

Silicon Surface Barrier Detectors Irradiated by 500keV-1MeV Electrons

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The radiation effects on silicon surface barrier detectors by 500keV, 750keV, and 1MeV electrons have been investigated using fifty in-house fabricated detectors of 200-1000 Ω cm resistivities. The change of reverse current, forward current, depletion layer capacitance, and ^{210}Po alpha spectrum are measured.

The reverse current changes in complicated forms with electron fluence. The forward current and the capacitance begin to change at $1 \times 10^{16} \text{ cm}^{-2}$ and the capacitance tends to saturate at $5 \times 10^{16} \text{ cm}^{-2}$. The alpha spectrum begins to degrade at $1 \times 10^{14} \text{ cm}^{-2}$ and the double peaks are observed at higher fluences.

The detector characteristics are dependent on the total electron dosage, incident electron energy, and detector thickness. These effects mean the formation of trap centers is quite significant in the irradiated silicon.

1. Introduction

In space radiation researchs and in nuclear physics, surface barrier detectors have been widely used for the detection of various radiations. In spite of their many advantages, the damaging effects by radiations on detector properties are observed and they limit the effective life time of detectors. The damaging effects change mainly the electrical properties such as the reverse current, depletion layer capacitance, and energy resolution.

The mechanism of these effects has been known that the radiation interaction with detector lattice atoms produces vacancy-interstitial pairs called Frenkel defects, and the defects as well as the impurity atoms are assumed to form complex centers.¹⁾ These centers are partly annealed during the irradiation, but most of them are sinked in the detector and act as traps for electrons and holes and also as recombination centers.

The radiation damages are observed for most of the radiations, i.e., neutrons,²⁾ heavy charged particles,³⁻⁶⁾ electrons,^{2,7)} and gamma rays.⁸⁾ Since each radiation produces different number and distribution of defects because of its respective interaction cross section, mass, and energy distribution of recoil silicon atoms, the damaging effect is different in each case.

We have investigated the damaging effects of surface barrier detectors by 500keV, 750keV, and 1MeV electrons for fluences over the range from 10^{14} to 10^{18} cm^{-2} at

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room temperature of $23 \pm 1^\circ\text{C}$. The experimental results are presented for the properties of reverse current, forward current, depletion layer capacitance, and also energy spectra of ^{210}Po alpha particles. From these results, we discuss about the defect properties produced. A comment is done about the life time of surface barrier detectors under the energetic electron irradiations.

2. Experiments

In-house fabricated silicon surface barrier detectors with the active area of $7 \times 7 \text{ mm}^2$ were used in the experiments. These detectors were fabricated from the phosphorus doped n-type silicon single crystals with the resistivities of 200, 500, and $1000 \Omega\text{cm}$, and with the thicknesses of 400, 900, and $400 \mu\text{m}$, respectively. Each front surface of the detectors was covered by a $200 \text{ \AA}$ evaporated gold to form an active layer, and the rear ohmic contact was made by a thick electroless plated nickel. Using a Dotite paint, it was backed by a 2mm thick copper plate for the sake of setting the detector in an irradiation chamber and preventing it from electron beam heating. The profile of the detector assembly is shown in Fig. 1.

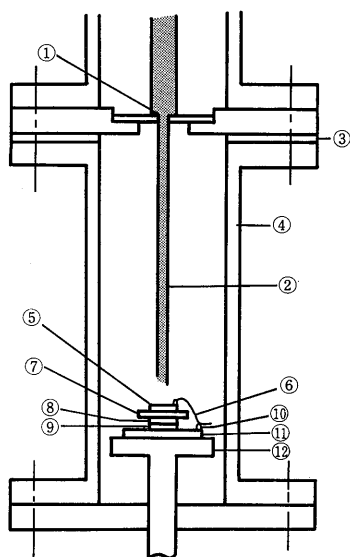


Fig. 1 Target assembly for electron irradiation.

- ① 4mm slit, ② electron beam,
- ③ insulator, ④ irradiation chamber,
- ⑤ evaporated gold, ⑥ copper lead,
- ⑦ silicon substrate, ⑧ nickel plate,
- ⑨ Dotite paint, ⑩ epoxy resin,
- ⑪ copper plate, ⑫ copper holder.

and a Q-meter. ^{210}Po alpha energy spectra was also measured by the collimated alpha beam incident on the damaged gold surface.

