

1) **Bulk damage:**

- **Electrical characterization:**

It has been observed that the introduction rate of the deep hole traps associated with extended defects is not dependent on the oxygen concentration, as similar values were obtained for DOFZ and STFZ materials. In order to distinguish whether the annealing behavior of the deep hole traps has a dependence of the oxygen content we have compared their annealing behavior with the temperature, during TSC measurements. The typical annealing behavior consists in the increase of their concentration with a maximum value around 200 °C, afterwards it decreases. The annealing out of the H defects is slightly different for the two materials: in DOFZ diode the annealing-out start around 200 °C, whereas for the STFZ diode starts around 240 °C. The results obtained indicate that upon isochronal annealing, in the temperature range 200 °C to 300 °C, a transformation of the H defects to another center occurs in the two Si materials (see Tab. I for the annealing out time constants). Examples of TSC spectra measured on the two types of samples are given in Fig.1.

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<thead>
<tr>
<th>Defect</th>
<th>@ 200°C</th>
<th>@ 250°C</th>
<th>@ 275°C</th>
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<tr>
<td>H(116K)</td>
<td>555 min. /265 min.</td>
<td>54 min. /172 min.</td>
<td>43 min. /42 min.</td>
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<td>H(140K)</td>
<td>2570 min. /600 min.</td>
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<td>H(152K)</td>
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**Tab. I. Time constants for annealing out of the H defects at different temperatures.**

By performing these isothermal treatments of the STFZ and DOFZ samples in the 200 ÷ 290°C temperature range, the annealing kinetics of H defects has been explored. In the whole interval an exponential decrease (for every measured temperature) as a function of annealing time holds with a good accuracy. The values of the time constants \( \tau \) obtained for the STFZ samples are higher than those for the DOFZ samples and the extracted values for the frequency factors \( k_0 \) and for the activation energies of the annealing out process \( E_a \) are

![TSC spectra recorded on STFZ and DOFZ diodes annealed at 200 °C.](image-url)

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Main results 2013

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![TSC spectra recorded on STFZ and DOFZ diodes annealed at 200 °C.](image-url)
displayed in Fig.2. A dissociation process of the H defects can be ruled out as the dominant process since the frequency factors obtained are in the $10^6$–$10^9$ s$^{-1}$ range, which is a factor of $10^5$–$10^8$ s$^{-1}$ lower, than expected if dissociation prevails ($10^{12}$–$10^{13}$ s$^{-1}$). This suggests strongly that the annealing out of the H defects is predominantly controlled by a migration process. However, No electrically active defects have been detected with a growth correlated to the loss of H defects.

In the case of both as-received Si-13C and Si-17O samples implanted with the enriched $^{13}$C and $^{17}$O ions and annealed, the ESR spectra are similar and visible only at $T \leq 140$ K. As shown in Fig. 2b, for the Si-13C sample, the ESR spectrum consists of a narrow line centered at $g = 2.0062$ and linewidth $\Delta B = 0.84$ mT, with parameters close to those of the A-center, and a broad, asymmetrical line at $g = 2.0061$ and linewidth $\Delta B = 1.3$ mT. Although the parameters of the second center are close to those of the B1 center, we will call the center observed in the implanted Si samples, the B2 center.

![Fig. 3. Frequency factors and activation energies of H(140K +152K) defects in STFZ and DOFZ diodes.](image)

- **EPR/ENDOR Characterization**

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![Fig. 4 - The ESR spectra recorded at low temperatures.](image)

The ESR spectra (Fig.4 and 5) of the implanted samples exhibit after irradiation similar features. They consist of the narrow line centered at $g = 2.0061$ and linewidth $\Delta B = 1.15$ mT, parameters very close to those of the A center. In the case of the broad line one finds parameters close to those of the B
center, but slightly different, namely: \( g = 2.059 \) and linewidth \( \Delta B = 11.3 \, \text{mT} \) in the case of the irradiated Si-13C sample, and \( g = 2.057 \) and linewidth \( \Delta B = 13.4 \, \text{mT} \) in the case of the irradiated Si-17O sample.

\[-\text{HRTEM investigations}\]

Figure 5 shows a HRTEM image along the \([110]\) zone axis of the 15 MeV electron irradiated STFZ Si sample revealing by the dark contrast the presence of clusters of defects and their evolution with annealing time and temperature. Small cluster of defects give the black dotted contrast better observed in the brighter zones of the image, while the dark patches reveal the presence of larger cluster defect agglomerates. A particular contrast at defects, the so called "coffee bean", is indicated by white arrows in figure 5. These are plate-like extended defects, appearing in the image as brighter lines surrounded by the dark contrast of the surrounding strain field. The plate-like defects are oriented along the \(<110>\) directions. Their average size, considering also the surrounding strain field where the Si lattice is disturbed, is approximately 5 nm. As observed in the HRTEM images, in the zones with clusters of defects the Si lattice is not amorphous, the Si lattice is disordered by their presence, but the lattice remains crystalline. Increasing the annealing time \textit{Two types of defects start to form:}

