High-Temperature Radiation Dosimetry with Zener Diodes

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Zener diodes have been tested as "high-temperature" dosimeters. They were heated above 50°C, and irradiated with 10-MeV electron beams and cobalt -60 γ rays. For both radiations, the radiation-induced change in breakdown voltage of the zener diode when it is kept around 100°C have shown good linearity as a function of irradiated dose. It can be concluded from the present experiment that the zener diodes are promising candidates for dosimetry at temperatures above 50°C.

1. Introduction

Photons and electrons are widely used as ionizing radiations for industrial processing of variety of materials. Many kinds of dosimeters have been used to monitor such processing, and some of them give satisfactory performances. However, dosimetry is still limited mainly to a "low-dose" range (1-50kGy) and to "low temperatures" (below 50°C). Nevertheless more and more irradiations requiring good knowledge of absorbed dose are carried out at high doses and high temperatures. In industrial γ-ray and electron-beam plants, the temperature becomes higher than 50°C under the practical dose rate of about 10^4Gy/h.

The use of electronic circuits composed of semiconductor devices has expanded in nuclear and space radiation environments, and the effects of various kinds of radiation on these devices have been a subject of fairly intensive investigations for many years. One of the useful applications of the radiation effect on these devices is the measurement of high-level doses. The breakdown voltage of the zener diode is shifted to a higher absolute value by electron or γ-ray irradiation. This process has been used for determining high-level dose of electrons[1)] and γ-rays.[2,3)] For instance, a typical zener diode of Toshiba 05Z18 has been found to be useful for measuring irradiated doses from 15.5kC/kg(6×10^7R) to 2.6MC/kg(1×10^{10}R) within an error of a few percents.[2)] In this case, the zener diode has been used at temperatures below 50°C. Radiation-induced defects in zener diodes do not recover easily, and so we guess that it can also be used at temperatures above 50°C. The present work shows that the use of zener diodes for dosimetry can be extended up to temperatures as high as 100°C provided that a sufficiently stable zener diode is chosen.

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2. Experimental

The zener diodes used in this experiment are commercial products from Tosiba Corp. (02Z9.1, 05Z24, 05Z51). The digits of 02 or 05 in the code of the zener diode indicates internal power dissipation. The breakdown voltage of the diode 02Z9.1 is about 9.1V, and that of 05Z24 is about 24V. The breakdown voltages of the zener diodes were measured by using a Keithley Model 195A digital voltometer.

Gamma-ray irradiation was performed in a irradiation pool, in which a ^{60}Co-source assembly (basket type) was installed. A high exposure rate of 1.4kC/kgh (5.4×10^6R/h) was available in a stainless-steel canister inserted in it. Because samples were held at the center of the canister, these were exposed to γ rays through all the vertical sides of the canister.

Electron-beam irradiation was also performed by using a linear accelerator which was operated at 10 MeV with a peak beam current of 350 mA, a pulse duration of 4μS and a pulse repetition rate of 20 pps. In order to determine the absolute value of the electron fluence and to obtain the reproducibility of the irradiation, the portion of the narrow beam that is flat in the profile was used for irradiation. Electron beams with a current density of about 4μA/cm^2 was incident on the sample through a brass-collimator of 10mm in thickness and 8mm in diameter placed at the distance of 24cm from a 20-μm-thick titanium window of the linear accelerator. The charge of the electrons was collected by a Faraday cup placed behind the sample, and was accumulated with a current integrator. Irradiations were made to very high-level doses, and care was taken so that temperatures during irradiation might be constant. In the case of the diode attached directly ahead on the collimator, it was heated above 100°C during irradiation both directly by the electron beam and through conduction of heat from the collimator.