In this procedure, fifty detectors were irradiated by electrons and investigated the

The detectors were irradiated by 500keV, 750keV, and 1MeV electrons from the 2MeV Van de Graaff accelerator (VE-20) at the Research Laboratory of Heavy Ions in Kyoto University. All irradiations were carried out at room temperature, in vacuum, and at open circuit. The electron beam was collimated so that the 4mm diameter area at the center of the front gold layer could be irradiated uniformly. The dose rate of electrons was estimated by the beam current using a high impedance electrometer, and the dose rate was adjusted over the range from 2×10^{12} to $1 \times 10^{14} \text{ cm}^{-2}\text{s}^{-1}$, and the irradiation time was 60 to 1600s, and so the total dosage was chosen from 1×10^{14} to $1 \times 10^{18} \text{ cm}^{-2}$.

After each irradiation, the detectors were took out from an irradiation chamber and annealed in room environment for two hours. The reverse current, forward current, and capacitance were measured by using a digital voltmeter, a micro-ammeter,

damaging effects. Some of the irradiated detectors were re-fabricated as new surface barrier detectors for investigating the damaged areas, depths, and the damage properties. However this work is in progress, so the precise knowledge is not attained at present.

3. Results and Discussions

Generally, the radiation damage by electrons degrade the properties of surface barrier detectors, i.e., the increases of leakage current and noise level take place. A degradation of energy resolution is also seen in the spectrum for monoenergetic alpha particles. It has been said that electrons below about 250keV in energy cannot produce electrically active defects in silicon⁹⁾ and that, in some lower fluence, the detector properties can be improved. Therefore in the present study, we have selected the minimum electron energy as 500keV and determined the initial fluence as high as the damaging effects may appear.

When the reverse current was measured immediately after the irradiations, the voltage-current characteristics were very unstable, and especially for higher fluences remarkable hysteresis behavior and breakdown at low bias voltages were observed. Under such conditions, the alpha spectrum could not be resolved since the noise level was high enough. These would be attributed to the appreciable agitation of produced defects by applying the electric field.

However, the detectors annealed by slow degrees, and then the reverse current reached an equilibrium state, and the phenomenon like breakdown disappeared. The alpha spectrum also became detectable. Therefore we measured the properties of each irradiated detector after two hours' annealing. The measured detector was carefully resetted in the irradiation chamber without discrepancy of the irradiated region, and summed up the dosage repeatedly.

3.1. Reverse Current

Reverse current is composed of saturation current, surface leakage current, and thermal generation current in a depletion layer. Since the surface current is strongly dependent on the fabrication technique and environment of the detector, the samples having equal characteristics are hardly preparable. However, this feature has been found to have no appreciable correlation with electron fluence.

The general behavior of reverse current I_R against bias voltage V_R with electron and proton fluences has been observed by Coleman and others⁵⁻⁷⁾. We have obtained the similar characteristics, but as shown in Fig. 2, the V_R - I_R relation does not change monotonically according to the dosage. Such behaviors

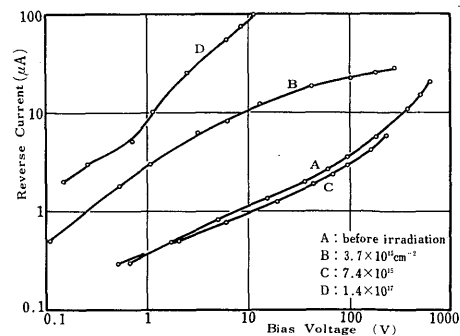


Fig. 2 Reverse voltage-current characteristics of a silicon surface barrier detector for various electron fluences.

are also seen in many complicated data of various detectors under the fluences of different electron energies. Qualitatively we find the V_R - I_R relations at 500keV irradiation have a saturating property above $1 \times 10^{16} \text{ cm}^{-2}$, but these at 1MeV rise steeply as the fluences increase.

To explain these complicated aspects, the following possibilities would be considered:

- a) Surface leakage current changes under fluence. For example the surface contaminations are sputtered by the colliding electrons.
- b) Depletion layer thickness becomes wider at the constant bias voltage by fluence, and so the generation current increases at low bias voltage.
- c) Electron range in silicon depends on electron energy, so the defect densities produced are not uniform in a detector. At high energy irradiation, some electrons can pass through the detector without producing defects completely, and some will be backscattered by the copper plate and produce additional defects in the whole detector volume. For example, the electron ranges in silicon are about $700\mu\text{m}$ and $1800\mu\text{m}$ for 500keV and 1MeV electrons, respectively.
- d) Electrons scattered by the slit edge or by the target assembly are different for each irradiation, and so the effectively exposed area is not 4mm diameter or displaced to some extent.
- e) Annealing effects may be in progress at the measurement time.

