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《Original》 The Relative Effectiveness of Various Radiation Sources on the Resistivity Change in n-Type Silicon*

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Abstract

Resistivity changes of n-type float-zone silicon crystals with 6.4×10^{14} to 1.25×10^{17} phosphorus atoms/cm^3 due to irradiation by (1) 1 MeV electrons, (2) two types of research reactors, and (3) Co^{60} γ-ray sources were investigated. The results were analyzed on the basis of a simple exponential formula derived by Buehler. While the formula gave a fair fit in the low fluence range in most cases, the deviation was quite appreciable in the case of 1 MeV electron irradiation, and a linear change gave better fit in some cases. The large change in the carrier removal rate in electron-irradiated samples in the high fluence range was analyzed in detail in terms of the Fermi level cross-over of the defect levels. Based on the damage constants evaluated from the initial portion of data where the formula was applicable, the relative effectiveness of various radiation sources in causing the resistivity change in n-type silicon was compared. The TRIGA Mark II reactor neutrons, for example, were found to be about 40 times more effective than 1 MeV electrons. The dependence of the damage constant on the initial carrier concentration was also examined. The physical basis of the exponential law and the effect of the Fermi level cross-over of the defect levels on the resistivity change in the high fluence ranges are discussed.

요 약

燐原子添加濃度가 6.4×10^{14}부터 1.25×10^{17}/cm^{3}까지인 n型실리콘 單結晶들을 (1) 1 MeV 電子線과 (2) 두가지 硏究用原子爐와 (3) Co^{60}감마線源으로 照射하고 이에 따르는 比抵抗의 變化를 測定하였고 이 측정결과를 Buehler가 提議한 實驗式을 適用하여 분석했다. 이 指數實驗式은 照射量이 적은 범위내에서는 대부분의 경우 잘 적용되나 1 MeV電子線照射에서는 측정결과와 잘 맞지 않으며 경우에 따라서는 線型變化式이 오히려 더 잘 적용된다는 것이 알려졌다. 특히 電子線照射 試料에서 照射量이 많을때 carrier除去率에 큰 변화가 나타나는데 이것을 缺陷準位와 Fermi level과의 交叉效果로 보고 자세히 살펴 보았다. 위의 실험식이 적용되는 범위안에서 損傷係數를 계산하고 손상계수에 의해서 n型실리콘의 비저항변화에 미치는 여러가지 放射線源의 상대적효과를 비교하였다. 예컨대 TRIGA Mark II 硏究爐內의 中性子照射는 1 MeV電子線照射에 비하여 약 40倍나 더 효과적으로 비저항변화를 일으킨다는 것이 알려졌다. 照射前의 carrier濃度와 損傷係數와의 관계도 調査하였고 또 指數實驗式의 物理的根據와 照射量이 많을때의 缺陷準位와 Fermi level와의 交叉가 비저항변화에 미치는 효과도 아울러 고찰하였다.

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1. Introduction

The Santa Fe Conference on Radiation Effects in Semiconductors in October, 1967, marked the 20th anniversary of the earliest experiments in this field:[1] Since 1947 when the electrical properties of silicon and germanium were found to be profoundly affected by nuclear radiations, a flourishing research field has been developed, and a huge bulk of work accumulated on this subject.[2] However, the overall systematic formulation of the fragmentary data on various effects, particularly to bridge the gap between the experimental physics and practical application is in its incipient stages.

The irradiation produces two types of electrical effects on the semiconductors; one is the immediate transient ionization and the second longer lasting cumulative lattice displacements. Intensive investigations on the effect of the former are still being carried out in connection with the device performance immediately after the nuclear explosion, and part of the results found applications in the fabrication of solid state particle detectors. The latter causes the decrease in conductivities (that is, increase in resistivities) and the shortening of minority carrier lifetimes. While the change in the minority carrier lifetime is perhaps the most sensitive indication of radiation, the resistivity change is more direct and convenient means of detecting the radiation effects. The following discussions are confined to the lattice displacement effects.

The rate of the change of electrical properties is dependent on (1) the dopant or impurity atoms and their concentration, (2) the material preparation (oxygen concentration, dislocation density, and other electrically inactive imperfections), (3) direction of irradiation with respect to crystallographic orientation and irradiation temperature, (4) the type of radiation sources and the energy spectrum of the incident particles, (5) the amount of irradiation accumulated (fluence), and even on the rate of irradiation (flux), in some cases. Recently efforts have been directed toward establishing an overall description of the effects of those parameters, primarily to bridge the gap between experimental physics and the device design. One of the latest of such work is the one reported by Buehler.[3] He combined the empirical exponential change of the resistivity of silicon due to fast neutron irradiation and the initial carrier concentration dependence of carrier removal rate, and derived an empirical formula. The formula fits relatively well in the low fluence range, and can be used to estimate the resistivity change of silicon under irradiation for the device design purpose.

