed at 400 K during 20 min. Lines 1 and 2 show spectra for epitaxial diodes of different resistivity:50 Ω cm (1) and 10 Ω cm (2). Curve (3) shows experimental data for a diode made of Czochralski-grown silicon with a resistivity of 10 Ω cm.

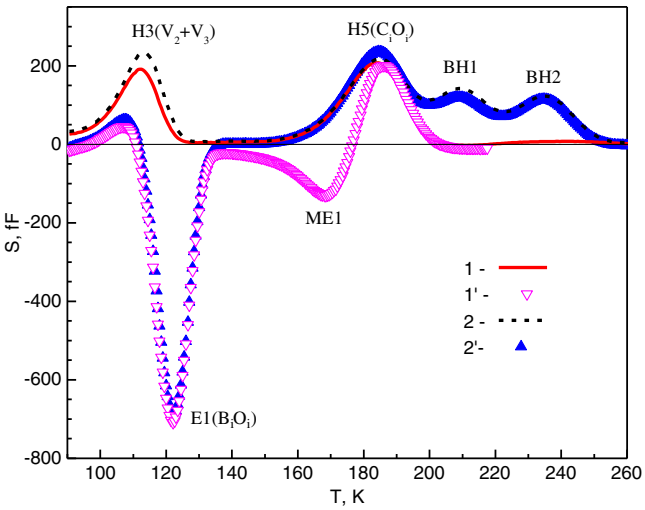

Figure 4. Conventional DLTS (lines) and MC-DLTS (symbols) spectra for alpha-irradiated epitaxial (set 1) diodes contained bistable defect after stabilizing annealing (1, 1′) and after forward current injection with density $J_f = 1.6\ \mathrm{A\ cm^{-2}}$ (2, 2′). Measurement settings were emission rate window $e_w = 19\ \mathrm{s^{-1}}$ for all spectra, bias change −3 ⟶ 0 V, and filling pulse duration $t_p = 10$ ms for spectra 1, 2; bias change −3 ⟶ +2.0 V, and filling pulse duration $t_p = 10$ ms for spectra 1′, 2′.

given in the study by Kimerling et al.[21] for $K_{IC}/K_{IB} = 1/7$ is used, we determine that the concentration of carbon in the structures based on epitaxial silicon is $[C_s] \approx (1.5\text{–}2) \times 10^{15}\ \mathrm{cm^{-3}}$ and in the structures based on Cz-silicon is $[C_s] \approx 3 \times 10^{16}\ \mathrm{cm^{-3}}$.

However, more reliable is the estimation of the ratio between the carbon concentrations, in all three types of samples, from the data shown in Figure 3. Based on the obtained data, ratios $(\eta^*_{BC})_{epi1} : (\eta^*_{BC})_{epi2} : (\eta^*_{BC})_{Cz} \approx 1:4:15$ are obtained for the three sets of diodes.

Thus, we have three types of samples with approximately the same oxygen content, but with different ratios between carbon and boron concentrations.

3.2. Some Features of the Configurational Defect Transformation Process

Some characteristics of the configuration transformation of the BH center have been already determined in the study by Lastovskii et al.[13] However, to unambiguously interpret the data and the kinetics of this center formation, we need some additional information about the characteristics of the transition from one defect configuration to the other.

First, information on the injection currents needed to transform the DBH defect into the BH-configuration is required. Typical DLTS and MC-DLTS spectra obtained for diodes irradiated with alpha particles after subsequent stabilizing annealing are shown in **Figure 4**. In the DLTS spectrum obtained immediately after annealing, only two hole traps are observed, the divacancy (H3 peak) and the complex C_iO_i (H5 peak). In the MC-DLTS spectrum, two electron traps appear: E1 and ME1. The first of these is related to the B_iO_i complex, and the second is the ME1 trap is a metastable center.[16] The latter one disappears after electron injection using sufficiently large forward currents at T = 300 K. This current stimulates the transformation of the ME1 defect into its metastable configuration, which appears in the form of the BH1 and BH2 peaks. These peaks, observed earlier in the study by Fleming et al.,[12] belong to the same DBH.[13]

