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Complex Profile in Neutron Irradiated High Resistivity
Silicon Junction Particle Detectors***

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Abstract

Distributions of the A-center (oxygen-vacancy) in neutron damaged silicon detectors have been studied using Deep Level Transient Spectroscopy. A-centers have been found to be nearly uniformly distributed in the silicon wafer depth for medium resistivity (0.1–0.2 k Ω -cm) silicon detectors. A positive filling pulse was needed to detect the A-centers in high resistivity (>4 k Ω -cm) silicon detectors, and this effect was found to be dependent on the oxidation temperature. A discussion of this effect is presented.

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SUMMARY

Silicon junction particle detectors manufactured on high resistivity n-type silicon wafers ($\rho \geq 4 \text{ k}\Omega\text{-cm}$ or $N_d < 10^{12}/\text{cm}^3$) have been widely used in high energy physics experiments. Silicon detector systems proposed for the new large accelerators, the Superconducting Super Collider and the Large Hadron Collider, will be subject to significant radiation damage from both ionizing and fast neutron fluences. One of the major concerns is the effect of neutron radiation damage causing leakage current degradation [1-4], dopant compensation and/or donor removal [2], and type-inversion ($n \rightarrow p$) [5]. It may be possible to minimize the bulk displacement damage of fast neutrons by controlling the initial impurities in the silicon crystal. Oxygen, for example, has been used [6-7] to "getter" vacancies (V) through the formation of the A-center (O-V, $E_c - 0.18 \text{ eV}$), and because of its competition for the damage-induced vacancies, decrease the concentration of the deeper E-Center (P-V, $E_c - 0.44 \text{ eV}$) and the divancy, which are much more effective SRH generation centers than A-center. Thus, gettering of vacancies might help to decrease the leakage current degradation and donor removal. A detailed study of the A-center as a function of material resistivity and processing schedules was undertaken to help understand its availability and effectiveness as such a getter. The determination of the profile of the A-center in the depth of the silicon junction detector fabricated with oxides formed at several oxidation temperatures may help resolve issues concerning of type-inversion at high neutron fluences ($> 10^{13} \text{ n/cm}^2$) where there appears to be a difference between the surface region and the bulk [7-8] and a less understood role between the A-center and thermal donors. Further, basic information on defect characteristics of high resistivity material will be important to suggest other material hardening approaches should gettering by A-centers prove not to be entirely worthwhile.

Deep Level Transient Spectroscopy (DLTS) has been widely used to characterize the parameters (e.g., the trap energy E_t , its crosssection σ_t , and its concentration N_t) of single defects in low resistivity silicon ($\rho < 10 \Omega\text{-cm}$) caused by electrons, γ -ray [9-10] and neutrons [11-12]. Some DLTS and thermally stimulated current (TSC) work on high resistivity silicon detectors has been reported [13-14], but does not deal with the profile of A-centers versus depth into the detector or the effects of processing thereon. In this work, A-centers in neutron damaged detectors fabricated on various oxides (975°C - 1200°C in oxygen ambient with and without TCA, trichloroethane) are studied using DLTS, and the profile of A-centers in medium resistivity silicon ($\rho \sim 0.1$ to $0.2 \text{ k}\Omega\text{-cm}$) is determined. The junction detectors used in this study were implanted $p^+ - n - n^+$ detectors made on n-type $\langle 111 \rangle$ silicon wafers, with intermediate resistivities of $0.15 \text{ k}\Omega\text{-cm}$ in order to directly compare float zone (lower as-grown oxygen) and Czochralski (high as-grown oxygen, available only up to this resistivity) and representative, high resistivity, detector grade, float zone material of $4 \text{ k}\Omega\text{-cm}$. Different oxides, with oxidation temperature ranging from 975°C to 1200°C , were used to introduce various concentrations of oxygen [6], into the high resistivity FZ silicon. Fast neutrons from 10 keV to 2.2 MeV , with $\bar{E} = 1 \text{ MeV}$, were obtained from the $^7\text{Li}(p,n)$ reaction using 4 MeV protons.

Table I lists the A-center concentration determined by DLTS measurements on neutron damaged detectors made on medium resistivity CZ and FZ silicon. In spite of the vast difference of oxygen concentrations (N_o) between CZ silicon ($N_o \sim 10^{17}/\text{cm}^3$) and FZ silicon ($N_o \sim 10^{15}/\text{cm}^3$), the A-center concentrations are almost the same for the two materials damaged to about $5 \times 10^{11} \text{ n/cm}^2$. Our data also have shown no difference in leakage current for

detectors damaged up to a few times 10^{12} n/cm², indicating no gettering effect in the low neutron fluence region ($\leq 10^{12}$ n/cm²) [7].