In this work the experimental results of the resistivity changes in n-type silicon due to irradiation by (1) 1 MeV electrons, (2) two types of research reactors, and (3) Co^{60} γ-ray sources were analyzed on the basis of Buehler's formula. An attempt was made to compare the effectiveness of various radiation sources in causing the resistivity change in silicon. By suitably defining the average reactor neutron energy,[4] the rate of resistivity change of silicon can be related to the reactor power level. The limitation in the applicability of the simple formula is also discussed.

2. Background

General: The resistivity of a material is inversely proportional to carrier concentration and mobility. Unlike in metals, the mobility change in irradiated semiconductors is relatively unimportant and the change in carrier concentration is the dominant effect of the radiation-induced lattice displacements. The rate of decrease of carrier concentration (per unit fluence) is called *the carrier removal rate.* The lattice defects produced by atomic displacements and the subsequent motions of *primary defects* (vacancy and interstitial pairs) give rise to carrier trapping centers having the trapping energy levels (characteristic of the microscopic structure of the defects, and hence, the material and the incident radiations) in the forbidden energy gap. From

optical and EPR experiments, as well as Hall coefficient and minority carrier lifetime measurements, a number of shallow and deep *defect levels* has been determined in irradiated silicon and germanium.[5-7] As the defect levels lying above *the Fermi level* of the material are inactive in carrier removal, the carrier removal rate is dependent on the Fermi level (and hence, on the initial carrier concentration). Therefore, by measuring the carrier removal rate on a group of samples with different Fermi levels, the defect levels and the the introduction rate of these defects can be determined.[8]

Since the Fermi level, in turn, recedes into the middle of the energy gap toward the intrinsic value as the free carrier concentration decreases, the carrier removal rate changes drastically as the irradiation progresses. Moreover, the charge state of defect not only modifies the carrier capture cross section, but also may affect the stability of the defect configuration, to a certain extent. Thus the carrier concentration and the resistivity after a prolonged irradiation vary with the fluence in a very complicated way.

Mathematical Formulation: As described by Hill,[8] the *initial* carrier removal rate for a single defect level can be expressed in terms of a given defect level E_B and the Fermi level E_F in the initial stage of irradiation as follows:

$$-\frac{dn}{d\varphi}=\frac{A_B}{1+\alpha\ \exp\frac{E_B-E_F}{kT}}, \qquad (1)$$

where A_B is the introduction rate of the defects. The α is the statistical weight (or *degeneracy*) ratio determined by the number of ways the electrons in the defect rearrange themselves with the addition of a trapped electron.

The Fermi level, on the other hand, is defined by [9]

$$n=\frac{2N_C}{\sqrt{\pi}}\int_0^\infty\frac{\epsilon^{1/2}d\epsilon}{1+\exp\left(\epsilon-\frac{E_F-E_C}{kT}\right)}$$

$$\approx N_C\exp\frac{E_F-E_C}{kT}\quad\left(\text{when}\frac{E_F-E_C}{kT}\ll 1\right) \qquad (2)$$

where $N_C=2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}=4.831\times10^{15}\left(\frac{m_e}{m}T\right)^{3/2}$ is the density of state in the conduction band for effective mass m_e, and E_C is the conduction band edge. On introducing the approximation, one obtains the carrier removal rate in terms of carrier concentration:

$$-\frac{dn}{d\varphi}=\frac{A_B}{1+\alpha\frac{N_C}{n}\exp\left(\frac{E_B-E_C}{kT}\right)}$$

$$=\frac{nA_B}{n+\alpha N_C\exp\left(\frac{E_B-E_C}{kT}\right)}. \qquad (3)$$

Thus, it is easy to see that in the range of $n\ll\alpha N_C\cdot\exp\left(\frac{E_B-E_C}{kT}\right)$, the carrier concentration is expected to decrease nearly exponentially. The effect of the presence of more than one trap levels and the method of determining the defect levels are described by Blackemore,[9] Sonder and Templeton,[10] Saito and Hirata,[11] Vitovskii, Mashovets, and Ryvkin,[12] and by Buehler and Kendall,[13] to name only a few. The carrier concentration and resistivity as a function of fluence are much more difficult to predict quantitatively, on other than empirical basis.

Empirical Formula: Experimentally the initial carrier removal rate in irradiated silicon is found to depend on the initial carrier concentration approximately as

$$-\frac{dn}{d\varphi}\Big|_{\varphi\to0}=K_n\ n^{0.23} \qquad (4)$$

where the coefficient K_n ranged 444 to 3300 for n-type material in various nuclear reactors.[3]

The resistivity, on the other hand, is found, to vary exponentially, consistent with the change in carrier concentration expected from Eq. (3) and the assumption of only a small change in mobility, in the early stage of irradiation:

$$\rho=\rho_o\exp\frac{\Phi}{k_n} \qquad (5)$$

where k_n is called the *damage constant* and is the fluence needed to bring about the resistivity change of a factor of e. The k_n thus is a measure of effectiveness of a radiation source in producing the resistivity change in a given material. In other words, the effect of all experimental parameters such as material characteristics and irradiation condition described earlier is lumped in this way into a single parameter k_n. While limited in the applicability, this formula provides a quanti-

tative basis for comparison of the effectiveness of electrical damage of different radiation sources, say, with respect to 1 MeV electrons.