To understand the complicated V_R - I_R relations more clearly, we rearranged the data by calculating the factor

$$[(I_R)_X / (I_R)_{0.5}]_s / [(I_R)_X / (I_R)_{0.5}]_0,$$

where the denominator and numerator are the ratio of the reverse current at the bias voltage X volt to that at 0.5 volt before and after the irradiation $\phi \text{ cm}^{-2}$, respectively. This factor versus bias voltage relations are shown in Fig. 3. These curves express the reverse current changing rate against bias voltage under the constant fluences. At low fluences the most curves show the independence on bias voltage, which means the defects are produced uniformly. However for the 200 Ωcm detectors at low fluences of 500keV electrons, the curves are concaved upward against bias voltage, which means the defect density is localized and the depletion layer having many defects will appear according to the increase of bias voltage. At higher fluences the curves show decreasing behaviors against bias voltage for all the detectors. This means the reverse current at low bias voltage increases remarkably. At very high fluences some curves increase rapidly against bias voltage, which means the breakdown begins to occur.

The complexity of the V_R - I_R relations is attributed to the inequality of detector surfaces and to the distribution of defects. The distinct difference of the 200 Ωcm detectors by 500keV electrons to others would clarify the reverse current properties by electron irradiations.

3.2. Forward Current

The forward current of surface barrier detectors is characterized by the diode law of

$$I_F = I_{F0} [\exp(-eV/kT) - 1],$$

where I_F is the forward current at the bias voltage V_F . And e , k , T is the electron

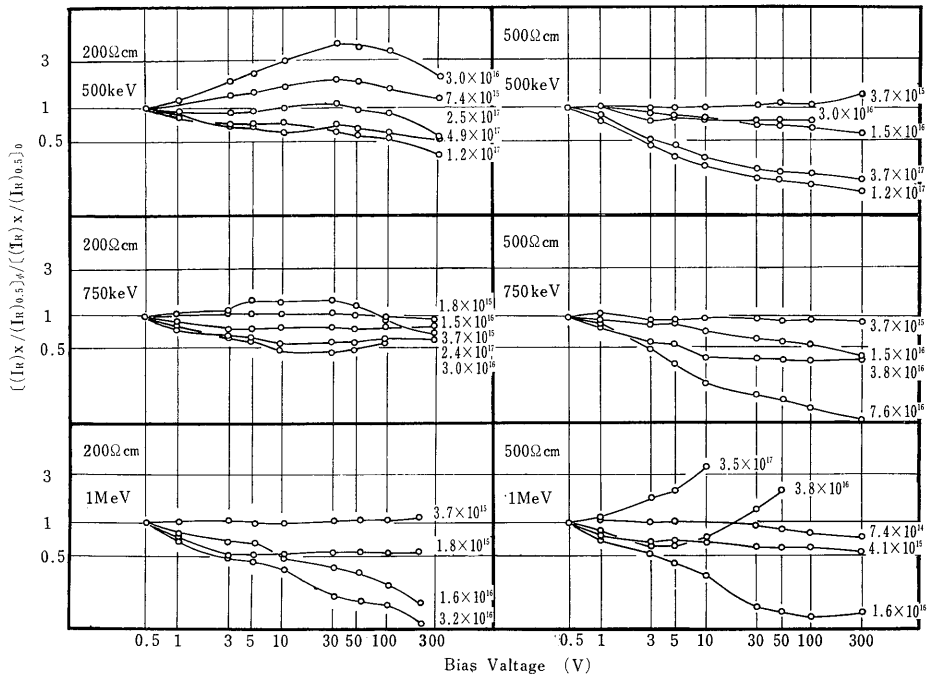


Fig. 3 Rate of reverse current characteristics against bias voltage for 200 and 500Ωcm detectors under various fluences.

charge, Boltzmann constant, and absolute temperature, respectively. I_{F0} is the saturation current which depends on the junction potential, diffusion length, and other parameters. This theoretical formula generally does not coincide with the actual forward current characteristics of detectors. In Fig. 4, the illustrative relation V_F - I_F relations under various fluences are shown. The forward current begins to decrease at the fluence of about $5 \times 10^{15} \text{ cm}^{-2}$ and this tendency is seen for all the detectors. But since I_{F0} is a resultant of many parameters, one cannot analyze at present which parameter is significantly affected by electron fluences.