Similar spectra transformations are observed after irradiation of n^+-p diodes with high energy ($E_e = 3.5$ or 5.5 MeV) electrons.[13] However, forward current injection did not induce any changes in DLTS and MC-DLTS spectra for diodes irradiated with 0.9 MeV electrons (Figure 2). It means that to produce the bistable defect a high energy of knocked-out atoms are required similar to divacancy production in silicon crystals.[24]

As the forward current density increases, the amplitudes of the peaks BH1 and BH2 grow until they reach their saturation values (**Figure 5**). At the same time, the amplitudes of peaks H2 and H3 increase. The H2 peak is found to be related to electron emission from the donor level of the trivacancy in its metastable state.[25] The appearance of the H2 peak and the growth of the H3 peak are associated with the rearrangement of the trivacancy from the stable part of a hexagonal ring configuration to the metastable fourfold coordinated configuration.[5,6]

As seen in **Figure 6**, the current density required for the complete rearrangement of the defect depends on the irradiation dose. This result can be easily explained if we take into account the fact that with increasing the radiation dose, the lifetime of minority carriers decreases. Accordingly, it can be expected that the density of injected minority carriers with the same forward current will be less in the diodes irradiated with the highest dose.

A similar dependence on the dose of radiation occurs in the rearrangement rate of the trivacancy (Figure 6, curves 1′-2′). The presence of the dose dependence for rearrangement rates explains the difference between the time constants of the rearrangement of a tri-vacancy obtained in the study by Markevich et al.[6] for diode structures made of different materials.

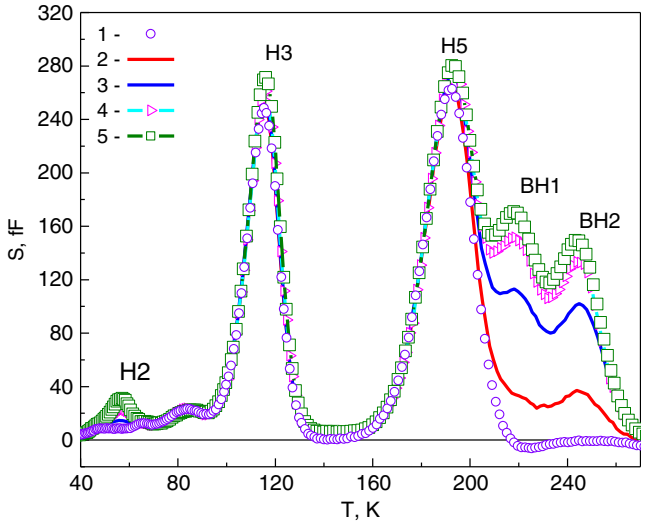

Figure 5. Conventional DLTS spectra for epitaxial (set 1) diode irradiated with electrons $\Phi = 5 \times 10^{14}$ cm^{-2} after stabilizing annealing at 400 K during 20 min (1) and after forward current injection with different densities: $J_f = 0.8$ A cm^{-2} (2), $J_f = 1.6$ A cm^{-2} (3), $J_f = 2.4$ A cm^{-2} (4), $J_f = 3.2$ A cm^{-2} (5). Measurement settings were emission rate window $e_w = 57$ s^{-1} for all spectra, bias change –3 ⟶ 0 V, and filling pulse duration of $t_p = 10$ ms.