By equating the initial carrier removal rate expected from Eq. (5) with Eq. (4), Buehler derived an empirical expression for the resistivity change in silicon for various initial carrier concentrations:

$$\rho=\rho_o \exp[\varphi/K_n n_o^{0.77}]. \qquad (6)$$

Figures 1(a) and 1(b) show the plot of Eq.(6), "the design curve" for p-type and n-type silicon based on the highest value of initial carrier removal rate (K_p=387 and K_n=444) observed in reactor-irradiated silicon so far.

Application of the Empirical Formula: In the case of reactor irradiation, Kantz found a linear relation between the carrier removal rate in silicon and the average reactor neutron energy when the latter was suitably defined.[4] Thus the damage constant of the resistivity change in silicon can be directly related to the average reactor neutron energy. And since the neutron energy spectrum is supposed to be nearly independent of the power level of the reactor, the resistivity change provides a simple and convenient way of measuring and accumulating the neutron flux, and hence, the record of the reactor output level.[14]

As will be discussed below in comparison with the actual experimental data, the applicability of the simple formula Eq. (5), is very limited, and there are cases where the resistivity change is almost linear with fluence, particularly in the area removed from the reactor core.

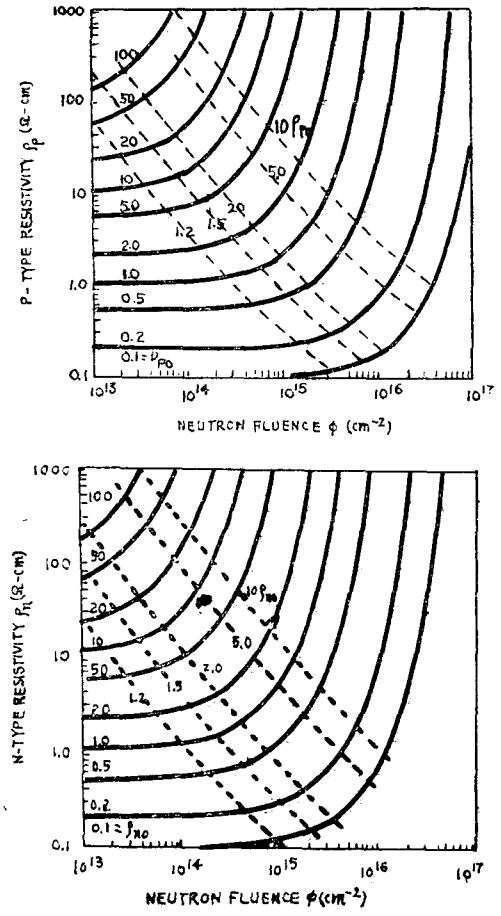

Fig. 1. Design curves for neutron-induced resistivity changes in silicon. (Based on assumptions described in Ref. 3.)

3. Experimental

3.1 Sample Preparation and Electrical Measurements

The present experiments were confined to four batches of n-type float zone silicon single crystals. (The oxygen content of the float zone materials is quoted to be of the order of 10^{16}/cm^3.) The initial resistivities ranged from 0.077 to 7.9 ohm-cm, corresponding to phosphorus concentration of 1.25×10^{17} to 6.4×10^{14} atoms/cm^3. The crystals were cut in bridge shape with an ultrasonic cutter (see Fig.2) and the surfaces were sandblasted to a satin finish. This configuration minimizes the electric field distortion due to the proximity of the finite-sized metallic contacts. The electrical leads were attached by (1) spot welding of gold wire

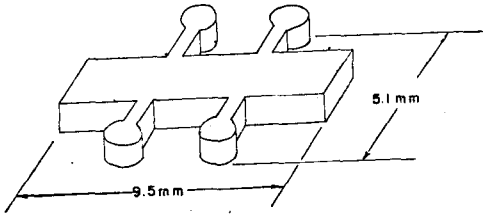

Fig. 2. Bridge-shaped sample for resistivity measurements.

(doped with 0.1 weight % antimony) on some and (2) ultrasonic soldering of indium on others. The current and voltage were measured with a portable potentiometer and a network of standard resistors. As discussed below, the temperature of the crystals during irradiation was 10 to 50°C above room temperature. The resistivity measurements were made *in situ*, that is, with the samples in the irridiation position. The Hall coefficients of electron-irradiated silicons were measured periodically over the temperature range of 4.2 to 300°K to check the mobility change.

