A System for Radiation Damage Monitoring

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Abstract

An automatic radiation damage monitoring system has been developed and tested. The system is based on two passive sensors for the measurement of integral ionizing and non-ionizing energy losses in silicon devices. Ionizing dose is measured in terms of dose in SiO_2 and displacement damage in terms of 1 MeV(Si) equivalent neutron fluence. The system uses MOSFETs and PIN dosimetric diodes.

I. INTRODUCTION

In many applications electronic devices operate in mixed radiation fields. In such fields, the operating lifetime is difficult to predict due to the different damage mechanisms resulting from exposure to the various components of the radiation field. Also, it is difficult to compare the results of radiation hardening experiments obtained from different radiation facilities if results are reported in terms of particle fluence without detailed information on the energy spectrum. From these points of view, the development of a standard radiation damage monitoring system for silicon devices, which will be universal in different mixed radiation fields, is an important goal.

The main mechanisms of damage by radiation in Si devices is due to the deposition of ionizing and non-ionizing energy. The dose associated with ionizing energy loss (IEL) is responsible for the build up of charge within CMOS devices. Such effects are understood in terms of the ionization dose measured in SiO_2 [1]. The dose associated with non-ionizing energy loss (NIEL) is responsible for atom displacements within the silicon bulk. For NIEL, the device effects are understood in terms of displacement KERMA in silicon. KERMA is the kinetic energy released per unit mass.

The same kind of radiation can contribute to both ionizing and displacement KERMA but with different efficiency. The quantity of dose deposited in either form is dependent upon the incident radiation type and the energy.

Existing dosimeters such as TLDs and ionization chambers are not capable of discriminating between the two forms of dose in Si. A need exists for a system capable of responding independently to both ionizing dose and displacement KERMA in Si.

The aim of this work was to develop a radiation damage monitoring system for a mixed radiation field containing high energy electrons and soft x-ray synchrotron radiation. Such a mixed radiation field is found within the silicon vertex detector (SVD) of the High Energy Physics (HEP) BELLE experiment at KEK, Japan [2]. The radiation environment within the inner cavity of collider experiments cannot be known with absolute certainty. It will also differ from the environment used for device testing programs. Such uncertainty makes simulations of radiation damage within the detector components impossible and a verification of the damage is required.

The proposed system for radiation damage monitoring is based on two semiconductor sensors. For displacement damage (displacement KERMA), PIN dosimetric diodes manufactured from detector grade Si will be used. The ionizing dose will be measured by MOSFET detectors (RADFETs). Both of these passive detectors can utilize the same electronic readout process which involves the measurement of a voltage shift.

The PIN dosimetric diode response is dependent on the reduction of the minority carrier lifetime and changes to the resistivity of the Si base [3]. Both of these effects occur due to the accumulation of displacement damage within the Si bulk. As such the PIN dosimetric diode response is insensitive to ionization effects in Si. For the MOSFET structure, response is mostly due to ionization effects within the gate oxide. Displacement damage can affect the response of MOSFET detectors through displacement damage in the Si substrate. But due to the low resistivity of the Si normally used for MOSFETs, this effect will not contribute significantly to the MOSFET response [4].

Previous radiation damage monitoring systems have utilized MOSFETs for measurement of the cumulative ionizing dose as well as photodiodes for the measurement of the ionizing dose rate [5]. Photodiodes have also been used for the measurement of the ionizing dose rate followed by integration of the signal for a dose accumulation measurement [6]. It should be mentioned that such systems are not capable of measuring the displacement KERMA component of the total dose.

In this paper we demonstrate that a system based on a photodiode for the measurement of the ionizing dose would be unreliable in a high energy electron field. Degradation of the phtotodiode repsonse was studied in a 20 MeV electron field and a 1 MeV neutron field. We also studied the displacement damage within ion-implanted Si detector structures in the 20 MeV electron field. An attempt was made to describe the displacement damage in Si caused by the 20 MeV electrons in terms of 1 MeV (Si) displacement KERMA. The response of RADFETs with different gate oxide thickness was studied during irradiation with a 20 MeV electron beam in terms of the ionizing dose in silicon.

II. Radiation Environment within BELLE SVD and Expected Damage

The KEK B-factory is a high luminosity asymmetric electron-positron collider built at KEK, Japan. For the BELLE series of experiments, which are directed to the study of CP violation, the collider will accelerate positrons to an energy of 3.5 GeV with a beam current of 2.6 A, and electrons to an energy of 8 GeV with a beam current of 1.1 A [2].