A dc bridge network[1] was used for measuring the radiation-induced changes in the breakdown voltage of the zener diode. It consists of the current feeders and two zener diodes of the same kind. A small change in the breakdown voltage of the zener diode can be easily detected, because each drift of the breakdown voltage of two zener diodes during measurement due to the change in the ambient temperature is compensated for. One of the zener diodes is used as a reference voltage indicater and the other as a dose detector. Before irradiation the difference of the breakdown voltage of the detector diode from that of the reference diode is measured at a constant reverse current of 7 mA. After irradiation the change in this voltage difference caused by irradiation is measured. A handmade cryostat was used to control the temperature and to minimize the temperature drift of the diode. This permits the diodes to be rapidly cooled down from the room temperature in the range 4±1°C within 2 minutes. Using the network and the cryostat, changes in the breakdown voltage of about 10 mV can be detected with good reproducibility.

3. Result

Before irradiation, the thermal annealing characteristics of radiation damage for ^{60}Co γ-rays and 10-MeV pulsed electrons were investigated to estimate the temperature dependence of dose response during irradiation. Some diode types tested for applying to electron and γ dosimetries have been used. The results are shown in Figs. 1-5. The annealing curves are dependent on breakdown voltage; for the diodes

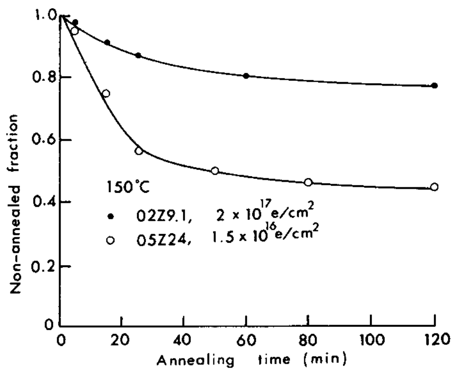

Fig. 1 Isothermals of radiation damage annealing in the zener diodes of 02Z9.1 and 05Z24 after irradiation with electron beams.

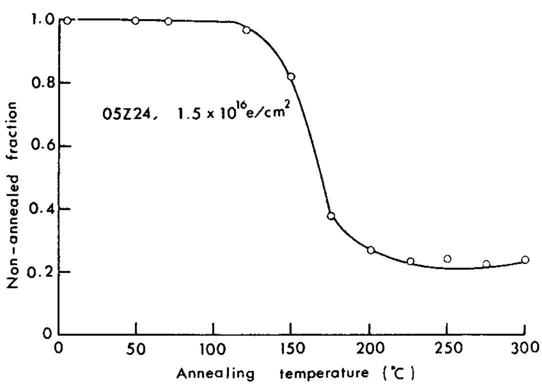

Fig.2 Isochronal annealing of radiation damage in the zener diode of 05Z24 after irradiation with electron beams.

of a higher breakdown voltage, rates of annealing are observed significantly to be higher. As seen from Figs.2, 3 and 5, no significant annealing was observed in these conditions below 100°C. It is predicted from these results that these diodes can be used as a high-temperature dosimeter around 100°C.

The relationship between irradiated dose and the radiation-induced change in breakdown voltage of diodes irradiated at different temperatures was investigated. The irradiated dose is represented as "electron fluence" for electrons, and is represented as "exposure" for γ rays. The irradiation process of a single sample was periodrically interrupted. This was done by the following procedures: (1) irradiation

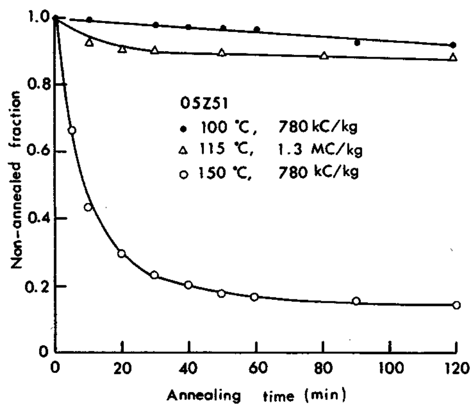

Fig. 3 Isothermals of radiation damage annealing at different temperatures in the zener diode of 05Z51 after irradiation with γ rays.

