

Damage Effects of Silicon Surface Barrier Detectors with Protons, Alphas and Nitrogen Ions

Shunsuke NAKAMOTO*, Takashi AOKI*, and Keishi KAWABATA**

(Received August 21, 1973)

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1. Introduction

Surface barrier silicon detectors have been generally used for detecting heavy charged particles such as protons and alphas. In spite of its usefulness, the effects of radiation damage have restricted the applicable lifetime of the detectors. These effects have been known through the investigations of the radiation effects in bulk silicon and germanium. Since the development of the artificial satellites orbiting around the earth, silicon detectors of diffusion or surface barrier type were operated for the detections of cosmic rays and also silicon solar cells were used for power supplies. At the same time, silicon detectors were found superior to the former detectors such as ionization, proportional, or scintillation counters to detect heavy ions in nuclear physics experiments. Then the effects of radiation damage in silicon detectors have become necessary to be more and more investigated. The studies began about ten years ago, but the obtained results are a few. The damage effects by protons¹⁻⁵⁾ and alphas^{6,7)} appear in the changes of energy spectrum resolution, depletion layer capacitance and leakage current. Some of the defects created by the incident heavy ions are stable at room temperature and trap and/or recombine excess carriers. These defects have been concluded as acceptor type by Dearnaley⁸⁾, acceptor and donor type by Coleman^{3,4)}, and donor type by Scott^{1,2)} and Aukerman⁵⁾.

We have irradiated two hundred surface barrier detectors with protons (0.5-2 MeV), alphas (1-6 MeV) and nitrogen ions (1-4 MeV). Then we have investigated the damage effects by measuring various electrical properties which are important for the detector performance. Some of the irradiated detectors were annealed up to 400°C and the annealing effects of electrical properties have been investigated.

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2. Experimental Procedure

The detectors of 0.3-0.9 mm in thickness were fabricated from phosphorous-doped float-zone silicon having the resistivity of 200-500 Ω cm, and the sensitive area was made by evaporating gold onto the surface by 5 mm in diameter (20mm²). The surface barrier detectors were found quite reliable in electrical properties.

The irradiation was done at room temperature in a vacuum chamber, at the bottom of which the detector was placed with circuit open. The broad ion beam was refined by an entrance slit of 10mm in diameter and so the detector was exposed to an uniform ion beam. The beams of 0.5-2 MeV protons, 1-2 MeV alphas and 1-4 MeV nitrogen ions were produced by using a 4 MV Van de Graaff accelerator (VI-40) in Kyoto University. The dose rate was $1 \times 10^{10} - 1 \times 10^{11}/\text{cm}^2 \cdot \text{s}$ and the total fluence was $5 \times 10^{10} - 3 \times 10^{13}/\text{cm}^2$.

The beam current entering into the chamber was measure by an electrometer and the total charge by a pen-recorder. However, since the beam intensity was too small and unstable, it was difficult to read the total fluence by the recorder output. Therefore we have devised newly a pA current-integrator combined with the electrometer. The mV output of it is amplified and led to an integrator, and when the integrator output reaches a given level, a comparator works to reset the integrator to zero level and again the integrator starts. The reset number is thus proportional to the total fluence. The circuit block diagram as well as the irradiation arrangements are shown in Fig. 1.

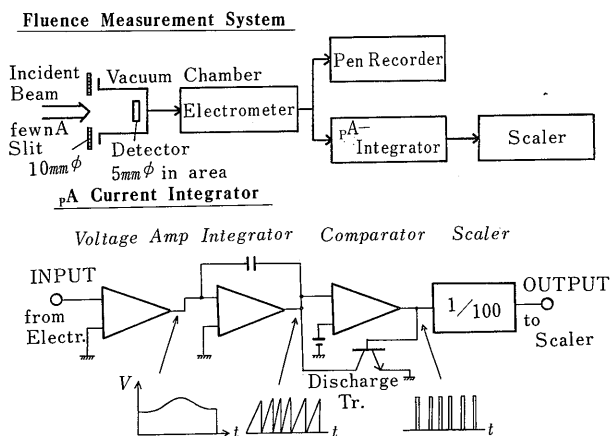


Fig. 1 Block diagram to measure ion fluence and circuit diagram of pA current integrator.

capacitance by 800 kHz frequency of a Q-meter. These measurements were done at room temperature ($23 \pm 1^\circ\text{C}$) and two hours after the irradiation in order to make the electrical properties stable enough.

The isochronal annealing (10 min) of the irradiated detectors was done in air up to 200°C with a temperature controlled oven ($\pm 0.5^\circ\text{C}$), and in N_2 gas up to 400°C with an oven ($\pm 2^\circ\text{C}$). The device of controlling temperature is shown in Fig. 2. The measurements were done half a day after the annealing.