A BELLE Silicon Vertex Detector super-module is composed of two layers of Double Sided Silicon Strip Detectors (DSSD) with electronic CMOS LSI boards located at both ends of the module. The SVD surrounds the beryllium beam-pipe with the innermost layer of the SVD located only several millimeters away from the beam-pipe [7].

The large beam currents and high beam energies create unique radiation background problems within the SVD. Quadrapoles near the detector generate synchrotron radiation in the range of 5-15 keV. Residual gas within the beam-pipe scatters many of the leptons. The secondary showers produced by these particles will contribute to the radiation damage of the SVD. Additionally, high energy particles are created as a product of the electron-positron beam collisions. Estimations by Monte Carlo simulations have given the maximum ionization doses in the SVD at up to 50 krad(Si)/yr in a worst case scenario [8]. Ninety nine percent of this dose is due to the electron contribution [9]. The expected flux is approximately 2×10^{12} $cm^{-2}\cdot yr^{-1}$.

For this radiation environment, most attention was initially placed on damage to the detector system due to the deposition of ionizing energy. IEL is responsible for a build up of charge within the gate oxide of MOS transistors thus causing a shift of the threshold voltage and eventual degradation of the signal to noise ratio, S/N. These are critical parameters of the front-end electronics. In the strip detectors, the ionization will cause a build-up of charge in the passivation oxide between the p-n junction strips. This build up can lead to a decrease of the interstrip resistance and an increase of the interstrip capacitance thereby increasing the amplifier noise. Special methods such as p-stop layers between strips can reduce these effects [10].

In the background simulations [8,9] the NIEL was not taken into account. Although the simulated doses are based only on the ionizing component, the effect of non-ionizing energy loss can be considerable in silicon exposed to high energy electrons. It was recently demonstrated that highly energetic electrons, (~500 MeV), produce a similar amount of damage in silicon per unit fluence as 1 MeV neutrons and high energy protons [11]. This result was inferred from the increase of the reverse current measured in silicon strip detectors.

The NIEL will lead to bulk damage in the Si strip detectors causing an increase of the reverse current, alteration of the conductivity type and depletion of the detector sensitive volume [10,12].

III. Radiation Damage in a Photodiode Monitor and Silicon Detectors

An additional study of the photodiode response and Si detector behaviour in a high energy electron field is necessary to understand the optimum design of a radiation damage monitoring system.

A. *Radiation Sources and Experimental Setup*

The response of a Hamamatsu photodiode (device S3590-08) to ionizing radiation was studied before, during and after exposure to two radiation fields. We investigated its response following exposure to a 20 MeV electron field and a 1 MeV neutron field. The 20 MeV electron irradiation was performed to test if high energy electrons were capable of causing displacement damage sufficient to degrade the photodiode response. The 1 MeV neutron irradiation was used to model the BELLE high energy electron environment as the damage in the Si detector is expected to be similar [11]. The irradiating particle fluence was similar to that expected within the BELLE SVD ~ 2×10^{12} cm^{-2}.

Neutron irradiation was performed at the 3 MV Van de Graaff at ANSTO. The neutrons were produced on a Li^7 target bombarded by 2.7 MeV protons with a beam current at the target of about 22 μA. The neutron energy in the forward direction was ~1 MeV. The Hamamatsu photodiode, enclosed within an aluminum case, was located at a distance of 5 mm from the target. Measurement of the neutron fluence was made using a neutron long counter as well as with PIN dosimetric diodes calibrated in terms of a 1 MeV equivalent neutron fluence. The total fluence was ~ 2×10^{12} n/cm^2. The maximum uncertainty in this fluence was 20 %.

The response of the photodiode was measured using a LED (λ ~ 0.9 μm) and with a Sr-90 electron source to simulate the situation of minimum ionizing particles (m.i.p.) expected in the BELLE experiment. Photodiode and LED operating conditions were kept constant for all measurements. The relative position of the (~0.1 mCi) Sr-90 source to the photodiode was kept the same to exposure of the photodiode to a constant electron flux. The response to the Sr-90 source was measured before and after neutron irradiation.