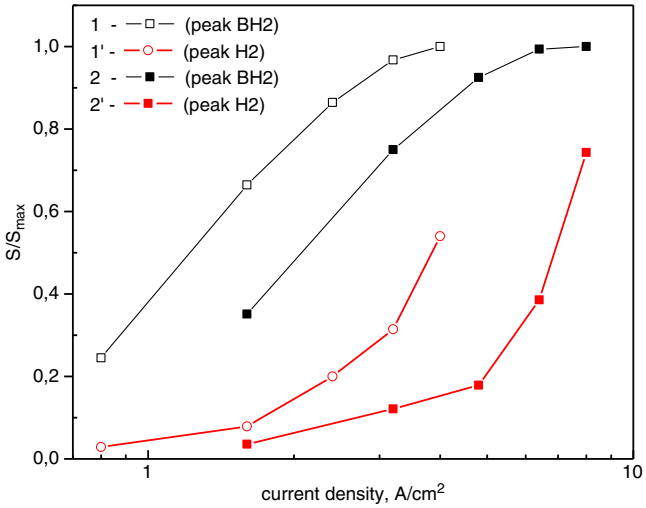

Figure 6. Forward current dependences of the parts of DBH defect (1, 2) and tri-vacancy (1′, 2′) transformed into their metastable configurations at room temperatures. Epitaxial (set 1) diodes were irradiated with different fluences of 5.5 MeV electrons: $\Phi = 5 \times 10^{14}$ cm^{-2} (1, 1′) and $\Phi = 1 \times 10^{15}$ cm^{-2} (2, 2′).

The BH configuration of the DBH defect is metastable in p-type silicon. Since the rearrangement into this configuration occurs as a result of electron capture, it implies that there is an energy level in the gap for its stable configuration.

As mentioned earlier, the ME1 trap is observed in the MC-DLTS spectra of irradiated n^+-p-p^+ diodes and disappears after electron injection using forward currents (Figure 4) with the simultaneous appearance of traps BH1 and BH2. When heated to temperatures of 40–60 °C, the BH1 and BH2 traps gradually disappear. Their disappearance is accompanied by the recovery of the trap ME1 signal. The disappearance of the BH1 and BH2 traps and the recovery of the ME1 traps correlate well with each other during isochronal annealing (**Figure 7**). This gives us a reason to assume that in p-type material the trap ME1 corresponds to the stable configuration of the DBH defect.

It is noteworthy that the amplitude of the signal of the ME1 trap is always higher than the amplitude of each of the two peaks BH1 and BH2. In diodes irradiated with smaller doses, when measuring MC-DLTS using the maximal possible currents of the injecting filling pulse, we found that the amplitude of the ME1 peak is twice higher than the amplitude of the BH1 or BH2 peak. This suggests that the trap ME1 emitted two electrons simultaneously. That is, the ME1 trap behaves as a negative-U center.

To observe the ME1 trap, a fairly large level of electron injection during the filling pulse is required. Therefore, it means that the ratio between the capture cross-sections of electrons and holes in the ME1 trap is not very different from unity. This makes it difficult to observe it in highly irradiated samples or in those with high boron content.

However, if during thermal annealing the lifetime of minority carriers does not change, then, it can be expected that the corresponding MC-DLTS signal will be proportional to the total concentration of the ME1 trap even when the occupation of this trap with electrons at the filling pulse is not complete. That is, even if it is impossible to achieve a complete filling of the ME1 trap and to determine its concentration correctly, nevertheless, one can investigate the relative changes of its concentration during the annealing studies.

3.3. Formation of Bistable Defect under Forward Current Injection

In the study by Lastovskii et al.,[13] it was suggested that the bistable defect is formed as a result of dissociation of the I_2O complex.

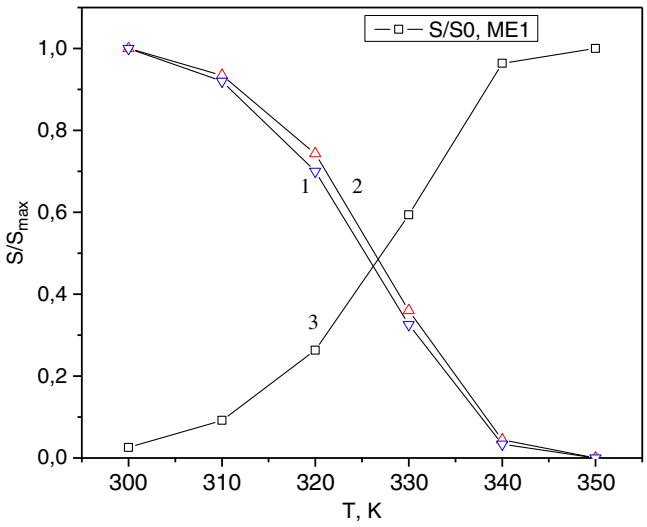

Figure 7. Transformation of bistable defect from the BH metastable configuration to the stable one, ME1, during the isochronal annealing of epitaxial, set 1, diode. The disappearance of BH1and BH2 traps are depicted by curves 1 and 2, respectively, while the appearance of ME1 trap is shown by curve 3.