The 6 MeV alpha particles from a ^{252}Cf - α source were also used, but the irradiation was done in air because it needed a long time. The dose rate was $2 \times 10^8/\text{cm}^2 \cdot \text{s}$ and the fluence was $1 \times 10^8 - 8 \times 10^{10}/\text{cm}^2$.

The electrical properties of the detector measured were the ^{241}Am - α spectrum, depletion layer capacitance against voltage (C - V relation) and reverse current against voltage (I - V relation). The spectrum measurement was done by 1 μs shaping time of a linear amplifier, and the

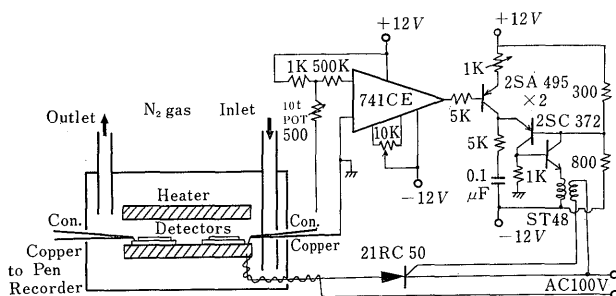


Fig. 2 Temperature controlled oven and its circuit.

3. Results

3.1 Proton Irradiations

The alpha spectrum at a constant reverse voltage of the irradiated detector degraded as to decrease the pulse height. The degree of decrease was more remarkable at lower bias voltage. But the rise time of alpha pulses was not influenced heavily, and it differed from the electron-irradiated detectors in which the pulse rise time was lengthened^{8,9)}. By the isochronal annealing, the spectrum recovered gradually up to 400°C but a complete recovery could not be obtained. An example of the proton irradiation and annealing effects is shown in the spectra in Fig. 3. The decrease of the peak channels was serious whereas the broadening of the peak was not. The broadening of the peak means the increase of noise level or the ununiformity of the damaged area. As seen in the figure, the spectra at lower bias show a faster degradation and also a faster recovery, but the complete recovery could not be obtained by annealing. Higher bias voltage was not applicable to the annealed detector, because the leakage current increased heavily.

The shift of the peak channels caused by irradiation are shown in Fig. 4. It is seen that the peaks at 10 V bias do not change up to $5 \times 10^{11}/\text{cm}^2$ for 0.5-2 MeV protons. An interesting result is that 2 MeV protons degraded the peak channels at 1 V bias most heavily and the channels at 10 V bias most slightly among 0.5-2 MeV protons. The difference of the detector resistivities has little influence upon the spectrum degradation which was seen

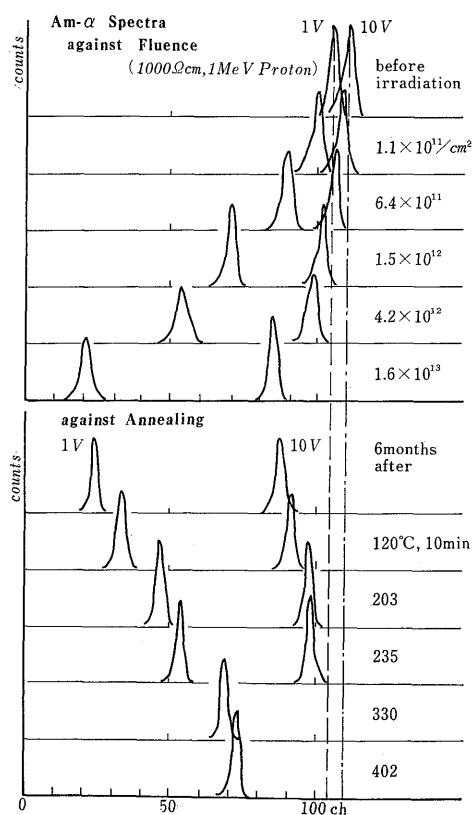


Fig. 3 ^{241}Am - α spectra against fluence and isochronal annealing temperature. The first spectrum in annealing is measured after 6 months storing at room temperature.

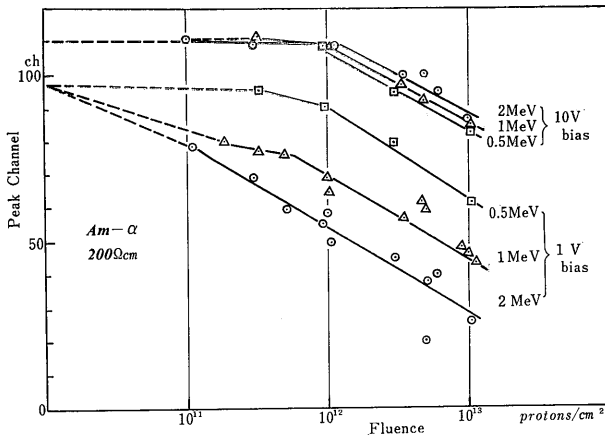


Fig. 4 Peak channel number of $^{241}\text{Am}-\alpha$ at 1 and 10 V bias against fluence of 0.5-2 MeV protons.