The photodiode response to 20 MeV electrons was measured in an electron field produced using a medical linear accelerator. Irradiation was performed in free air geometry. To receive the maximum possible flux the photodiode, (attached to a low noise current pre-amplifier and covered with a thin Cu foil housing), was placed at the minimum possible distance of 50 cm from the virtual electron source. Also situated close to the photodiode were ion implanted silicon detector test structures and PIN dosimetric diodes.

Stability of the LINAC output and the electron fluence were monitored with a transmission ionization chamber. Uniformity of the flux during the irradiation was found to be better than 2%. The irradiation was done in a uniform 10×10 cm^2 electron beam. The photodiode current output was monitored on-line via a 20 m interconnect cable.

The electron fluence was calculated from the dose measured in water at a distance of 1 m from the virtual electron source. The fluence at the point of irradiation was calculated using the inverse square law.

The electron fluence and dose in Si were measured independently using the Hamamatsu photodiode at the point of irradiation, using equation 1.

$$D(Si) = \frac{I_d w_{Si} t_{ir}}{e \rho_{Si} V_{Si}} \quad (1)$$

Where, I_d = photodiode current,
w_{Si} = 3.62 eV,
t_{ir} = irradiation time,
e = 1.6×10^{-19} C,
ρ_{Si} = density of Si,
V_{Si} = sensitive volume of the photodiode (1×1×0.03 cm^3),
$D(Si)$ = ionizing dose in silicon.

The minority carrier lifetime of the photodiode bulk was determined to be ~1.5 ms as measured from the reverse current characteristics. This corresponds to a diffusion length of L ~1.2 mm, which is much greater than the device thickness (300 μm). Thus the charge collection volume of the unirradiated photodiode in passive mode corresponded to the geometrical volume V_{Si} above.

The electron fluence was calculated at the point of irradiation from the measured *D(Si)* in the photodiode using the energy deposited by a m.i.p. in 300 μm of Si. The fluences is calculated using this technique and from the ionization chamber measurements were within 15 %.

A calibration of the LINAC at the point of irradiation of 1.56 krad (Si) per 1 minute of irradiation was obtained. This calibration was done at the beginning of irradiation when the photodiode was undamaged.

B. *Radiation Response*

Photodiode Response

The Hamamatsu photodiode response to the LINAC electron beam was monitored during irradiation. The degradation of the photodiode response in terms of cumulative dose in Si, *D(Si)*, to the 20 MeV electron field is shown in figure 1. It can be seen that after a dose of 50 krad, which is the ionization dose expected within the BELLE SVD per year in a worst case scenario, the response is degraded by ~ 15 %. This is for 20 MeV electrons which are significantly less damaging than the high energy electrons expected within the SVD of BELLE.

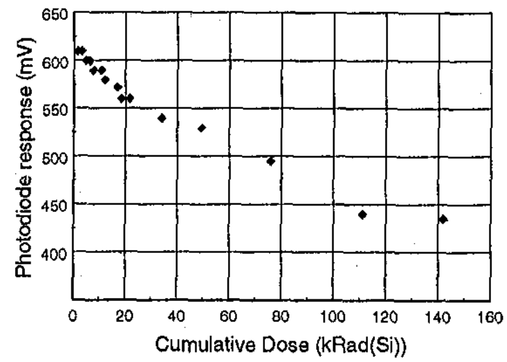

Figure 1: Hamamatsu photodiode response to a 20 MeV electron field as a function of absorbed dose.

The conclusion from this experiment is that an ionization dose monitor based on photodiodes would be unreliable for applications within a high energy electron field. The apparent radiation levels would continuously be underestimated as a function of time due to the continued degradation of the monitors charge collection characteristics. Further, such a detector is incapable of assessing the effects of displacement damage within the silicon bulk. Such a sensor would however still be useful as an alarm sensor for detecting sudden increases in the radiation level.

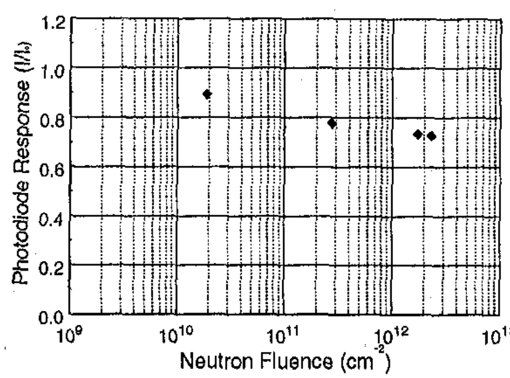

Figure 2: Relative response of photodiode to LED (λ ~ 0.9 μm) as a function of 1 MeV neutron irradiation.