3.3 Capacitance

The detector capacitance is measured by a Q-meter at 800kHz calibrated by a standard capacitance. For a step junction, the capaci-

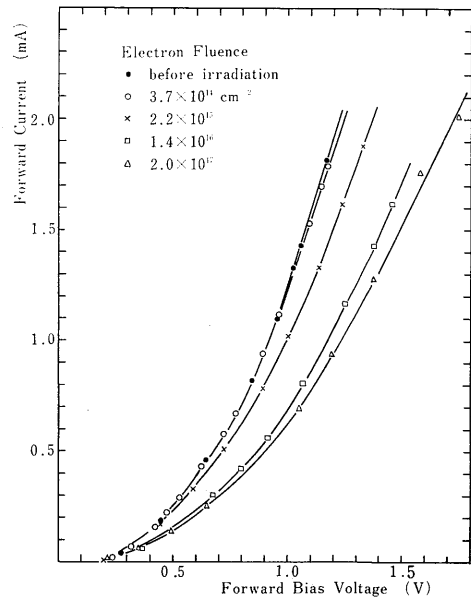


Fig. 4 Forward voltage-current behaviors of a silicon surface barrier detector up to $2 \times 10^{17} \text{ cm}^{-2}$ electron fluence.

tance C is correlated with the depletion layer thickness d as $C \propto d^{-1}$. The thickness d depends on the substrate resistivity ρ , bias voltage V_R , junction potential V_J , and electron mobility μ as $d \propto [(V_R + V_J)\rho\mu]^{1/2}$. For silicon surface barrier detectors, these relations can be approximated as

$$C = 1.06 \times 10^4 / d,$$

$$d = 0.50 \cdot (\rho V_R)^{1/2},$$

$$C : [\text{pF} \cdot \text{cm}^{-2}], d : [\mu\text{m}], \rho : [\Omega \cdot \text{cm}], V_R : [\text{V}].$$

Before the irradiation, the detector has been found to satisfy the above relations, but the capacitance decreases according to the fluence as seen in Fig. 5. It is interesting that the capacitance has shown the same value before and after annealing. Fig. 6 shows the normalized capacitance at 5V bias against fluence and the decrease is seen at about $5 \times 10^{15} \text{ cm}^{-2}$. This means that the effective donor density becomes low by damage

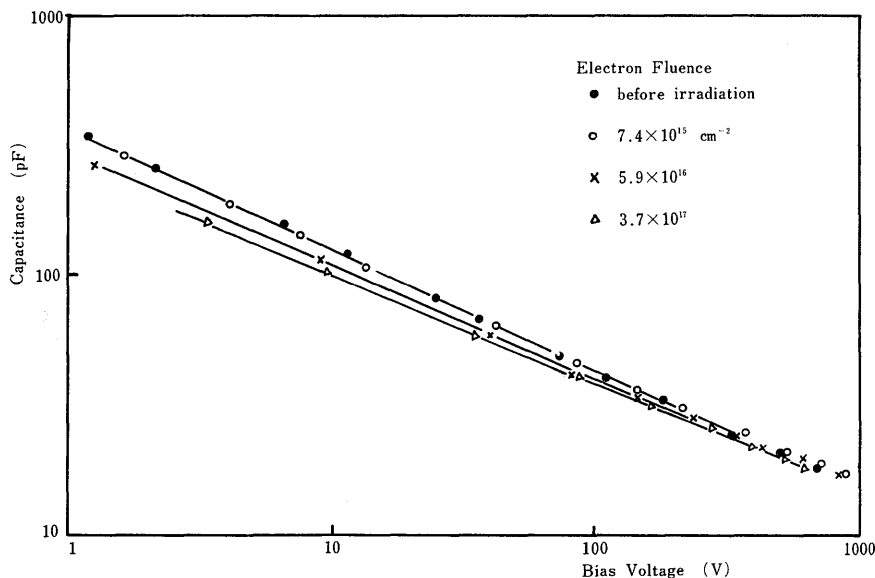


Fig. 5 Voltage-capacitance characteristics of a 500Ωcm detector under various electron fluences.