3.2 Irradiation

Electron irradiation: The 1 MeV electron irradiation was performed at the Van de Graaff facility of Bell Telephone Laboratories in Murray Hill, N.J., over a span of several months. The beam current used was 50 to 100 μA. Aluminum scattering foils insured a fairly uniform beam distribution over the samples. The actual beam density and the distribution profile were determined with a Faraday cup. The temperature of the samples was maintained close to room temperature by mounting the crystals on a water-cooled copper block, insulated with a thin mica sheet. A stream of dry nitrogen gas was directed at the surface of the samples to reduce the surface heating during the irradiation. The resistivity measurements were made from the adjoining control room separated from the irradiation area by a concrete wall. The electron beam was interrupted by a shutter at a five to ten minutes interval for resistivity measurements with the samples in place. The electron irradiation was discontinued periodically to perform Hall coefficient measurements as a function of temperature from 4.2 to 300°K. In spite of the precaution to minimize the thermal annealing, some spontaneous recovery of resistivity was noted after a series of Hall coefficient measurements. The fluence accumulated over three hours at a time amounted to 6.0×10^{17} electrons/cm^2.

In the *nuclear reactor* and *gamma-ray irradiations* where the irradiations were performed underwater, the sample block and electric leads were contained in a long dog-legged aluminum tubing to allow the resistivity measurements *in situ*. The bend in the dog-legged portion of the tubing minimized the streaming of the soft gamma-ray from the sample block area. The radioactivity level at the top of the tubing was within the safety standard. The temperature of the sample was estimated from the resistivity value extraporated to zero fluence and the resistivity vs temperature data taken prior to the irradiation. While the resistivity change of high resistivity material was much too rapid for this purpose, in low resistivity materials this method gave fairly reliable temperature estimate. The resistivities were measured at one to ten minute interval depending on the rate of resistivity change.

Battelle Research Reactor: The power level of the reactor was 2 MW. The sample block was lined with a cadmium shield to reduce the thermal neutron flux and suspended about 60 cm above the reactor core. The aluminum tubing was purged continuously with dry nitrogen gas to prevent the accumulation of radioactive gases. No other provision for cooling the sample block was made. The fast neutron fluence was calibrated against the activation of nickel wire enclosed in the sample block. The total time of irradiation was 26 hours and the calibrated fast neutron fluence 4.3×10^{15}n/cm^2.

TRIGA Mark II Reactor: The power level of the TRIGA Mark II research reactor of the Korean Atomic Energy Research Institute was 100 kW at the time. The samples were placed in one of the dummy element position in the core. The cadmium shield and nitrogen gas purging of the tubing were omitted in this case. The total irradiation time was 29 hours over a period of six days. The fast neutron fluence was 4.8×10^{16} n/cm^2, based on the fast neutron flux of 4.2×10^{11} n/cm^2•sec obtained in a separate nickel activation experiment by H. J. Kim and H. I. Pak of KAERI.

Co^{60} gamma-ray irradiation: The Co^{60} gamma-ray irradiation was performed at the gamma-ray

irradiation facility of the Atoms-in-Action Exhibition in Seoul, sponsored by the U.S. Atomic Energy Commission. The nominal activity of Co^{60} was quoted to be 4500 curies. The aluminum tubing containing the sample block and electric leads was positioned in one of the underwater irradiation rack. The gamma-ray flux in the sample block area was checked by a solar-cell detector and was 4.38×10^5 rad/hour. The irradiation was carried out for 120 hours over a period of one week. The total dosage was 5.76×10^7 rad being equivalent to 9.12×10^{16} photons/cm^2.

4. Results and Discussion

4.1 1 MeV Electron Irradiation

The result of the resistivity change measurements on 0.5 and 0.08 ohm-cm n-type silicon crystals in the early stage of 1 MeV electron irradiation is shown in Fig. 3. The temperature of the samples during irradiation was about 35°C. A spontaneous recovery of resistivity of about 10% in the 0.08 ohm-cm material after a series of Hall coefficient meausrements can be seen on the lower curve. Since this is a semi-logarithm plot, the deviation from the exponential variation (straight line) is quite appreciable. The deviation even in the early stage of irradiation could be explained in terms of the approximation needed in Eq. (3), as discussed in Section 4.6. By fitting only a few points up to $\rho=2\rho_0$ to Eq. (5), the damage constant k_n was found to be 1.76×10^{16} and 1.24×10^{17} el/cm^2 for 0.5 and 0.08 ohm-cm material.

The change in the Hall mobility μ_H was less than 30% while the carrier concentration n varied over several orders of magnitude (Figs. 4 and 5). By interpolating the Hall mobility, the carrier concentration profile was determined from the resistivity data. In order to avoid the ambiguity, the ratio of Hall mobility to drift mobility was taken to be $3\pi/8=1.18$ throughout. The carrier removal rate $(-dn/d\varphi)$ was computed by numerical differ-