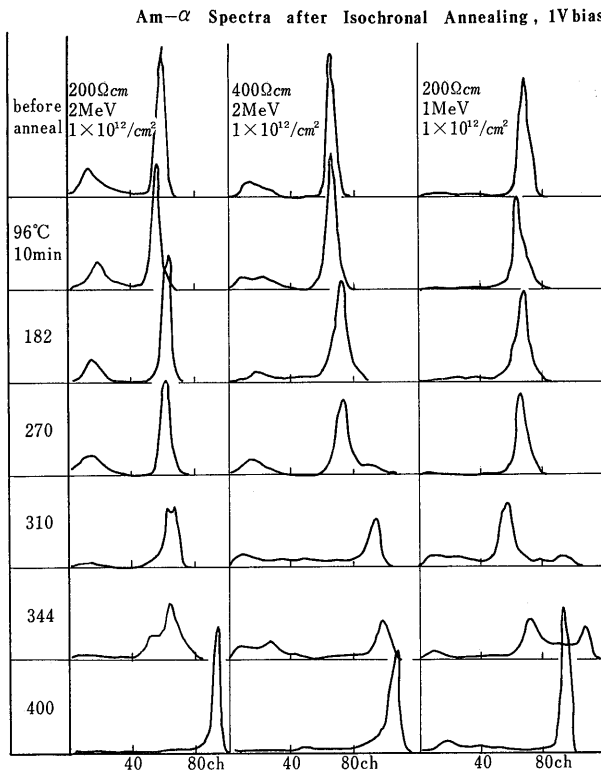


Fig. 5 Isochronal annealing effect (10 min) of $^{241}\text{Am}-\alpha$ spectrum at 1 V bias.

becomes the constant capacitance value, which means the proton ranges influence on the C-V relations.

The I-V relations are also shown in Figs. 7 and 8. The leakage current increased monotonically against fluence and the dominant difference from the I-V relations in

clearly in the electron irradiations.⁸⁻¹⁰⁾

The annealing behaviors of the spectrum at 1 V bias are shown in Fig. 5. An incomplete recovery is seen even at 400°C. At 310-344°C, a simultaneous occurrence of recovery and reverse annealing is observed. Some examples of the peak channel shifts against annealing temperature are shown in Fig. 6. The complicated annealing behaviors are observed and, especially at about 340°C even the broadening of the peak exists. At about 400°C, the spectra begin to recover remarkably.

The behaviors of the C-V relations by irradiations have a tendency to keep the capacitance value constant up to a certain bias voltage determined by the fluence. The C-V relations of the same detector in Fig. 3 are shown in Fig. 7. The C-V relations, which have the relation of $C \propto V^{-1/2}$ before irradiation, have the nearly constant capacitance value of 100 pF by 1 MeV proton irradiations. The constant region extends to higher bias voltages according to the higher fluences. At a certain voltage, the capacitances decrease gradually and coincide with the non-irradiated C-V curve. The constant values of the capacitance is correlated with the proton energy as shown in Fig. 8. The higher is the incident energy, the lower be-

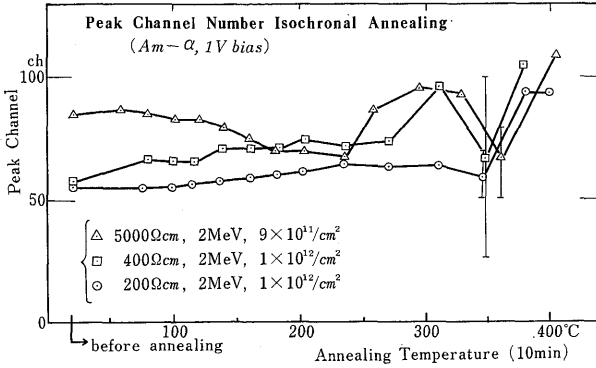


Fig. 6 Peak channel number of $^{241}\text{Am-}\alpha$ against isochronal annealing temperature at 1V bias in proton-irradiated detectors. The bars at about 350°C show the width of peak channels.

the electron irradiations is that the leakage current below about 1 V bias increases very fast against the bias voltage and above 1 V bias it increases gradually, which was also seen by Coleman.^{3,4)}

The annealing effects of the C - V and I - V relations are shown in Fig. 9 which follows Fig.