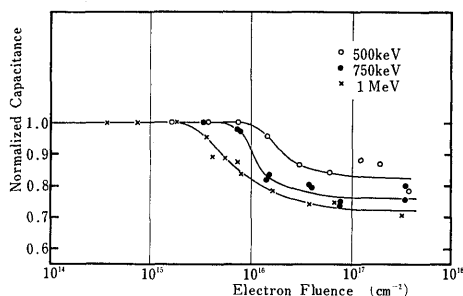


Fig. 6 Normalized capacitance of 500Ωcm detectors at 5V bias against electron fluence.

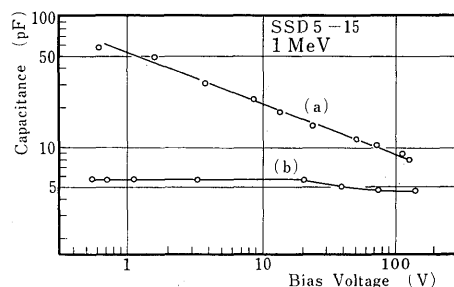


Fig. 7 Voltage-capacitance characteristics of a 500Ωcm detector at (a) zero and (b) $1.8 \times 10^{16} \text{ cm}^{-2}$ fluence.

and the depletion layer becomes thicker, breaking now clearly the simple diode law of $C \propto (\rho V_R)^{-1/2}$. The breakdown of the diode law can be seen more obviously in Fig. 7. In this figure, the sensitive gold layer of an irradiated detector is re-fabricated and only the irradiated area is left for the gold layer. In this case, the capacitance is independent on bias voltage just like an intrinsic detectors, but the characteristics of intrinsic detectors cannot be obtained at all and the alpha spectrum from this detector degraded very intensely as seen later.

From these features, we conclude that the produced defects behave as electron traps and compensate donor atoms. At high fluences, the probability of filling traps becomes constant since the inner electric field stays constant, and so the capacitance is independent on bias voltage. Since the donor density is characterized by the substrate resistivity, the capacitance should vary more easily for detectors of higher resistivities. This is supported by the fact of Fig. 8 that the 1000Ωcm detector changes its capacitance at $1 \times 10^{15} \text{ cm}^{-2}$, whereas the 200Ωcm one at $5 \times 10^{15} \text{ cm}^{-2}$. The behavior is also in agreement with the work by George and Gunnarsen²⁾.

Liu and Coleman⁷⁾ have reported the increase of capacitance at high fluences, which seems inconsistent with our observation. However, their detectors have a high resistivity of 20,000 to 45,000Ωcm. If such a detector is used, the saturation of capacitance would occur at low fluence because the necessary number of traps to neutralize the donor atoms is small enough. In fact, their detector shows a saturation at about 10^{13} cm^{-2} . At higher fluences, the traps would exceed the donors, probably resulting in an increase of capacitance. On the contrary, our detector shows the saturation at $5 \times 10^{16} \text{ cm}^{-2}$. Therefore the change in capacitance is explained by a competing phenomenon of traps with impurity densities.

3.4 Alpha Energy Spectrum

The detector life time for detecting heavy charged particles is the most remarkable factor in the radiation damage effects. ^{210}Po alpha energy spectra were measured in vacuum at room temperature with a collimated beam through a 1mm diameter slit after each irradiation. In Fig. 9, the alpha spectra of 200Ωcm detectors at various fluences are shown. The spectra degrade with fluence as expected, and even at the low fluences under which capacitance change still does not occur, the degradation appears as a broader alpha peak. At higher fluences, the spectra have discrete two peaks. This peak separation becomes remarkable with fluences. The counting efficiency of the upper peak decreases with fluences and finally this peak cannot be observed at low bias voltage.

These phenomena can be explained by the trapping of the created electron-hole

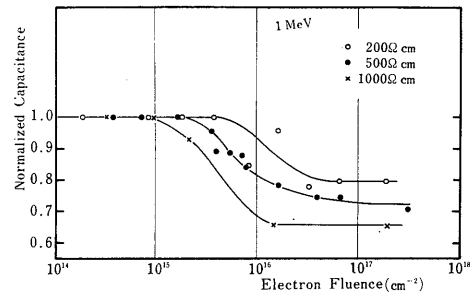


Fig. 8 Normalized capacitance against fluence for 200, 500, and 1000Ωcm detectors.