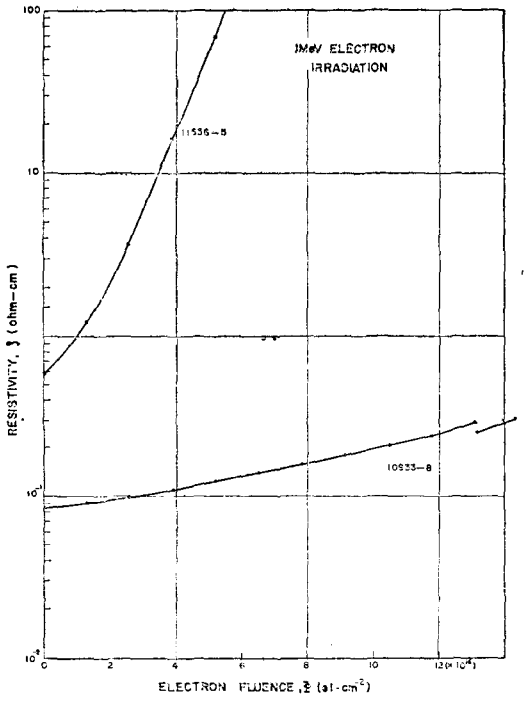

Fig. 3. Resistivity change in 1 MeV electron-irradiated n-type silicons (0.7 and 0.08 ohm-cm)

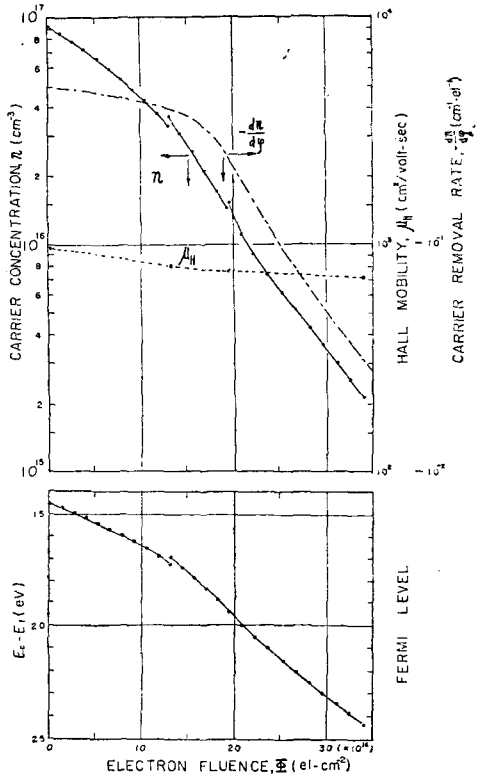

Fig. 4. (a) Carrier concentration (n), carrier removal rate ($-dn/d\varphi$), Hall mobility (μ_H), and (b) Fermi level (E_C-E_F) as a function of electron fluence in 0.08 ohm-cm n-type silicon.

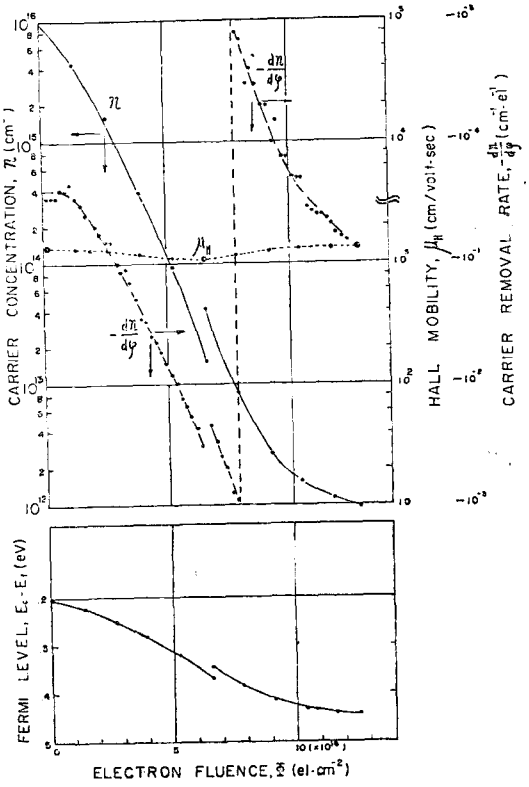

Fig. 5. (a) Carrier concentration (n), carrier removal rate ($-dn/d\varphi$), Hall mobility (μ_H), and (b) Fermi level (E_C-E_F) as a function of electron fluence in 0.7 ohm-cm n-type silicon.

entiation and its results are shown in Figs. 4a and 5a for 0.08 and 0.5 ohm-cm material. Note the change of four orders of magnitude in the carrier removal rate in 0.5 ohm-cm material (Fig. 5). The corresponding changes in the Fermi level at room temperature are shown in Figs. 4b and 5b. In the computation of the Fermi level, the spin degeneracy ratio and the effective mass ratio were taken to be unity to eliminate the ambiguity. The error introduced by this simplification is about 4×10^{-3} eV in the Fermi level. The change in the slope of the Fermi level curve at 0.17 eV corresponds to the sharp decrease of the carrier removal rate, indicating the presence of a major defect level at this position (Fig. 4b). This defect level is currently attributed to the oxygen-vacancy complex (Si-A center). The drastic change of carrier removal rate in Fig. 5b indicates the presence of additional deep defect levels. The defect levels due to the divacancies and phosphorus complexes have been variously estimated to be somewhere between 0.33 and 0.42 eV below the conduction band edge.[2, 11, 13] From these analyses, the deviation of the resistivity change from the simple formula of Eq. (5) in the advanced stage of irradiation is seen to be due to the cross-over of the Fermi level with the 0.17 and 0.4 eV defect levels, and the corresponding decrease in the carrier removal rate.