Table I. DLTS data of A-center concentrations for n-damaged CZ and FZ silicon detectors $\phi_n = 5.0 \times 10^{11}$ n/cm²

	#138-7 CZ Silicon 0.2 k Ω -cm 1100°C oxide	#141-3 FZ Silicon 0.2 k Ω -cm 1100°C oxide
A-Center Content	3.0×10^{11} /cm ³	3.1×10^{11} /cm ³

Physical parameters of the A-center, E-center and double vacancy (V-V) centers in different charge states for a medium resistivity FZ silicon detector are shown in Table II. These results essentially agree with other measurements of these defects [9,10,11,12,13].

Table II. Trap parameters for a FZ silicon detector (#143-7), $\phi_n = 5 \times 10^{11}$ n/cm², $\rho = 0.2$ k Ω -cm, 1100°C oxide.

	A-Center	V-V ⁼	E-Center and V-V ⁻
$E_c - E_t$ (eV)	0.17	0.21	0.41
σ_t (cm ²)	2×10^{-15}	1.3×10^{-16}	6×10^{-16}
N_t (cm ⁻³)	2.5×10^{11}	1.2×10^{11}	3.3×10^{11}

Figure 1 shows the A-center concentration as a function of depletion depth obtained by DLTS measurements on detector #143-7 (FZ, medium resistivity). This profile was obtained by varying the depletion voltage while keeping the difference between the pulse maximum $|V_{\max}|$ and minimum $|V_{\min}|$ at a constant, i.e., $|V_{\max}| - |V_{\min}| = 1$ Volt. One can therefore study those traps near the depletion edge [15]. A specific distribution of the A-center cannot be distinguished as either a near-surface or uniform through the bulk distribution from the range of depletion depths available from material of this resistivity.

For high resistivity silicon (4K Ω -cm), however, it has been found that one has to use a positive filling pulse (forward bias, $0 < V < 0.7V$) to detect the A-center concentration. Table III summarizes the data of the dependence of the A-center concentration on the positive filling bias for detectors fabricated after various temperature/oxidation schedules. The negative results for the high temperature oxidation (first column) are included only for direct comparison with the other samples as they are results from the search as a function of filling bias. The positive filling bias effect becomes more evident as the oxidation temperature increases. This effect does not occur in medium resistivity silicon detectors regardless of oxidation temperature; the A-center was observable without requiring the fill pulse to go positive. No significant differences in E-center concentrations among detectors made on various oxides up to $\phi_n = 5 \times 10^{11}$ cm² were observed.