In order to estimate the photodiode response in a high energy GeV range electron field we analyzed results of the neutron irradiation.

Figure 2 shows the degradation of the photodiode response to a LED photon source (average λ ~ 0.9 μm) as a function of neutron fluence during the 1 MeV neutron irradiation. A degradation of approximately 25 % was observed after a neutron fluence ~ 10^{12} n/cm^2.

Using the same photodiode we measured the response to the Sr-90 electron source before and after neutron irradiation. In this case, the photocurrent degraded by a factor of 27 after a fluence of 2×10^{12} n/cm^2.

The observed differing degradation of the photodiode response to the LED and to the Sr-90 electron source can be explained in terms of the differing contribution of diffusion charge to the total charge collected. In the LED case the generated charge density is much higher near the surface (pn junction region) of the photodetector. For the m.i.p. from Sr-90 the ionisation is uniform throughout the device. Thus charge diffusion contributes more significantly to the total collected charge. The degradation of the diffusion length in this latter case will have a more significant effect on the photodiode response as observed.

This result suggest that the role of bulk damage within the expected GeV electron field limits the performance of the photodiode as a cumulative dose monitor. Secondly, an independent bulk damage monitor must be incorporated into the system.

IV. BULK DAMAGE MONITORING

It is reasonable to assume that the best sensor of radiation bulk damage in silicon should be based on silicon and similar to that found within the strip detectors of the SVD, i.e. high resistivity silicon.

Ion implanted silicon detector test structures and PIN dosimetric diodes were irradiated with a 20 MeV electron beam simultaneously at the same point. Degradation of silicon radiation detectors is measured by the increase of the reverse current and change of conductivity and material type from n-to p-type [10].

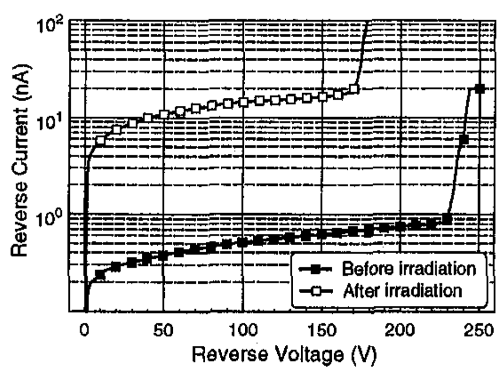

Figure 3: Detector reverse current measured before and after 20 MeV electron irradiation at a fluence, $\Phi_e = 9.2\times10^{11}$ cm^{-2}.

In figure 3 the reverse current measured under full depletion conditions before and after electron irradiation, with Φ_e~10^{12} e/cm^2, is plotted as a function of reverse voltage. Following irradiation, the reverse current increased by a factor of ~13.

The reverse current was monitored as a function of time to determine the effects of room temperature annealing. Over a period of 2 months, the reverse current was seen to decrease by 35% from the value measured 5hrs after electron irradiation. All measurements were made at a constant temperature of 20°C.

The radiation damage of the detector is measured by an increase in the reverse bias current per unit volume of fully depleted detector according to equation 2. In equation 2, α is the reverse current damage constant which is dependent on the type and energy of the radiation.

$$\frac{I - I_o}{Vol} = \alpha\ \Phi \qquad (2)$$

Where I_o = reverse current before irradiation,
I = reverse current after irradiation,
Vol = full depletion volume of the detector,
Φ = particle fluence.

At the completion of room temperature annealing the reverse current damage constant for 20 MeV electrons, α_e (20 MeV), was calculated to be 1.0×10^{-18} A/cm. For comparison, the room temperature annealed reverse current damage constant for 1 MeV neutrons, α_n (1 MeV), is 2.5×10^{-17} A/cm [13].

Even for 20 MeV electrons we can see that the radiation damage is much greater than that for 1 MeV electrons, for which α_e (1 MeV) is 5.1×10^{-20} A/cm [11]. Taking into account that bulk damage of Si devices is strongly dependent on the electron energy, standardization of this damage independently of the electron energy spectra is needed. Such damage cannot be characterized by ionizing dose in silicon.