However, no unambiguous experimental data were presented on the existence of such a correlation between the disappearance of I_2O and the appearance of the DBH center in that work. In a later report by Gusakov et al.,[14] an attempt was made to establish such a correlation. However, the data presented in the study by Gusakov et al.[14] look somewhat controversial. First, the annealing temperature of the I_2O complex does not correspond to the previous data on the annealing rate of this defect.[26] Second, it is unclear why there are different fractions of the I_2O complex spent to form the bistable defect at different stages of isochronal annealing. Thus, if after annealing at 50 °C, more than 60% of the annealed complexes were spent on the formation of the bistable defect, then, at 75 °C the ratio between the concentrations of appeared and disappeared defects is only ≈20%, and after annealing at 100 °C, this ratio becomes less than 10%. However, in the study by Gusakov et al.[14], these discrepancies are not explained.

At the same time, Gusakov et al.[14] mention in their conclusion section that they observed an injection enhancement of some defect reactions associated with di-interstitials. Evidently, since it is necessary to use the injection of minority charge carriers to determine the concentration of the bistable defect, one expects that this injection will stimulate not only the configurational transformation of the defect but also its additional production.

We performed more detailed studies of the effect of electron injection on the formation of the DBH bistable defect. Results of these studies are shown in **Figure 8** after irradiation with alpha-particles. In these DLTS spectra, in addition to the peaks described earlier, the H1 peak is also observed. This peak was earlier identified as related to the I_2O complex.[26] From Figure 8, it is clearly seen that an increase in the forward current density leads to the gradual disappearance of this peak and the appearance of those corresponding to the bistable defect (BH1 and BH2).

In addition, the spectra from Figure 8 show also the transformation of defects related to interstitial carbon and its complexes. The H4 trap, related to C_i, gradually disappears. Its annealing-out is accompanied by an increase in the amplitude of the H5 peak associated with the C_iO_i complex. At the initial stages of annealing, a half of the C_iO_i complex is in its metastable state.[27,28] This is manifested in the slightly lower temperature of the H5* peak position as compared with the stable H5 peak. The signal of H5* peak is the superposition of signals from the metastable and stable configurations of the C_iO_i complex.

The appearance of BH1/BH2 peaks begins when injecting forward currents have relatively low densities (≈1.5 A cm^2). With increasing the forward current density, the amplitude of the H1 peak decreases and the amplitudes of the BH1/BH2 peaks increase. Such a correlation confirms the assumption made in the study by Lastovskii et al.[13] that a bistable defect is formed as a result of the annealing-out of the I_2O complex. Therefore, considering that in the studies of the bistable defect formation during thermal annealing in the study by Lastovskii et al.,[13] forward currents with a density in the range of 6–15 A cm^{-2} were used to monitor BH1/BH2 traps, then, an additional production of the bistable defect is expected to take place. Such additional production can explain the discrepancy in the annealing results obtained in the study by Gusakov et al.[14]

To study the ME1 center formation, there is no need to use a preinjection treatment of the diodes. Therefore, contrary to the studies of the formation of the bistable defect in its BH configuration, additional injection treatment of the diodes will not distort the thermal annealing data. As shown in **Figure 9**, the ME1 trap is formed in the same temperature range of thermal annealing, in which the H1 (I_2O) trap disappears. Therefore, the data shown in Figure 9 provide additional confirmation that the peaks ME1 and BH1/BH2 belong to the same DBH defect.