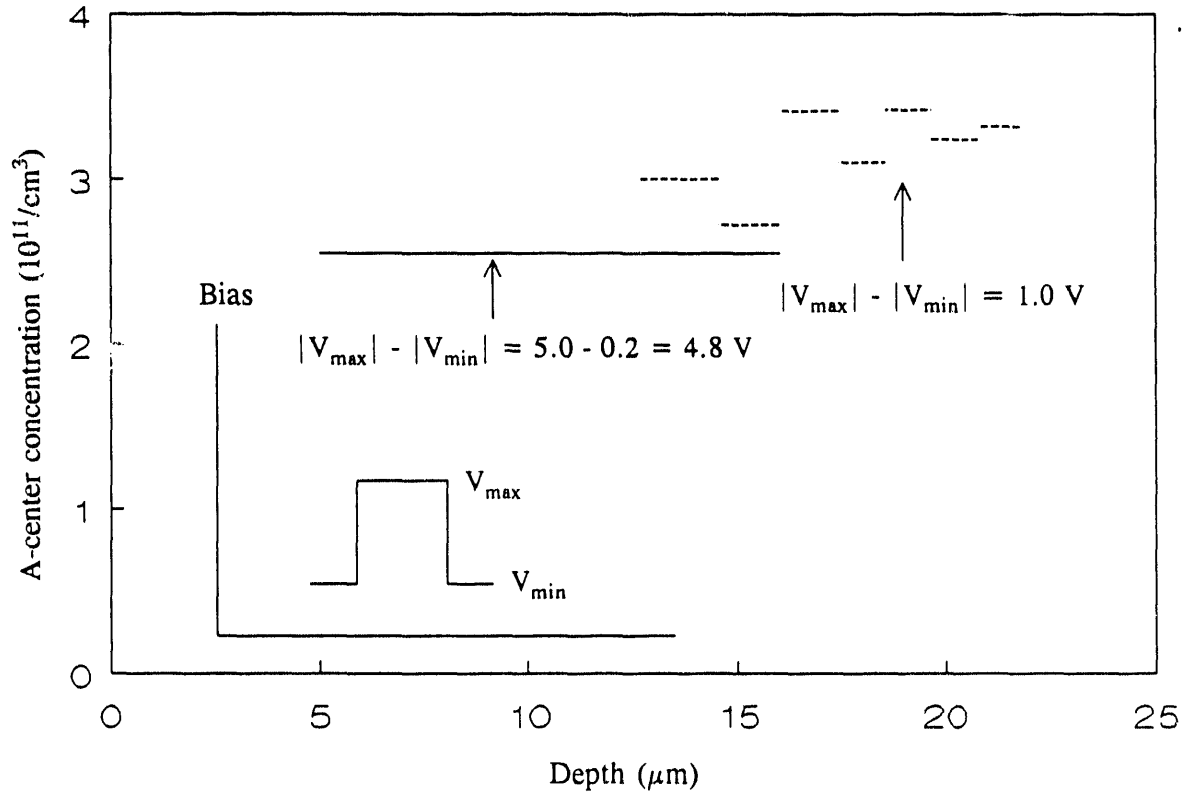


Fig. 1. A-center profile obtained from DLTS using various reverse bias with fixed $|V_{\max}| - |V_{\min}|$. (#143-7, $\rho = 0.1 - 0.2 \text{ k}\Omega\text{-cm}$, $\phi_n = 5 \times 10^{11} \text{ n/cm}^2$)
The solid line extending to $15\mu\text{m}$ is the concentration for the full bias of 5V including the volume up to the depletion of $15 \mu\text{m}$.

The difficulty in observing the A-center in high resistivity samples compared with the medium resistivity samples must lie in part with the different positions of the fermi level, which lies below the A-center in the $4\text{K}\Omega$ material, but very close to the A-center defect level at medium resistivity. Therefore substantial fast detrapping must occur for the majority carriers after filling under normal conditions with large reverse biases. Slight forward biases, however, permit filling of centers near the surface, p+ contact, where band bending permits the centers to remain filled longer over the course of the measurement. A slight positive bias, of the order of the diffusion potential is required to do this.

Table III. A-center concentrations at various filling voltages, $\phi_n = 5.0 \times 10^{11} \text{ n/cm}^2$

	#132-3 FZ 4 k Ω -cm 1200°C Oxide+TCA	#130-4 FZ 4 k Ω -cm 1100°C Oxide	#133-4 FZ 4 k Ω -cm 975°C Oxide
V_{fill} (V)	A-center (cm ⁻³)	A-center (cm ⁻³)	A-center (cm ⁻³)
1.0	not detected	7.2×10^{10}	1.3×10^{11}
0.9	not detected	1.8×10^{11}	1.6×10^{11}
0.8	not detected	4.2×10^{11}	3.0×10^{11}
0.7	not detected	1.10×10^{11}	6.5×10^{11}
0.6	not detected	1.0×10^{11}	6.0×10^{11}
0.5	not detected	7.2×10^{10}	6.0×10^{11}
0.4	not detected	6.3×10^{10}	6.1×10^{11}
0.3	not detected	3.1×10^{10}	5.7×10^{11}
0.2	not detected	$< 10^{10}$	5.7×10^{11}
0.1	not detected		4.6×10^{11}
0.0	not detected	$< 10^{10}$	2.9×10^{11}
-0.5	not detected		4.5×10^{10}
-1.0	not detected	$< 10^{10}$	4.5×10^{10}
-1.5	not detected		4.8×10^{10}
-2.0	not detected		4.8×10^{10}
-3.5	not detected		5.6×10^{10}
-5.0	not detected		5.5×10^{10}

(Some data for a 1200C oxidation without TCA did yield a detectable A-center concentration of about $5 \times 10^{11}/\text{cm}^3$ only for filling pulses between +0.3 and +0.8 volts).

If one pursues the possibility of the A-centers being surface concentrated, one can consider the oxidation conditions. The 1200C oxidation parameters were chosen to follow [6] who after reasonable assumptions about the source oxygen concentration believe one achieves a concentration of at least $10^{17}/\text{cm}^2$, to be equivalent to CZ material, throughout the bulk of the wafer with an approximate diffusion length of $60\mu\text{m}$. The lower temperature oxidations give diffusion lengths of a few microns. If one assumes the source oxygen concentration--at the surface--is essentially equal for both high and low temperature processes, one would not expect a substantially different near-surface oxygen concentration acting as a sink for vacancies and thus giving the higher A-center concentration observed. The shorter time lower temperature oxidations might, however, produce a higher concentration of free, available, uncomplexed oxygen for more effective A-center formation. Alternatively, the high temperature (1200C) oxidation using oxygen plus TCA is known to create a denuded zone of silicon interstitials near the surface and some growth of interstitial precipitates in the bulk during cool-down[16]. The silicon interstitials and precipitates, though still a good sink for vacancies, may not provide enough free oxygen to form single defect A-centers. Certainly, further experiments with samples having different thermal histories may help confirm these suggestions.

We have shown that the A-center has a nearly uniform depth profile for medium resistivity silicon detectors under a variety of oxidation conditions after somewhat low fast neutron fluences. In high resistivity silicon, the detection of the A-center is dependent on both

the fill pulse and the oxidation process. Measurements will continue to further explore A-center behavior and to quantify the depth profile in high resistivity silicon.

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