- \{111\} \textit{type planar defects} - are intrinsic partial Frank dislocation loop formed by the \textit{aggregation of vacancies} [L Fedina et al. Phys. Stat. Sol. (a) 171, 147 (1999)]

- \{113\} \textit{type defect - planar defects} - formed by \textit{agglomeration of interstitials} [S Takeda, T. Kamino Phys Rev. B 51 2148 (1995)] and has been the most often type of extended observed in the annealed sample. The defect size did not vary after a further annealing at 200\(^{\circ}\) C. (the \{110\} \textit{defects are the precursors} of the \{113\} \textit{defect}. [S. Takeda, Phys Rev. B 51 2148 (1995)])
Fig. 5. HRTEM images, just after irradiation with electrons of 15 MeV (left), after 73,300 min. @ 80 °C and 30 min @ 200°C (middle) and after 60 min. @ 275°C (right).

The large extended defect revealed in the last HRTEM image is of interstitial type. It is formed from three segments. The outer two segments are of {113} -type defects closed in the middle by an {110} type defect. The total extension of the defect is ~33 nm. Note that such large extended defects have been seldom observed.

2) **Surface radiation damage**

It has been investigated the annealing behavior of the surface currents. In figure 6(a), the temperature dependence of the I-V curves of an irradiated gate-controlled diode measured at different temperatures from 213 K to 295 K is shown. The following scaling formula allows to describe the data

\[
I_{surf}(T) = I_{surf}(T_{max}) \cdot \frac{T}{T_{max}} \cdot \exp \left( \frac{0.605eV}{k_B} \cdot \frac{1}{T_{max}} - \frac{1}{T} \right)
\]

with \(k_B\) the Boltzmann constant. Figure 6(b) shows the comparison between the measured surface currents and the calculated ones according to the scaling formula (1) in the temperature range from 203 K to 295 K, which shows good agreement. Thus, all surface currents extracted from the measurements in our study have been scaled to the values at 20 °C. The surface-current density at 20°C, \(J_{surf}(T = 293\ K)\), is calculated from the surface current scaled to 20°C and the area of the 1st gate ring: \(J_{surf}(T = 293\ K) = \frac{I_{surf}(T = 293\ K)}{A_{1\text{st}\text{ gate}}}\).

![Graph](image-url)

Experimental results from the study of radiation damage on test structures and sensors built on high-ohmic n-type silicon for X-ray doses in the range 0–1 GGy have been implemented in
TCAD simulations and used for optimizing the pixel sensor for the AGIPD (Adaptive Gain Integrating Pixel Detector) at the European X-Ray Free-Electron Laser. The simulations show that the specifications required for AGIPD can be met for X-ray dose values between 0 and 1GGy. In the optimization of the pixel layout, breakdown voltage, inter-pixel capacitance and dark current have been considered. To estimate the inter-pixel capacitance and the dark current, the values from 2D simulations have been extrapolated to the 3D situation using empirical formulae. Given that accumulation layers form at the Si–SiO₂ interface, the inter-pixel capacitance depends only weakly on the distance between the p+ implants of the pixels. Fig. 7 shows the results. For \( N_{\text{ox}}=10^{12} \text{ cm}^{-2} \) values for \( V_{\text{bd}} \) above 200V are found for \( \text{tox} >300 \text{ nm} \). For \( 3 \times 10^{12} \text{ cm}^{-2} \) and \( \text{tox} \geq 300 \text{ nm} \), \( V_{\text{bd}} \) drops to about 20V. The simulations show that, with the optimized parameters, the specifications of the AGIPD sensor, in particular a break down voltage above 900V, a distance between the edges of the outer pixels and the cut edge of 1.2mm, an inter-pixel capacitance below 500 fF, and a dark current for the sensor of less than 50 μA can be achieved for the values of \( N_{\text{ox}} \) and \( J_{\text{surf}} \), which correspond to X-ray dose values between 0 and 1GGy. The optimized design of a corner of the sensor is shown in Fig.7 (right).

![Breakdown voltage vs. oxide thickness](image1)

![Layout of the pixel sensor](image2)

**Fig. 7.** TCAD simulation of the breakdown voltage for different oxide thicknesses and without guard-rings (left) and the layout of the pixel sensor with 15 guard-rings.