We investigated the possibility of bulk damage monitoring in terms of a 1 MeV (Si) equivalent neutron fluence for a high energy electron field. Previously this was done for the standardization of different neutron energy spectra [14]. It was necessary to do so due to the neutron energy dependence of displacement damage in Si. As a result of this fact, facilities with different energy spectrums will cause different amounts of damage within silicon devices under the same fluence. To permit easy comparison of damage in a silicon device each spectrum is characterized in terms of an equivalent mono-energetic 1 MeV(Si) neutron fluence which would result in an identical deposition of displacement KERMA. The equivalent neutron fluence at 1 MeV, Φ (1MeV), is defined by equation 3.

$$\Phi(1MeV) = \frac{\int_{E_{min}}^{E_{max}} \Phi(E) \cdot \kappa_D(E)dE}{\kappa_D(1MeV)} \qquad (3)$$

Where $\Phi(E)$ = neutron energy spectrum,
$\kappa_D(E)$ = neutron damage function in Si,
$\kappa_D(1MeV)$ = neutron damage in Si at a neutron energy of 1 MeV.

Other radiation fields demand a similar approach to permit the estimation of radiation damage in silicon devices. This is important because radiation damage of silicon devices and Si-strip detector performance has been well studied within 1 MeV neutron fields.

As demonstrated in references [3,15-19], PIN dosimetric diodes can be used for different neutron fields to standardize them in terms of a 1 MeV (Si) equivalent neutron fluence. The suitability of the PIN diode is based on its simplicity of operation. The equivalent neutron fluence is measured by the change of forward bias voltage under constant current. PIN diodes are also small (2-3 mm^3), easy to read out and are passive devices.

The PIN dosimetric diodes used for the 1 MeV (Si) neutron fluence monitoring at the Van de Graaff were also used in the 20 MeV electron field.

The PIN diode showed a good linear response as a function of fluence of the 20 MeV electron beam. A forward voltage shift of 317±15 mV was observed for an electron fluence of $2x10^{12}$ cm^{-2}. The forward bias voltage of the PIN diode was measured before and immediately after irradiation in water at a temperature of 21°C in order to avoid a temperature error. Using the known sensitivity of the diode in terms of 1 MeV(Si) neutrons, the forward voltage shift corresponded to an equivalent neutron fluence of 5.9×10^{10} cm^2. Based on this value, and the measured increase of the ion implanted Si detector reverse leakage current, $\Delta I=7.2\times10^{-9}$ A, the reverse current damage constant for 1 MeV neutrons was simulated. The value of α_n obtained using equation (2) was 1.6×10^{-17} A/cm which is in good agreement with the average value of 2.5×10^{-17} A/cm for similar Si detectors [13].

To further understand the nature of the displacement damage in 20 MeV electron irradiated silicon on an atomic level we used the technique of deep level transient spectroscopy (DLTS) [20]. DLTS permits the detection of deep level defects within semiconductor materials. The technique involves the periodic filling of deep level defect states with carriers. Rate analysis of the exponentially decaying, thermally stimulated, carrier emission is applied as the sample temperature is slowly ramped.

A DLTS spectrum shown in figure 4 was obtained from the 20 MeV electron irradiated silicon detector. Majority carrier peaks associated with majority carrier trapping deep level defects are shown in the upper half of the figure. Minority carrier peaks associated with minority carrier trapping deep level defects are shown in the lower half of the figure. Spectral features were identified based on the measured defect state energies and comparison to the literature. All defects observed have previously been observed in 1 MeV neutron irradiated silicon [21].

This result demonstrates that the type of displacement damage found in 20 MeV electron irradiated silicon is the same as the type of damage found in 1 MeV neutron irradiated silicon.

This result supports the suitability of PIN diodes for the measurement of damage in high energy electron fields in terms of a 1 MeV(Si) equivalent neutron fluence.

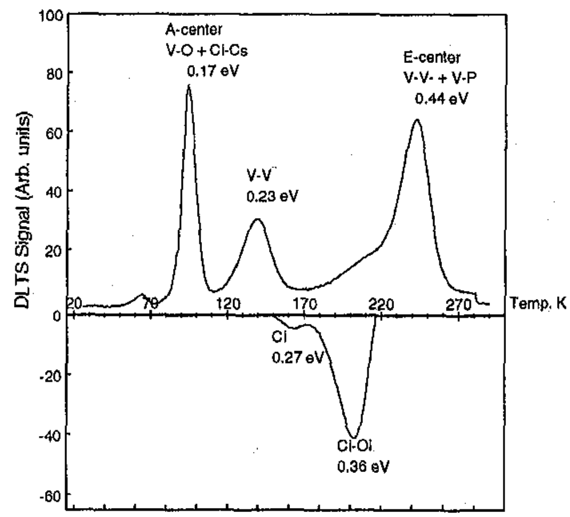

Figure 4: DLTS spectrum of a 20 MeV electron irradiated silicon detector (Φ_e=9.2×10^{11} cm^{-2}). Majority and minority carrier peaks shown in the upper and lower half respectively.