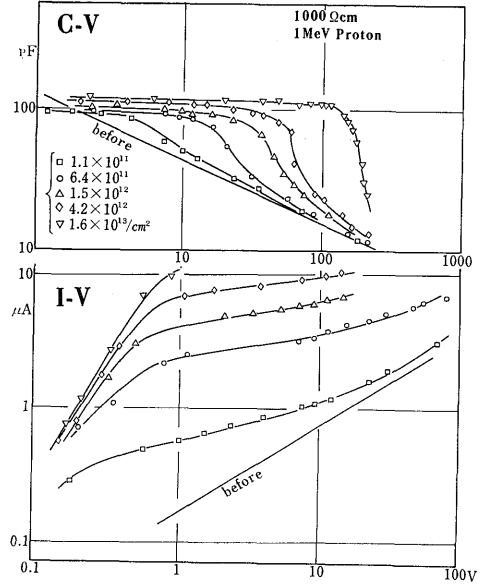


Fig. 7 C - V and I - V relations against 1 MeV proton irradiation. The detector is same as that in Fig. 3. The letter "before" means "before irradiation".

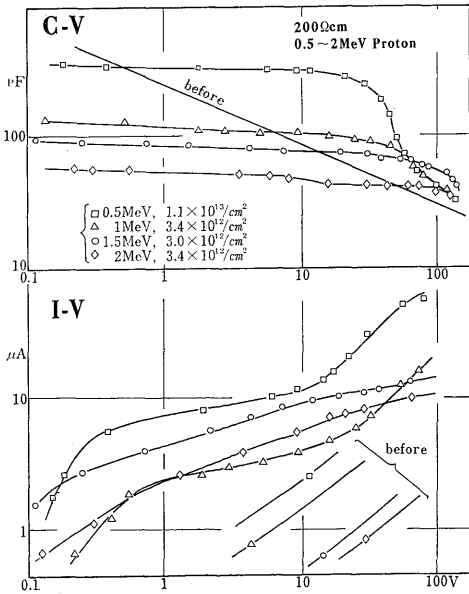


Fig. 8 C - V and I - V relations against 0.5-2 MeV proton irradiation.

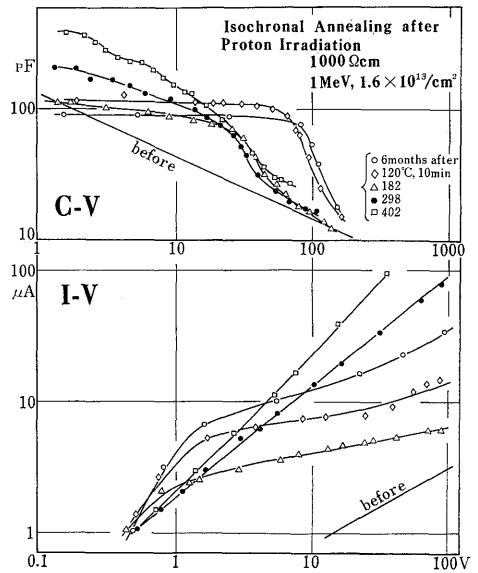


Fig. 9 Isochronal annealing effects of C - V and I - V relations of proton-irradiated detector. The detector is same as that in Figs. 3 and 7.

7. A slight recovery of the C - V and I - V relations as well as in the spectra is observed in the detector stored at room temperature during 6 months after the irradiation. The C - V relations do not recover up to 402°C. The I - V relations are rather improved by annealing up to a certain temperature, but become bad above its temperature. Therefore we observe that the full recoveries of these relations cannot be obtained by annealing.

The necessary bias voltage to make the capacitance constant against annealing temperature are shown in Fig. 10. The constant capacitance values are selected at the decreasing regions of the capacitance curves proceeded by the constant capacitance regions. These voltage curves are qualitatively similar to almost all the annealed detectors.

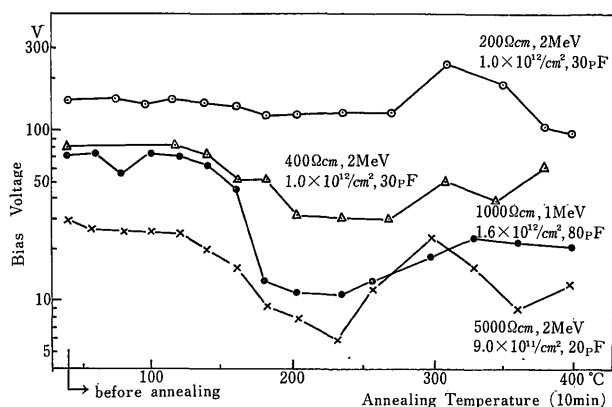


Fig. 10 Voltage required to make the capacitance value constant against isochronal annealing temperature. The line connected with triangles comes from the necessary voltages for 80 pF in Fig. 9.