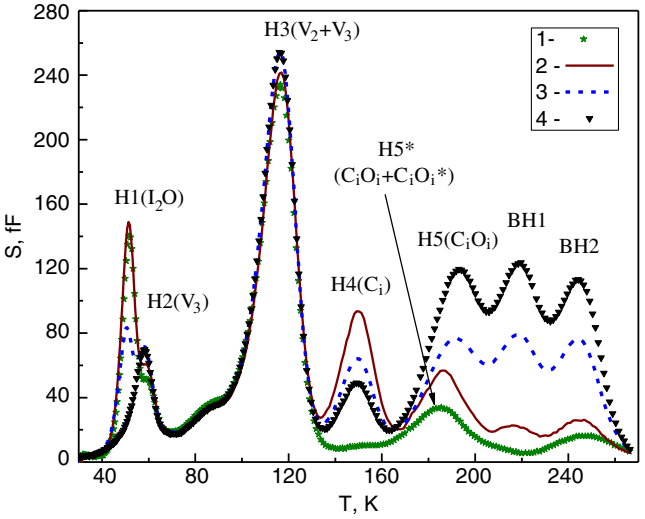

Figure 8. DLTS spectra registered after irradiation with alpha-particles (1) and after subsequent forward current injection during 2 min and density $J_f = 1.6$ A cm^{-2} (2), $J_f = 6.4$ A cm^{-2} (3), $J_f = 12.8$ A cm^{-2} (4). Measurement settings were emission rate window $e_w = 57$ s^{-1} for all spectra, bias change –3 ⟶ 0 V, and filling pulse duration of $t_p = 10$ ms.

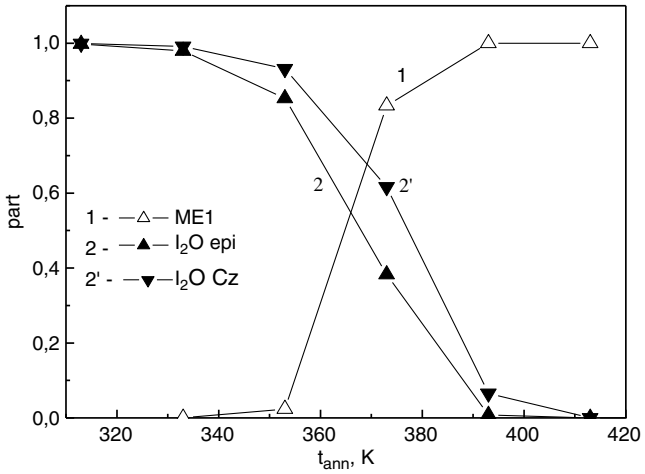

Figure 9. Formation of ME1 trap in epitaxial, set 1, diode during isochronal annealing (1). Curves 2 and 3 (calculated from experimental data from the study by Markevich et al.[25]) correspond to the disappearance of I_2O center under the same annealing conditions in epitaxil (2) and Czochralski-grown (2′) diodes. Annealing duration was 20 min for each temperature in steps of 20 K.

3.4. Carbon and Boron Effects on Bistable Defect Formation

In previous studies,[13,14] the following mechanism of the bistable defect formation was proposed. First, the I_2O complex dissociates

$$I_2O \longrightarrow I_2 + O_i \tag{9}$$

The released di-interstitials can migrate over the crystal before being trapped by the substitutional atoms of boron or carbon

$$I_2 + B_s \longrightarrow IB_i \tag{10}$$

$$I_2 + C_s \longrightarrow IC_i \tag{11}$$

Thus, one of these newly formed complexes can be, presumably, the bistable defect.

In previous studies,[13,14] it was assumed that the carbon-containing complex IC_i is most likely to be the DBH bistable defect. Theoretical studies of this complex properties were carried out.[14] According to these studies, the bistability of the IC_i complex was established in the neutral charge state. However, experimental studies using the IR absorption method, carried out in the same work, did not allow detecting any particular absorption line associated with such a bistable defect. Therefore, data on its formation during thermal annealing, obtained with the use of DLTS method, are of essential importance to give more clarity to its nature.

For DLTS studies, we have used crystals with different boron and carbon content. The ratio between the concentration of the I_2O complex and the concentration of the bistable defect formed as a result of its annealing was determined.

As previously demonstrated, complete annealing of I_2O occurs in 20 min at 400 K.[13] Therefore, all three types of materials previously irradiated with electrons were annealed at this temperature. The DLTS spectra were measured immediately after the heat treatment and after subsequent forward current injection at $T \approx 300$ K. The current density was chosen from the condition of the complete transformation of the DBH center into its BH configuration (Figure 6).