V. IONIZING DOSE MONITORING

For ionizing dose monitoring in an unknown radiation field the response of the sensor should be based on the effect of degradation caused by ionizing KERMA in the gate oxide. The most suitable sensor for this is the MOSFET radiation dosimeter which has been used on-line or in storage mode [15,22].

Radiation creates charge within the thin silicon dioxide layer and this charge and its long term trapping lead to a change of the threshold voltage of the MOSFET transistor. Using preliminary calibrations in terms of ionization dose to Si or SiO_2 this detector can be used for the characterization of a high energy electron field.

The importance of such a measurement was previously noted for applications involving CMOS electronics which rely on the properties of gate oxide layers.

The MOSFET sensors used were REM RADFET TOT500 type devices, supplied by Radiation Experiments and Monitors (REM), Oxford, UK. The device integrates four p-channel dosimeters onto a single die approximately 1 mm x 1 mm in size, with the die connected on top of a thin circuit board.

Two different oxide thickness were used. The first pair of dosimeters had a 0.93 μm thick oxide, and the second pair had a thickness of 0.13 μm. The thicker oxide provides greater sensitivity to ionizing dose, giving a dosimeter that is sensitive within the low rad(Si) range. This dosimeter was designated as type 'R'. The thinner oxides give a dosimeter suitable to higher doses, in the krad(Si) range, and hence these are denoted type 'K'.

To obtain calibration curves for the RADFET system under high energy electrons in terms of dose in Si, four such devices were exposed to the 20 MeV electron field. We irradiated 4 RADFETs, TOT500 (2 in DIL package, 2 in CC-3 package). The shift of the threshold voltage under a constant current corresponding to the thermal stable point was measured. All measurements were done during the 3 hour irradiation. The spread in the change in threshold voltage (ΔV_{th}) as a function of the dose in silicon (D(Si)) was found to be less than 3% for different RADFETs from the same batch. Figure 5 shows the calibration curves for both 'R' and 'K' type RADFETS in the 20 MeV electron field in terms of dose in Si. The analytical expressions derived from the calibration curves for the 'K' type RADFET is $D=40.23\times(\Delta V_{th})^{1.250}$, where D is the dose measured in krad(Si), and ΔV_{th} is the voltage shift in Volts. For the 'R' type RADFETs, $D=1.81\times(\Delta V_{th})^{1.304}$.

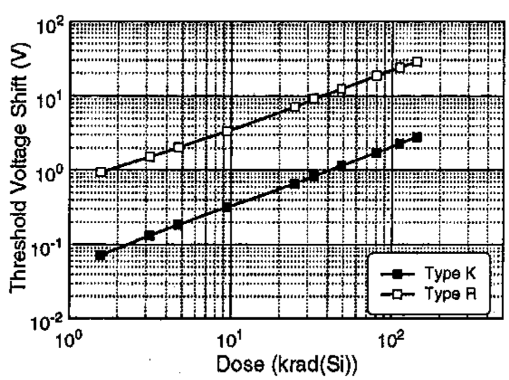

Figure 5: Calibration curves for the RADFETs in terms of dose in Si.

The possible dose ranged from 10 to 2.5×10^6 rad(Si) for the RADFETs in a high energy electron field using both 'K' and 'R' type devices.

Temperature stability of the RADFET dosimeters was investigated at a readout current of 160 μA. Before electron irradiation, the average temperature instability coefficient of change in threshold voltage was found to be approximately -2 mV/°C for type 'R', and 0.7 mV/°C for type 'K' dosimeters. The stability of the 'K' type dosimeters did not change much after irradiation, and was consistent, at 0.8 mV/°C, for all of the 'K' type dosimeters tested. The 'R' type dosimeters, however, had varying responses, ranging from -8 mV/°C to -3 mV/°C and an average value of -5 mV/°C. This represents a dose dependence of approximately 15 rad(Si)/°C at the beginning of the irradiation, which is negligible for the expected dose range in the present application.