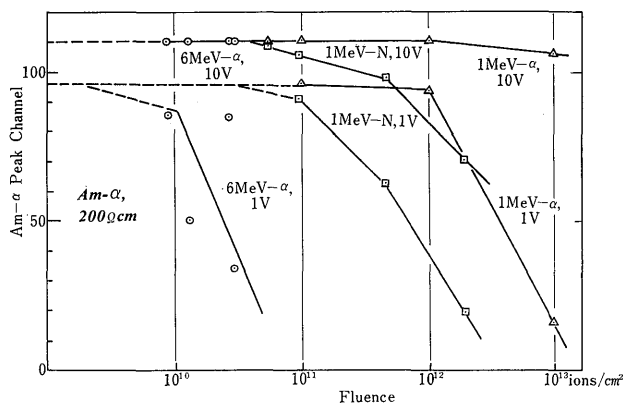


Fig. 11 Peak channel number of $^{241}\text{Am}-\alpha$ at 1 and 10 V bias against fluence of 1 and 6 MeV alphas and 1 MeV nitrogen ions.

3.2 Alpha Irradiations

The degradation of the spectrum occurred as in the proton irradiation. The shifts of the $^{241}\text{Am}-\alpha$ peak against 1 and 6 MeV alphas are shown in Fig. 11. With the bias voltage of 10 V, the peak channel remains at the original position up to $1 \times 10^{12}/\text{cm}^2$ with 1 MeV alphas and at least up to $3 \times 10^{10}/\text{cm}^2$ with 6 MeV

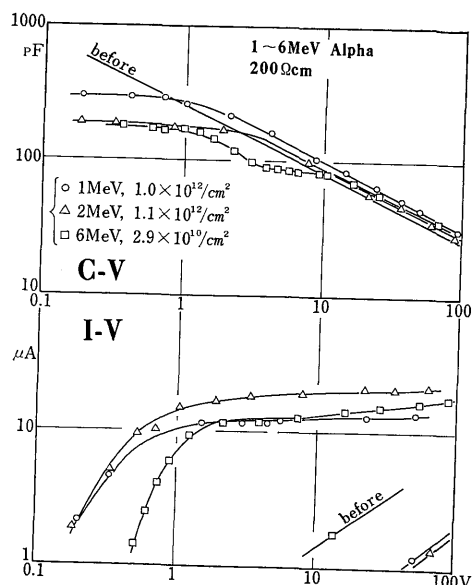


Fig. 12 C - V and I - V relations against 1-6 MeV alpha irradiation.

alphas. However the resolution becomes worse at those fluences because of a large leakage current. The C - V and I - V relations were also similar to those with the proton irradiations. As shown in Fig. 12, the regions of constant capacitance values appear according to the irradiations and the constant values have a relation with the incident alpha energies. But these regions do not extend remarkably as compared with the regions induced by 0.5-2 MeV protons, which means that the constant capacitance values probably are related with the alpha ranges in silicon, but the properties of the defects are not equal with those by proton irradiations. The annealing effects of the irradiated detectors were similar to Figs. 5, 6 and 9, and the results are shown in Figs. 13 and 14.

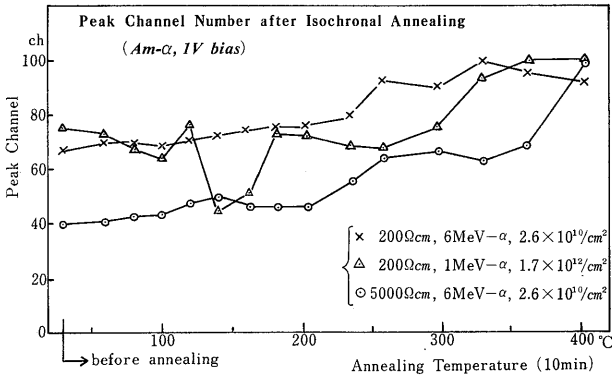


Fig. 13 Peak channel number of $^{241}\text{Am-}\alpha$ at 1 V bias against isochronal annealing temperature in alpha-irradiated detectors.

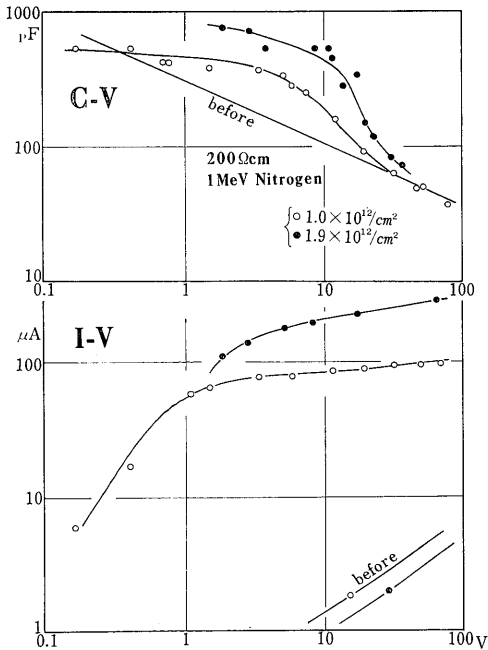


Fig. 15 C - V and I - V relations against 1 MeV nitrogen ion irradiation.