4.2 BRR Irradiation

The resistivity changes of three samples irradiated by Battelle Research Reactor are shown in Fig. 6. The resistivity of 7 ohm-cm material (3664-01) increased by a factor of 500 in a matter of a few minutes before it settled down to almost linear change. The large scatter in the data points

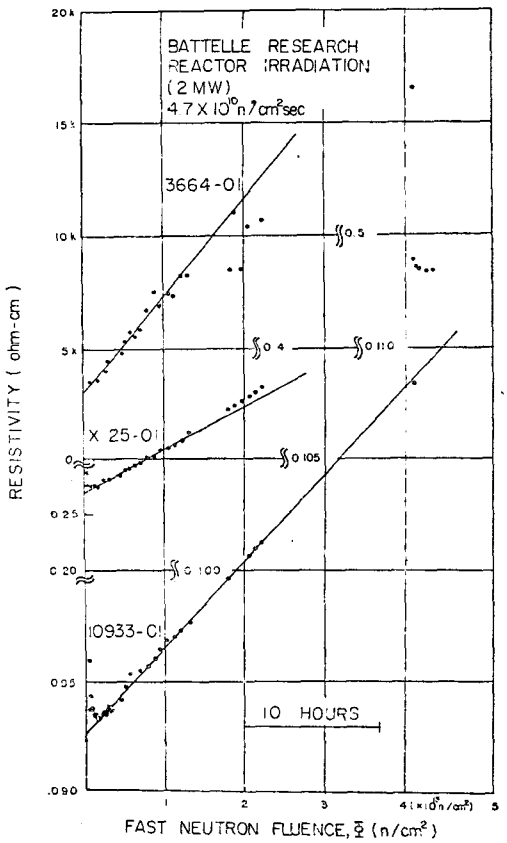

Fig. 6. Resistivity changes in neutron-irradiated n-type silicons (7.0, 0.25, and 0.08 ohm-cm). (Battelle Research Reactor)

is due to the extremely high impedance of the sample. The other two samples (0.25 and 0.08 ohm-cm) also showed similar rapid increase in the resistivity immediately after the sample block was lowered into the reactor. As described below, similar change was observed in TRIGA Mark II irradiation when the reactor was scrammed at the end of daily eight-hour operation. The transient initial change is believed to be due to the ionization effect. Note that the data points are plotted on a linear scale. The nearly linear change of resistivity with neutron fluence is quite apparent. Together with the relativiely low rate of resistivity change, the linear change is believed to be due to the modification of the neutron energy spectrum resulting from the large distance between the sample block and the reactor core. The resistivity changes after 500 minutes (1.41×10^{15} n/cm^2) gave the damage constants of 1.29×10^{15}, 7.8×10^{15}, and 2.4×10^{16} n/cm^2 for the three samples.

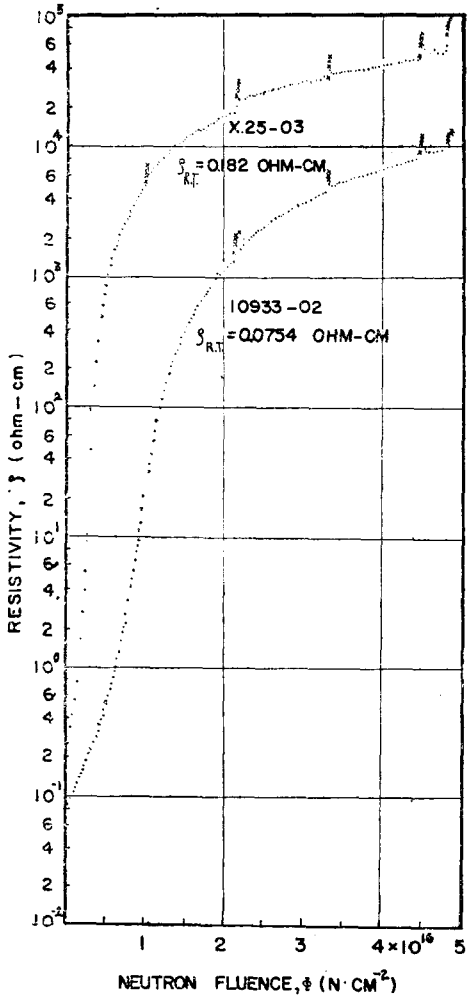

Fig. 7. Resistivity changes in neutron-irradiated n-type silicon (0.25 and 0.08 ohm-cm). (TRIGA Mark II Research Reactor of Korean Atomic Energy Research Institute)