The obtained DLTS spectra are shown in **Figure 10**. From these spectra, the ratio between the amplitudes of the divacancy (H3) and the I_2O (H1) peaks (η_{V2I2O}) can be estimated. This ratio remains approximately the same $\eta_{V2I2O} \approx 0.8 \pm 0.1$ for all three material types. However, there are some differences for the materials under study. The value of η_{VI2O} is slightly lower in diodes with high total concentration of boron and carbon. More significant differences for different materials are observed for the value $\eta_{DBHI2O} = [DBH]/[I_2O]$. With an increase in the ratio $\eta_{BC} = [B_s]/[C_s]$, the value of the η_{DBHI2O} ratio increases. For the materials under study, it reaches a maximum in epitaxial samples with a high boron content. In the framework of the model proposed in the study by Lastovskii et al.,[13] this means that not carbon but boron atom takes part in the formation of the DBH bistable defect.

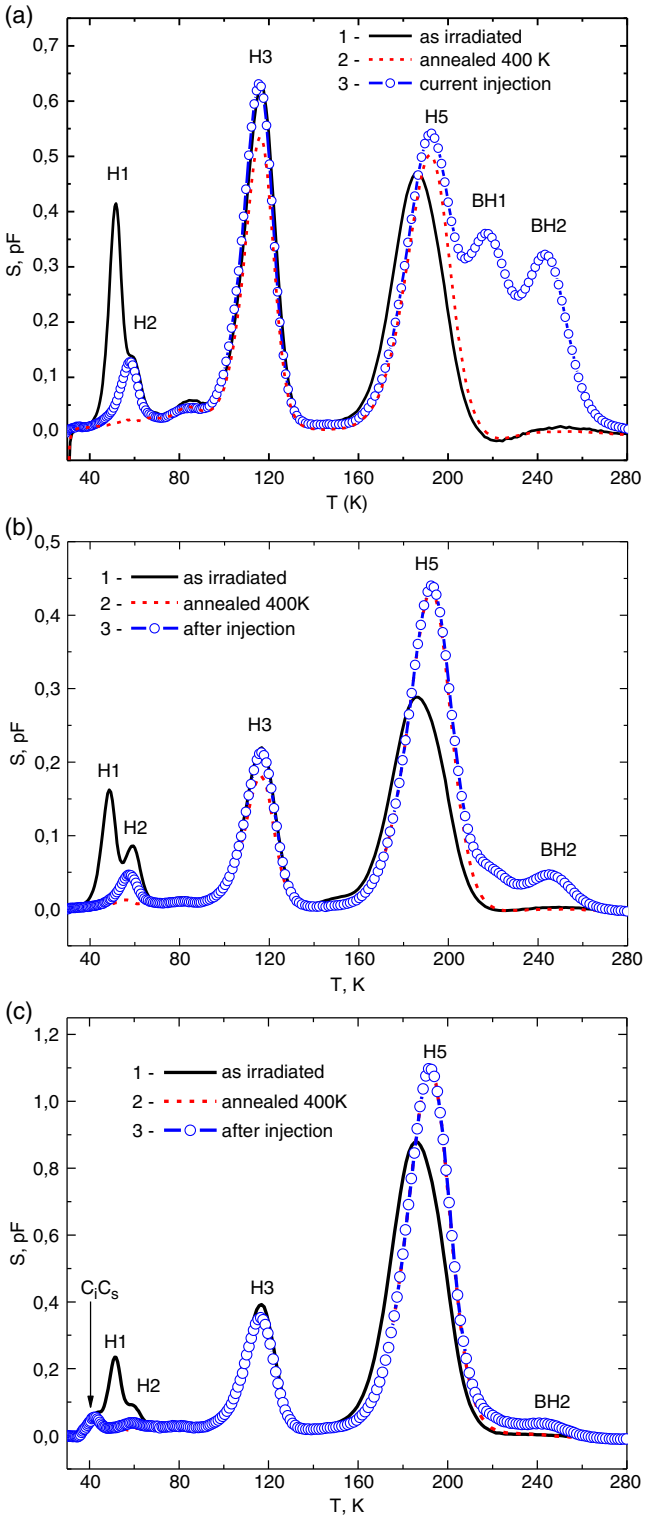

Figure 10. DLTS spectra of diodes made of epitaxial, set 1 (a) and set 2 (b), and Czochralski grown (c) silicon diodes after electron irradiation and stabilizing the annealing at 400 K during 20 min. Spectra were obtained immediately after irradiation (1) after the annealing (2) and after subsequent forward current injection at room temperature (3). The forward current density was chosen to transform completely the bistable defect into BH-configuration.