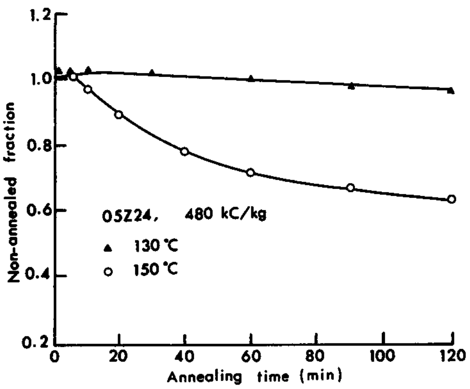

Fig. 4 Isothermals of radiation damage annealing at different temperatures in the zener diode of 05Z24 after irradiation with γ rays.

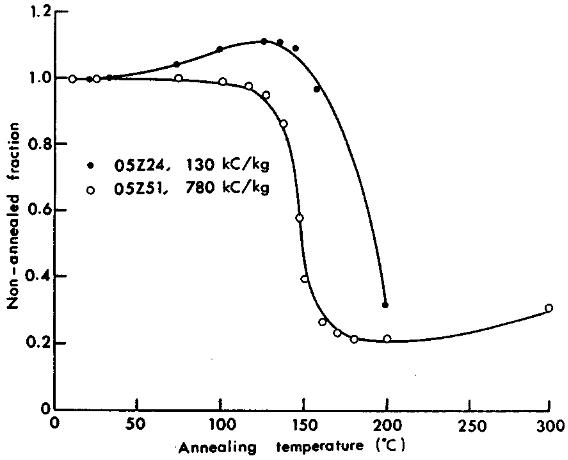

Fig. 5 Isochronals of radiation damage annealing in the zener diodes of 05Z24 and 05Z51 after irradiation with γ rays.

of appropriate dose at a constant temperature, (2) cooling the sample down to the measuring temperature, (3) taking data and (4) warming the sample up to the irradiation temperature.

The responses of two types of diode for electron-beam irradiation are shown in Fig.6. In the case of 05Z24, the response is nearly linear (the gradient n of the line passing through the data point is 1) at 100°C, but it is supralinear (n=1.15) at 150 °C. The diode 02Z9.1 shows a linear response at 150 °C, whereas it shows a sub-linear response (n=0.84) at 220°C.

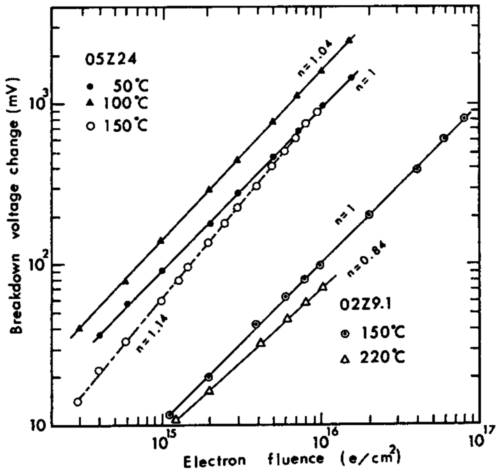

Fig. 6 Change in the breakdown voltage versus electron fluence for two kinds of diode at different temperatures during irradiation with electron beams.

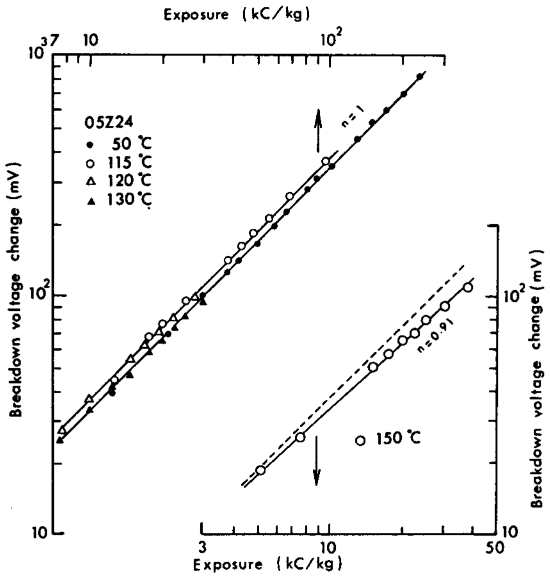

Fig. 7 Change in the breakdown voltage versus exposure for 05Z24 diodes at different temperatures during irradiation with γ rays.