4.3 TRIGA Mark II Research Reactor Irradiation

Figure 7 shows the results of the TRIGA Mark II research reactor irradiation of 0.25 and 0.08 ohm-cm samples. The deviation of resitivity changes from the exponential law of Eq. (5), particularly in the later stage of irradiation, is pronounced. The transient change in the resistivity due to ionization effects immediately after the reactor scram at the end of the daily eight-hour operation is to be noted. The resistivity changes in the heavy dosage range are similar to the electron irradiation experiments, and should be discussed in terms of the Fermi level cross-over of the major defect levels. The initial portion of the data is

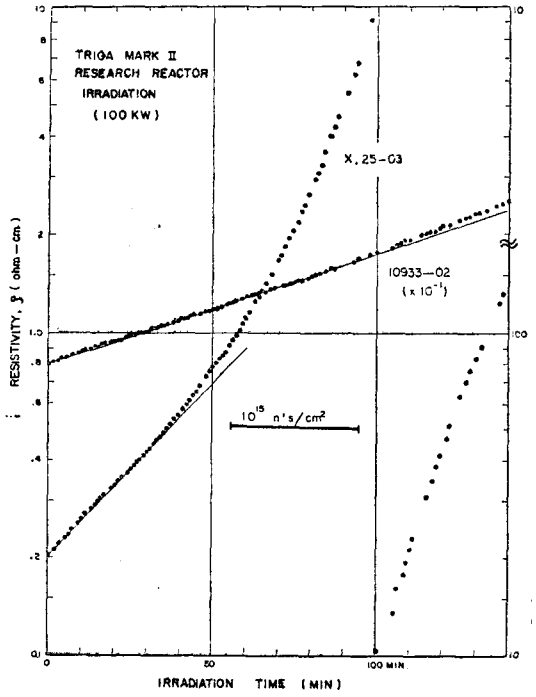

Fig. 8. Resistvity changes in neutron-irradiated n-type silicon (0.25 and 0.08 ohm-cm) in the early stage of irradiation. (TRIGA Mark II Reserarch Reactor)

replotted in an expanded scale in Fig. 8. The exponential law of Eq. (5) (straight line in semi-logarithmic plot) is seen to give a fairly good fit in the early stage of irradiation (first 40 and 100 min. for 0.25 and 0.08 ohm-cm material, respectively). The damage constants determined from the slope of the straight line portions were 1.03×10^{15} and 3.37×10^{15} n/cm^2, respectively.

4.4 Co^{60} Gamma-Irradiation

The results of the Co^{60} gamma-ray irradiation of 8.6, 0.18 and 0.077 ohm-cm samples are shown in Fig. 9. The seemingly large scatter in the data points is due partly to the expanded scale of the resistivity coordinates, as the total change in resistivity was only 3.1% in 0.077 ohm-cm material; and 20.3% even for 8.6 ohm-cm material, after 9×10^{16} photons/cm^2. The damage constants were estimated to be 1.12×10^{18}, 5.09×10^{18}, and 1.10×10^{19} in photons/cm^2 (5.85×10^8, 2.93×10^9 and 6.34×10^9 in rads), respectively, for the three samples.

4.5 Damage Constants for Various Radiation Sources

Although the simple exponential formula of Eq. (5) is seen to hold only approximately valid in the early stage of irradiation and shows a poor fit in some cases, the damage constants k_n is a very convenient parameter in comparing the relative effectiveness of the various radiation sources in causing the electrical changes in silicon. The damage constants evaluated in the four irradiation experiments are summarized in Fig. 10. The present data show that while $n^{0.77}$ law of the damage constant holds fairly well, the deviation in the individual cases is by no means insignificant. The

Table 1. Damage Constant of n-Type Silicon for Various Radiation Sources

Radiation Sources	K_n for $n=10^{17}$ cm^{-3}	Ratio	K_n	Exponent
1 MeV Electron (310°K)	1.06×10^{17}	1	8540	0.804
BRR (325°K)	2.45×10^{16}	4.47	1909	0.877
TRIGA Mark II (310°K)	2.6×10^{15}	40.4	211	0.86
Co^{60} Gamma-ray (300°K)	9.1×10^{18} (γ/cm^2)	0.0115	4.55×10^8	0.61
	5.2×10^9 (rad)	4.95×10^7	0.26	〃