4. Discussion

Evidently, the results obtained in this work explain the contradictory data on the formation of the DBH center obtained in the study by Gusakov et al.[14] The reduced annealing temperature is due to the recombination enhancement of the I_2O center dissociation during the current injection, which is necessary to transform the bistable defect into its BH configuration. Moreover, to determine the fraction of I_2O spent for the formation of the DBH center in isochronal annealing studies, it is necessary to compare the values of the concentrations of I_2O and DBH centers not at the same annealing temperature, but at two neighboring temperatures.

The lowering of the annealing temperature for the I_2O center, caused by the forward injection at 300 K, is about 50 °C. This is less in comparison with the B_iO_i center.[29] However, to enhance the annealing out of I_2O, lower densities of injection currents are required for the same diodes irradiated with comparable doses. Apparently, this is due to the magnitude of the energy barrier, which must be overcome for the dissociation of the complex. For B_iO_i, this energy is ≈1.4 eV,[29,30] and for I_2O ≈1.05 eV.[26]

Furthermore, it should be noted that the interpretation of our DLTS data is based on the previous results of studies performed using the IR absorption method.[31,32] Thus, the identification of the H1 trap ($E_v + 0.09$ eV) as related to the I_2O complex is based on the same annealing interval of this trap and the 936 cm^{-1} band, as well as the dependence of the production rate of this trap on the energy of the bombarding particles.[33]

Therefore, the revealing of IR absorption lines associated with the center of interest would be important. The detection of such lines, evidently, would allow to establish its nature and structure.[31,32] However, as follows from the data presented in this work, to conduct such experiments, it is necessary to choose crystals fulfilling several conditions related to the content of boron, carbon, and oxygen impurities. Thus, an increase of the boron impurity content can lead to a change in the dominant reactions for interstitial defects and the formation of another type of bistable defects will become possible.[34]

In the course of studies performed on the bistable center, a large amount of information about its properties has been accumulated. However, a number of unsolved issues still remains. One of such issues is the establishment of charge states of the center. Namely, it is unclear if the center under study is in the same charge states in the ME and BH configurations. According to the study by Watkins,[2] a defect is defined as bistable one, if it can be in two atomic configurations for the same charge state. Therefore, if the charge states corresponding to the BH1/BH2 and ME1 peaks prove to be different, then the definition of a DBH center as a bistable would be, strictly speaking, incorrect. Accordingly, at present, such a definition should be considered only as a working hypothesis.

The effect of the defect bistability on the characteristics of device structures also remains unexplored. As mentioned earlier, the bistability of a trivacancy has a significant effect on the characteristics of irradiated silicon bipolar transistors[4] and radiation detectors.[7,8,11] A similar effect can be expected for the DBH center, since there is a significant change in its energy levels after configurational transformation. Evidently, this effect will be most significant for silicon devices irradiated with heavy particles (protons, neutrons, etc.), as well as after irradiation with electrons having their energies significantly higher than 1 MeV.

5. Conclusion

The influence of the injection of minority charge carriers on the production of the DBH bistable defect formed in boron-doped silicon has been investigated.

A correlation between the behavior of bistable traps for holes BH1/BH2 and a metastable trap for electrons ME1 is observed, and it is concluded that these traps are associated with different configurations of the same DBH defect. The formation temperature of the defect can be lowered by about 50 °C when using forward current injection.

The dependence on the electron irradiation dose of the transformation rate of the DBH defect into the metastable configuration has been studied as well. It is found that for a complete configurational transformation, it is required to use injection with higher current densities for diodes irradiated with higher doses.

It is established that the formation of the DBH bistable defect occurs more efficiently in the material with a higher ratio of boron to carbon concentration. This allows us to conclude that a boron atom is a constituent of the observed bistable defect.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

annealing, bistable center, deep level transient spectroscopy, radiation defect, recombination-enhanced reactions, silicon

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