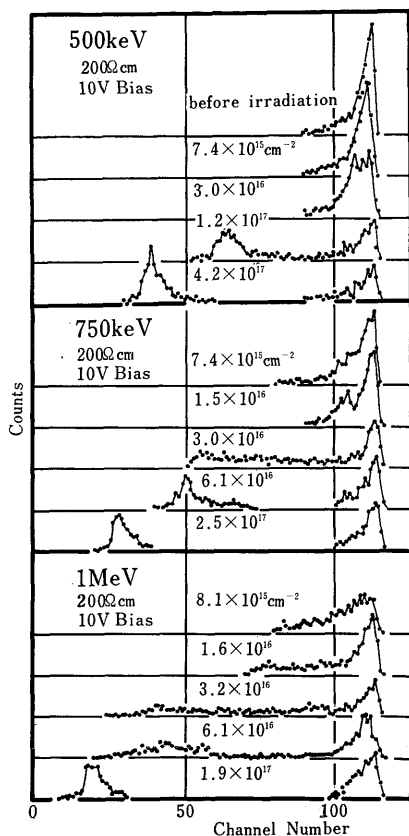


Fig. 9 ^{210}Po alpha spectra of 200Ωcm detectors at 10V bias by 500keV, 750keV, and 1MeV electron irradiations of various fluences.

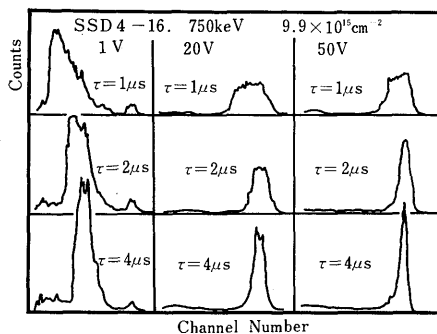


Fig. 11 Variation of ^{210}Po alpha spectra of a damaged detector for various clipping times of an amplifier and bias voltages.

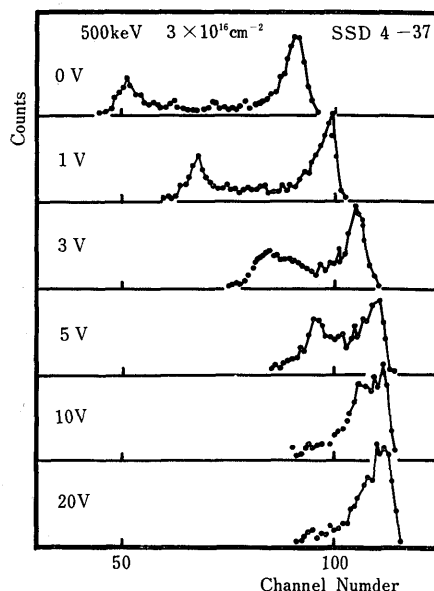


Fig. 10 Variation of ^{210}Po alpha spectra of a damaged detector for various bias voltages.

pairs along the alpha particle path. An incident alpha of 5.3MeV creates about 1.5×10^6 pairs along the range of $25\mu\text{m}$ in silicon. These pairs drift in the depletion layer according to the inner electric field. If the defects trap the drifting electrons for a moment, the charge collecting time in the detector becomes longer than that without trapping. This means the pulse rise time changes by the trapping action. So the alpha spectra degrade according to the defect formation, to the inner electric field intensity, and partly to the amplifier clipping time. If the bias voltage is raised, the trapping probability decreases according to the electron drift velocity and the double peaks tend to disappear as shown in Fig. 10. The similar behavior is attained by making the clipping time longer, which would be easily understood by Fig. 11.

4. Conclusional Remarks

The electrical properties and alpha spectra of the irradiated surface barrier detectors have been investigated systematically and the trapping action of the created defects has been found significantly. The maximum electron fluence under which the detector can perform as an allowable alpha counter is estimated as about $1 \times 10^{14} \text{ cm}^{-2}$. The capacitance change begins to occur at $1 \times 10^{15} \text{ cm}^{-2}$ and saturates at $5 \times 10^{16} \text{ cm}^{-2}$, but slightly depends on irradiated electron energy and initial detector resistivity.

The surface barrier detectors for heavy charged particles used in energetic electron environment must be thin detectors whose thicknesses can stop particles. The clipping time must be selected as long as the noise and pile-up effects can be neglected. The detector bias voltage is also selected as high as possible, but noise level and leakage current must be considered.

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