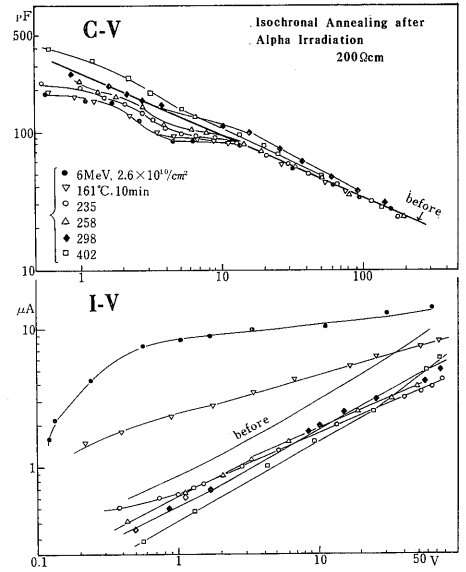


Fig. 14 Isochronal annealing effects of C - V and I - V relations after alpha irradiation.

3.3 Nitrogen Ion Irradiations

The spectrum degradation was similar to the above mentioned results and the peak shifts of 1 MeV irradiations are shown in Fig. 11. The C - V and I - V relations as shown in Fig. 15 are also similar to the above results. The shift of the peak at 10 V bias occurs below $1 \times 10^{11}/\text{cm}^2$ and the leakage current is very large. Moreover the capacitance values at low bias

voltage are large and inaccurate. These facts mean the nitrogen ions have small ranges in silicon and have the possibility to damage the surface region of the detector barrier.

4. Discussions and Conclusions Remarks

The damage effects by heavy ion irradiations appear as the degradation of the spectrum and the large leakage current. The C - V relations have regions of constant capacitance at low bias voltages. The annealing effects in the spectrum, C - V and I - V relations show complicated behaviors. The induced defects have many unknown factors, for example, concerning with the defect level, defect property, defect concentration and distribution, and defect stability. Moreover the implanted ions such as hydrogen, helium and nitrogen have the possibilities to act as the physical and chemical dopants. In other words, except the known defects up to date such as the divacancy, A center and E center, other defects coupled with the incident ions must also be considered. It is said hydrogen or nitrogen ions are electrically inactive in silicon, but unfortunately the works have been poorly reported.

It is meaningful to compare the present results with the results obtained by the electron irradiation.^{1,2)} The main difference between these results are as follows:

(1) The fluences to degrade the detector performance is two or three order lower compared with the electron irradiation. The detector of low resistivity is strong against the high electron fluence, but in the ion irradiation this tendency is obscure.

(2) The degradation of the pulse height in the electron irradiation are attributed mainly to the slow pulse rise time, but in the ion irradiation the pulse height itself degrades.

(3) The I - V relations under the electron irradiation have complicated behaviors, i. e., the leakage current after irradiation is sometimes lower than that before irradiation. In the ion irradiation, the current changes monotonically against fluence and the I - V curves have knees at low bias voltages. Moreover the current deviation at a constant bias voltage stay within a certain range as shown in Fig. 16.

(4) The annealing effect at 140°C is observed in the electron irradiation, but not in the ion irradiation.

On the other hand, there exist the similarities between the electron and ion results.

(1) Acceptor type defects are found in the C - V relations obtained with the electron irradiation. The similar relations are seen with the proton or 6 MeV alpha irradiation.

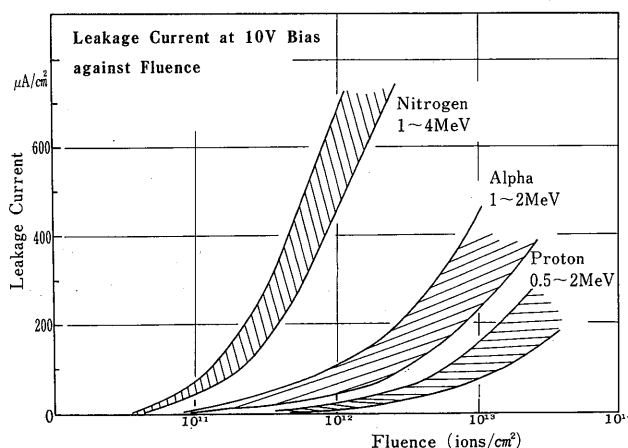


Fig. 16 Leakage current at 10 V bias against proton, alpha and nitrogen ion fluences.

(2) In the electron and ion cases, the spectra due to annealing are similar at 310-340°C and incomplete recovery at about 400°C is seen.