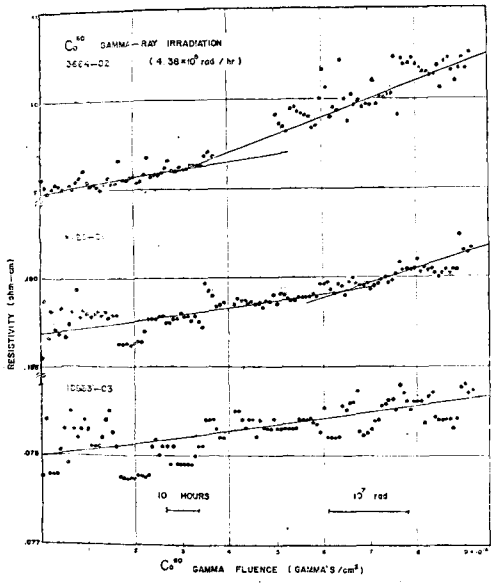

Fig. 9. Resistivity changes in Co^{60} gamma-ray irradiated n-type silicon (7.0, 0.25, and 0.88 ohm-cm). (4500-curie Co^{60} gamma-ray facility)

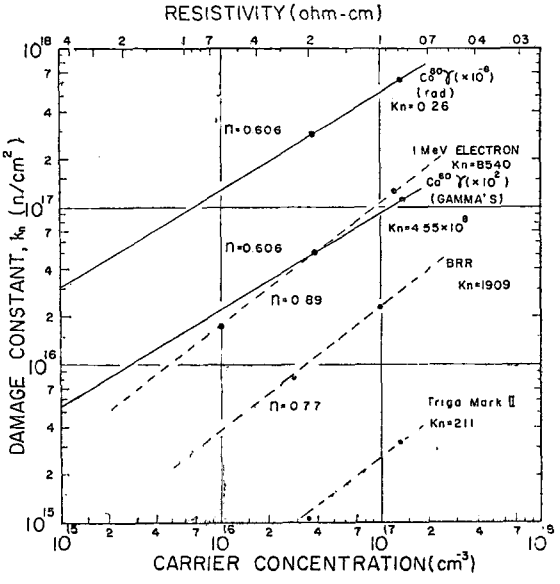

Fig. 10. Damage constant (k_n) as a function of initial carrier concentration for various radiation sources. Data points for high resistivity materials were omitted.

numerical values of the exponent of n determined in the four experiments are tabulated in Table 1. On the basis of these data, for example, by comparing the damage constant of an n-type silicon with $10^{17}/cm^3$ dopant atoms, one can conclude that TRIGA Mark II reactor neutrons are about 40 times more effective in causing the electrical damage than 1 MeV electrons, and so on. The fitted value of the coefficient K_n is very critically dependent on the choice of the exponent. However, it is to be noted that K_n of 211 for TRIGA Mark II reactor is much smaller than the limit of $K_n = 444$ quoted by Buehler. The discrepancy may be attributed to many factors including the exact location of the sample position in the core of the reactor, and not the least important of all, the temperature of the samples during the irradiation.

4.6 Physical Basis of the Exponential Law

Equation (3) can be rewritten as

$$-\frac{1}{n}\frac{dn}{d\varphi} = \frac{A_B}{n+\alpha N_C \exp\left(\frac{E_B-E_C}{kT}\right)}. \quad (7)$$

Therefore the smaller the relative magnitude of n with respect to $\alpha N_C \exp\left(\frac{E_B-E_C}{kT}\right)$, the better fit to the exponentical law of Eq. (5) is expected as long as the mobility change is unimportant. This can explain the deviation in the very low fluence region. And if n is much greater than $\alpha N_C \exp\left(\frac{E_B-E_C}{kT}\right)$, then the carrier removal rate would be nearly constant and the carrier concentration would linearly decrease with fluence. As the irradiation progresses the Fermi level recedes beyond the major defect level, the carrier removal rate undergoes a rapid change, and the exponential law holds no longer valid. The deviation from the exponential law in the high fluence range can be explained in terms of this Fermi level cross-over effect. Moreover, the presence of more than one defect level complicates the picture further.

5. Conclusion

The results of the resistivity change measurements of n-type silicon as a function of irradiation indicate that the simple exponential formula of Eq. (5) gives a fair fit in the low fluence ranges. It gives a fairly good fit for the first 40 to 100 minutes of irradiation in TRIGA Mark II research reactor. The deviation is quite appreciable in the case of 1 MeV electron irradiation. In similar experiments in Battelle Research Reactor (large distance between the sample block and the reactor core) and Co^{60} gamma-ray irradiations, the resistivity changed with fluence nearly linearly. The deviation of the resistivity change from the simple formula in the low and high fluence ranges is not unexpected in view of the simplifying assumption needed in its derivation. Nevertheless, the formula provides the means of predicting the electrical behavior of the silicon during the exposure to nuclear radiations. It also provides a basis for comparing the relative effectiveness of various radiation sources in causing the resistivity changes, even though the types of defects produced may be quite different. While the exact dependence of the damage constant on the initial carrier concentration needs further investigation, the $n^{0.77}$ law is seen to give reasonably good fit. The dependence of the damage constant on the irradiation temperature, particle energy spectrum, and the crystal preparation should be pursued further to apply the knowledge of experimental physics to the practical device design purposes. And once the damage coefficient is determined for a given material under a given irradation condition, the cumulative radiation fluence and the reactor power level, for examples, can be monitored by simply following the resistivity changes.

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