The responses of two types of diode for γ ray are shown in Fig. 7 and 8. The responses of 05Z24 and 05Z51 are nearly linear up to 130 and 115°C, but become sub-linear at higher temperatures. The responses of the high-sensitivity type become sub-linear at relatively lower temperatures than that of the low-sensitivity type, which corresponds to the thermal annealing trend (Fig.1−5) described above.

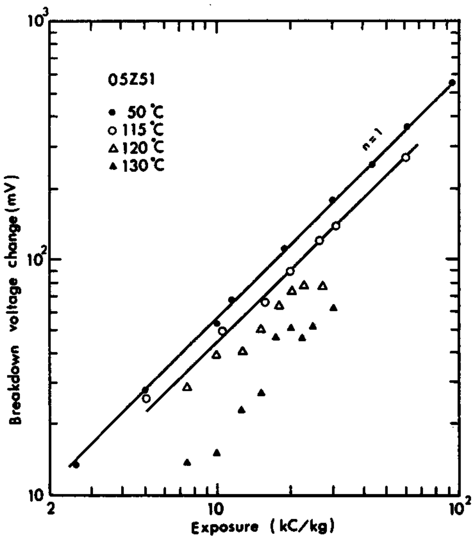

Fig. 8 Change in the breakdown voltage versus exposure for 05Z51 diodes at different temperatures during irradiation with γ rays.

The breakdown voltage of the zener diode is shifted to a higher absolute value by irradiation. The cause of this shift can be explained by the shift of the Fermi level in *n* or *p*-type silicon, i.e. the decrease of the net concentration of the impurities due to the appearance of radiation-damage centers in the space charge region of the *pn* junction, which leads to the widening of the junction space charge region and consequently to the reduction of the built-in-voltage. A higher breakdown voltage requires a low impurity concentration, whereas a low breakdown voltage requires high impurity concentration. A higher sensitivity to the doses can be obtained by using a zener diode with a higher breakdown voltage. Because the radiation damage of the diode doped with less impurity recovers at a relatively lower temperature, the breakdown voltage becomes lower compared with the value without recovery, thus causing a sub-linear response.

In the zener diode, the surface leakage current is sufficiently low and unimportant at normal device operation, because the surface of the *pn* junction is protected with the silicon oxide layer. In the conditions after irradiation at higher temperatures, the leakage current increases owing to the change in quality and state of covering materials of the surface on the silicon wafer such as SiO_2 because they are subjected to thermal stress and to radiation damage at additional times of irradiation. The net breakdown current is then decreased, because the breakdown voltage is measured at a constant current. At higher doses, the measured value of the change in the breakdown voltage is less than the value expected from a linear relationship at lower doses, causing a sub-linear response. Because of the two kinds of effect mentioned above, the response will become sub-linear. The experimental data are insufficient to make explanation for the cause of the supralinear response in electron irradiation.

The difficulty arising from high-temperature requirements of the dosimetric problem is not the same for both radiations. In the high dose-rate electron beams, the temperature of the diode rapidly increases, but radiation damage in the diode does not recover easily within a fairly short irradiation time. On the other hand, in the low dose-rate γ rays, thermal annealing occurs during a long irradiation time required for the same total dose. As the temperatures during irradiation have not been stable in this experiment, only trends related to linearity of dose response have been mainly described. To use zener diodes as a dosimeter, further experiments would be necessary to study such characteristics as the temperature dependence of sensitivity, the useful dose range and reproducibility.

4. Conclusion

Zener diodes are promising candidates for high-temperature and high-dose dosimetry. They are efficient above 10^6Gy, and they could be used as an on-line absorbed-dose integrator in industrial irradiation plants working at temperatures above 50°C.

Referenecs

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