The defect concentration and distribution in the electron irradiation must be almost incident heavy ions will stop within a few tens micron in silicon and so the defects concentrate near the surface region. If we consider the dominant defects are acceptor type and can trap and/or recombine excess carriers, the typical $C-V$ curve can be explained as follows: The capacitance in the region A-B in Fig. 17 (a) corresponds to a slightly damaged layer in Fig. 17 (b) and the energy level diagram is A in Fig. 17 (c). In this region the initial donor concentration is compensated by the acceptor type defects and the depletion layer width at a fixed bias voltage becomes wider than the initial width. When the bias voltage reaches B, the depletion width becomes equal to the range of the incident ions. Between B and C, the depletion width cannot exceed deeply to the undamaged region according to the bias increasing, because electrons are accumulated in the heavily damaged layer. At point C, the number of these electrons reaches maximum and above this voltage they tend to have a high possibility to be detrapped. The region C-D-E then means the depletion layer extends to the inner undamaged region according to the bias increasing. The point E means the field intensity is high enough to clean the trapped electrons in the defects and the $C-V$ relation coincides with the original one. In this model, differed from that of Aukerman⁵⁾, the defects created are acceptor type and the heavily damaged layer is considered as an electrode which can induce electrons as many as the created defects.

If this model is appropriate, one can estimate the defect concentration. In the slightly damaged region, we assume the defect density is uniform and use the relations

$$V = \frac{q}{\epsilon} \cdot \frac{N_d - N_t}{2} \cdot x^2 \quad (1)$$

$$\text{and } C = A/x \quad (2),$$

where V and C are the applied bias voltage including the build-in voltage and the capacitance. And q , ϵ , x and A are the electronic charge, dielectric constant, depletion layer width and capacitance area. N_d and N_t are the initial donor and created acceptor type defect concentration. Then $N_d - N_t$ (cm^{-3}) is expressed with C (pF) and V (V) as

$$N_d - N_t = -\frac{C^2 \cdot V}{3.4} \cdot 10^9 \quad (3).$$

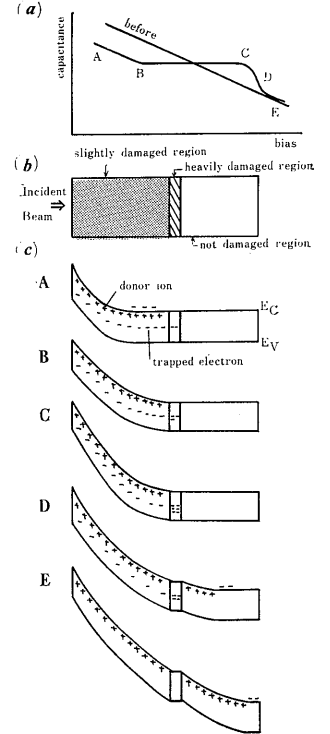


Fig. 17 Model to explain $C-V$ relation. (a) Schematic $C-V$ relation before and after proton irradiation. (b) Damage distribution in a detector. (c) Energy level diagram after irradiation, in which Figs. A-E correspond to the respective conditions written in (a).

On the other hand, the heavily damaged region is assumed as a thin electrode and the simple relation of $C \cdot V = Q$ holds, where Q is the induced charge in the electrode. The maximum charge induced appears at point C in Fig. 17 (a), then the number of the defects can be estimated. For example, the damage rate in the slightly damaged region is about 20 defects/cm by 1 MeV protons. By estimating the proton range, one proton creates 0.10 defects. In the heavily damaged region one proton creates about 0.05 defects. Then totally each proton creates about 0.15 defects along its range. This quantity is very small, comparing with 136 Frenkel defects per 1 MeV proton estimated from Dearnaley.¹¹⁾ If Dearnaley's calculation is correct, about 0.1% of the Frenkel defect pairs can form the stable defects. The same result is obtained in Aukerman's model by computing the defects in the heavily damaged region. However the point E , where the C - V relation returns to the initial one, cannot be explained by his model, whereas it is reasonably explained by our model.

With our model, the strange behaviors of the spectrum degradation is also explained. As in Fig. 18 and in Fig. 4, the higher energy protons degrade most promptly the spectrum at low bias, but most slowly at high bias. The 2 MeV protons have the range of about $47\mu\text{m}$ in silicon and this range is larger than about $27\mu\text{m}$ of $^{241}\text{Am}-\alpha$. The range of 0.5 MeV protons is $7\mu\text{m}$. Then at 1 V bias, the field strength in the depletion layer irradiated with 2 MeV protons is weaker than that by 0.5 MeV protons. So the degradation produced by 2 MeV protons is remarkable. At high bias as 10 V, the depletion layer width irradiated with 2 MeV protons is about $47\mu\text{m}$, but that with 0.5 MeV protons remains as $7\mu\text{m}$. So in the 0.5 MeV irradiation, the dead layer effect becomes dominant and the recovery of the spectrum against bias voltage is slow. In Fig. 18, the peak channels of the detector irradiated with 0.5 and 2 MeV protons are also represented. In this detector, the field effect and dead layer effect are combined and in spite of its low fluence the degradation is very obvious.