VI. Electronic Readout Set-up

The readout system developed allows the simultaneous readout of 32×2 channels on-line with automatic data logging to a computer.

The basic operation of the reader is to pass a constant current of 160 μA through the RADFET and 1 mA through the PIN diode followed by reading of the corresponding threshold voltage, V_{th}, and forward voltage, V_F, respectively. During the irradiation all pins of the RADFETs and PIN diodes are grounded. It is important to have a duty cycle much longer than the readout time for the RADFET to avoid a change of sensitivity due to the voltage on the gate. The readout for the RADFET and PIN diode sensors was made in a pulsed mode. Initial delay in sampling was about 1 ms to avoid any fast transients in the RADFET and PIN diodes.

The system is currently designed with a long ribbon cable interconnect (the BELLE experiments requires a 10 m cable from the SVD to the control room). A PC board with calibrated resistors is used for testing channels during the device operation or installation. Special adaptors connect the RADFETs and PIN diodes to the reader to allow readout scanning of individual sensors.

A reader has been designed to manage the parallel readout of the 32 R/K RADFET pairs or PIN diode simultaneously. Any channel can be read manually using the built-in digital display. The whole unit fits in a standard 3 unit 19" rack enclosure. The logger used is a TempScan/1100.

VII. Discussion and Conclusion

Radiation damage monitoring of silicon devices within mixed radiation fields requires separate determination of the ionizing and displacement damage.

In a mixed radiation field, containing synchrotron radiation and high energy electrons, it is impossible to predict displacement KERMA by relying upon ionizing dose rate only.

The application of photodiodes for radiation damage monitoring in SVD, in a radiation field similar to the BELLE experiment, can lead to an error in the determination of the integral ionizing dose. The error is due to the bulk damage in the silicon caused by the deposition of non-ionizing energy. Similar damage within the readout current amplifier, located close to the photodiode, will also contribute to this error. Such a system is suitable for the monitoring of uncontrollable beam losses [6] where a fast beam dump is required. The monitoring system with a photodiode sensor requires power for the readout preamplifier that demands additional cables and could not be used in the limited space close to the SVD readout electronics.

An alternative damage monitoring system should satisfy the following criteria:

- a capacity to measure both ionizing and non ionizing damage,
- sensors should be capable of independently measuring damage in terms of both ionizing dose in SiO_2 and non-ionizing dose in terms of an 1 MeV(Si) equivalent neutron fluence,
- the sensors should have a wide range of response due to uncertainties in the radiation field,
- sensor response should be well calibrated within the expected dose range,
- sensors should be small in size and preferably passive.

In this study such a system was designed based on MOSFET sensors for measuring the ionizing energy losses and PIN dosimetric diodes for monitoring the non-ionizing energy losses. These sensors are based on silicon and reflect the radiation damage mechanisms responsible for degradation of the CMOS gate oxide and bulk damage of silicon almost independently.

It was demonstrated that in the case of predicting the degradation of silicon detectors under 20 MeV electron field it is possible to standardize the damage in terms of a 1 MeV (Si) equivalent neutron fluence. This improves the universality of the PIN diode, beyond standardization of neutron fields containing different energy spectra.

The advantages of these sensors include passive operation, similar readouts, small size. The latter advantage may allow incorporation into a hybrid electronic system. The wide dose range in ionizing dose measurements is achieved by the simultaneous readout of MOSFETs with different oxide thickness as in the REM RADFETs. The extension of the range of measurement in 1 MeV (Si) equivalent neutron fluence is possible by the annealing of the PIN diode under 100°C after irradiation followed by reading the corresponding forward voltage shift [18]. The PIN dosimetric diodes are manufactured on the base of high resistivity silicon [3] and have a larger dynamic range enabling the measurement without annealing of the equivalent 1 MeV (Si) neutron fluence up to 7×10^{12} n/cm^2. The partial recovery of a PIN diode is achieved through current annealing as was previously proposed by us [15]. For this recovery process, short mA current pulses can be used. Such an annealing system has been developed and can be easily incorporated into the reader. Advantages of such an annealing system include non-removal of the sensor from the monitoring position and no additional cabling requirements. These advantages allow the consideration of this radiation damage monitoring system, which is based on MOSFETs and PIN dosimetric diodes with current annealing, as a possible standard for the characterization of any mixed radiation field.

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