The proton range in silicon has a relation with the capacitance at the region B - C in Fig. 17 (a). The ranges estimated from the C - V relations in Fig. 8 and eq. (2) are expressed in Fig. 19. The alpha ranges calculated from Fig. 12 are also represented. The solid curve for the proton range is obtained from Loferski¹²⁾ and that for alphas from sliding the former curve with the factor of four to the higher energy side. The proton ranges estimated coincide with the

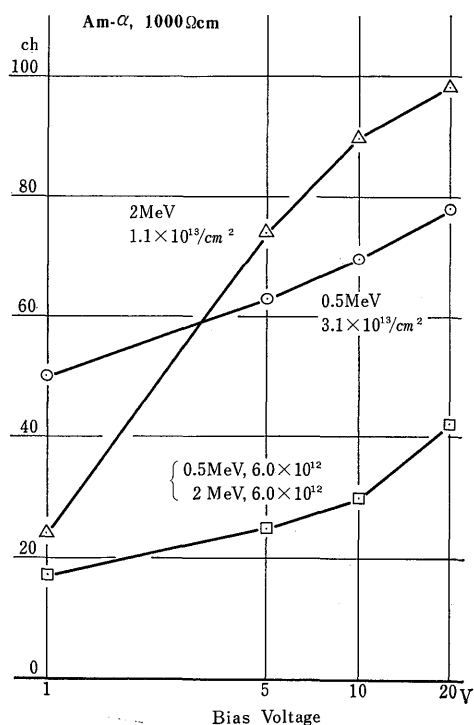


Fig. 18 Peak channel shift against bias voltage in detectors irradiated with 0.5 and 2 MeV protons.

solid curve, but the alpha ranges do not except the 6 MeV range. This is probably because the present model is not enough for the alpha irradiation. The C - V relations of the alpha irradiation have a difference from those of proton's, i. e., the constant-region of the capacitance does not extend to the higher bias region. The defect properties or concentration by the alpha irradiation would have another factor to be considered. The nitrogen ion irradiation also have unknown factors.

The annealing effects of the proton and alpha irradiations reveal some similarity as well as difference comparing with the previous results obtained by the electron irradiation. The similarity is a reverse annealing at about 300°C and a recovery at about 400°C. This means the defects are unstable above 300°C in both cases and, at the present state of knowledge, have been attributed to the divacancies and/or A centers. Which defects are probable is still undecided, and more annealing experiments or other measurements would be necessary. The irradiation experiment with 10 and 40 MeV protons using the Hall effect¹⁸⁾ has shown the defect levels are the divacancies and A centers.

In the present ion irradiation, a gradual recovery by annealing is seen. The gradual annealing has been known as the dissociation of the damage clusters in the high energy electron¹⁴⁾, neutron¹⁵⁾, and proton¹⁶⁾ irradiations. Then the annealing behaviors in our experiments have two annealing stages; one is the cluster dissociation and the other the divacancy and/or A center dissociations.

We have considered the defects as acceptor type, which is similar to Dearnaley⁶⁾, but Scott¹⁾ has considered as donors. The detectors used by Scott were p -type and so the donor type behaviors of the defects are ascribable to the donor charge state of the divacancy in p -type silicon.¹⁷⁾

The conclusions are as follows:

- (1) The damage effects in surface barrier silicon detectors have similar tendencies either with proton, alpha, or nitrogen ion irradiation, but an obvious difference appears in the C - V relations. At least in the proton irradiation, the proton range has a close relation with the capacitance value.
- (2) The model of the defect properties is presented and with this model the proton range and damage rate are estimated. Also the tendency of the degraded spectrum can be explained.
- (3) From the annealing experiments, it is found the defects are annealed having at least two stages. One is the cluster dissociation and the other the dissociations of divacancies and/or A centers.

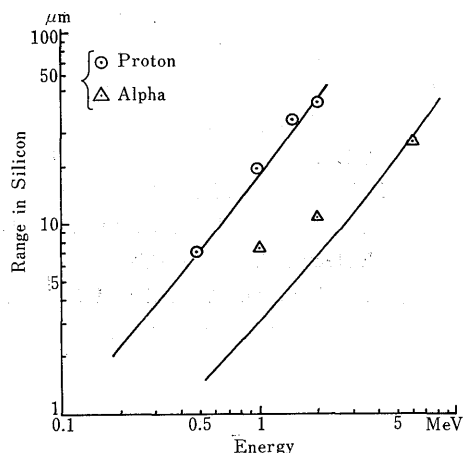


Fig. 19 Proton and alpha ranges in silicon calculated from C - V relations. Solid lines represent proton and alpha ranges in silicon vs. energy (ref. 12).

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