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Study of Radiation Damage of CCD Sensors by Electron Beam Irradiation

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CCD pixel sensors are expected to have very high performance as a charged particle tracking device because of the excellent spatial resolution and the very thin material thickness of the sensitive layer. One disadvantage of CCD sensors is its relatively low radiation hardness. We have exposed CCD samples to 140 MeV electron beam of LNS and studied their radiation tolerance. Comparing with the results of ^{90}Sr irradiation test, the energy dependence of the radiation damage has been clearly seen.

§ 1. Introduction

At the future e^+e^- linear collider experiment [1, 2, 3] the vertex detector has a great importance for physics analysis through b-quark, c-quark, τ, and gluon jet tagging. CCD pixel sensors are thought to be one of the primary candidates of the vertex detector. CCDs have advantages of the excellent spatial resolution through charge spread among adjacent pixels, and thin active layer thickness which reduces multiple scattering effects. One possible disadvantage of CCDs is their relatively low radiation tolerance. At the linear collider experiment, a large number of e^+ and e^- beam background, called pair background, is created through the beam-beam interaction at the collision point. The estimated background rate is larger than 1×10^{11}/cm^2/year at the innermost layer of the vertex detector located at R = 24 mm. So the study of radiation tolerance of CCDs is the most urgent issue for the application to the vertex detector at the linear collider experiment.

So far, we have studied the radiation damage effect of CCDs by ^{90}Sr β ray irradiation [4, 5]. However, the energy of the pair background hitting the vertex detector peaks at around 20 MeV, which is much higher than the energy of ^{90}Sr β ray. Bulk damage in Si is thought to be proportional to non-ionizing energy loss (NIEL). Figure 1 shows model calculations of NIEL [6, 7]. As can be seen from this figure, NIEL has a strong energy dependence below 100 MeV. Since extrapolation of the ^{90}Sr irradiation results to 20 MeV has a large ambiguity, we have directly measured the damage effect by high energy electrons [8].

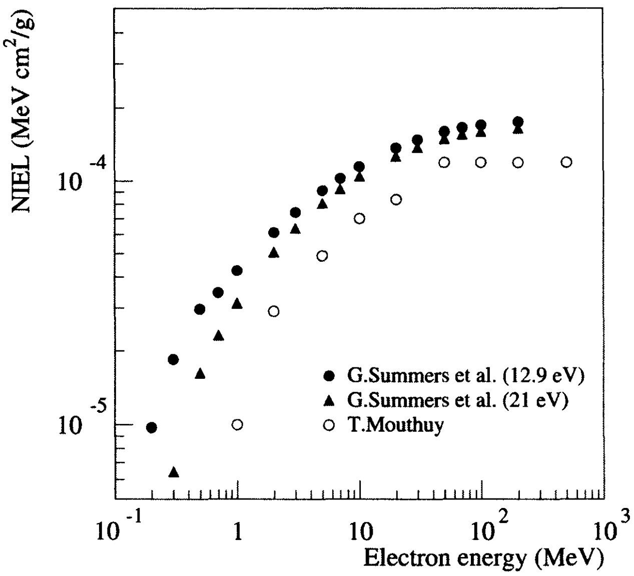

Fig.1. Model calculations of non-ionizing energy loss (NIEL) [6, 7]. The estimation by Summers *et al.* assumes two different threashold energies required for lattice dislocation.

§ 2. Irradiation Experiment

The electron beam irradiation was carried out at Laboratory of Nuclear Science, Tohoku University (LNS). A 140 MeV pulsed electron beam from the linac was fed into Stretcher Booster ring [9] and extracted as a quasi-DC beam. The beam was transported into BL-V beamline [10] and hit an aluminum frame of a foil-radiator which is usually used for tagged photon experiments. The beam was broadened by multiple scattering by the aluminum frame, bent by a dipole magnet, and irradiated CCDs uniformly.

The CCDs irradiated with the electron beam are special variants of S5466 made by Hamamatsu Photonics. They have 256 × 256 active pixels, and the pixel size is 24 μm.

We have irradiated the CCD step by step up to the dose of $5 \times 10^{11}/cm^2$. The characteristics of the CCD were measured after irradiation of $0.5 \times 10^{11}/cm^2$, $1.0 \times 10^{11}/cm^2$, $2.0 \times 10^{11}/cm^2$, and $5.0 \times 10^{11}/cm^2$, as well as before the irradiation. The irradiation was performed at the room temperature with all pins of the CCD grounded.

The irradiation dose was measured by a two-dimensional array of Si PIN photodiodes placed just downstream of the sample CCD. The photodiodes were placed at 10.16 mm pitch. The current induced by electrons passing through the photodiodes was converted to voltage, and the voltage for each photodiode was measured by multi-channel digital multi meter (DMM). The measured voltages were readout by a computer through RS-232C interface every 5 seconds, and recorded as a file. The time constant of this measurement circuit is longer than the time structure of the beam bunches. Therefore, we measured the averaged beam intensity. From the distribution of the beam intensity in the two-dimensional array, we observed the uniformity of the irradiation over the CCD area. We also used RadFETs [11] as an integrated dose monitor for the cross-check. Both measurements were consistent with each other.

§ 3. Measurement of Characteristics of CCDs

After the irradiation of a certain dose, the sample was brought back to KEK and its characteristics were measured to see the radiation damage effects.

The CCD sample was put inside of a cryostat using liquid nitrogen, and the temperature was controlled between −100°C and +20°C during the measurements. The CCD was read out at a clock rate of 250 kpix/s and the analog output of the CCD was fed into a correlated double sampling circuit, an amplifier, and read out by a VME ADC.

We measured dark current and charge transfer inefficiency (CTI) of the sample CCD as a function of temperature. The CTI was derived from the position dependence of the peak of Mn-K_α line (5.9 keV) of ^{55}Fe. The X-ray exposure was controlled using a mechanical shutter and the CCD was read out after the shutter was closed. The cycle time of the exposure and readout was two seconds.

§ 4. Results and Discussions

4.1 Dark current

The sample CCDs can be operated in multi-pinned phase (MPP) mode (or inverted mode). If the low level of the clock pulse exceeds some value, the CCD gets into MPP mode from normal mode. In MPP mode, the surface dark current is strongly suppressed and the bulk current dominates. After the irradiation, an increase of the dark current was observed. In MPP mode, the dark current at 10°C increased from ~ 40 electrons/pixel/s to ~ 200 electrons/pixel/s after 1×10^{11} /cm^2 irradiation of the high

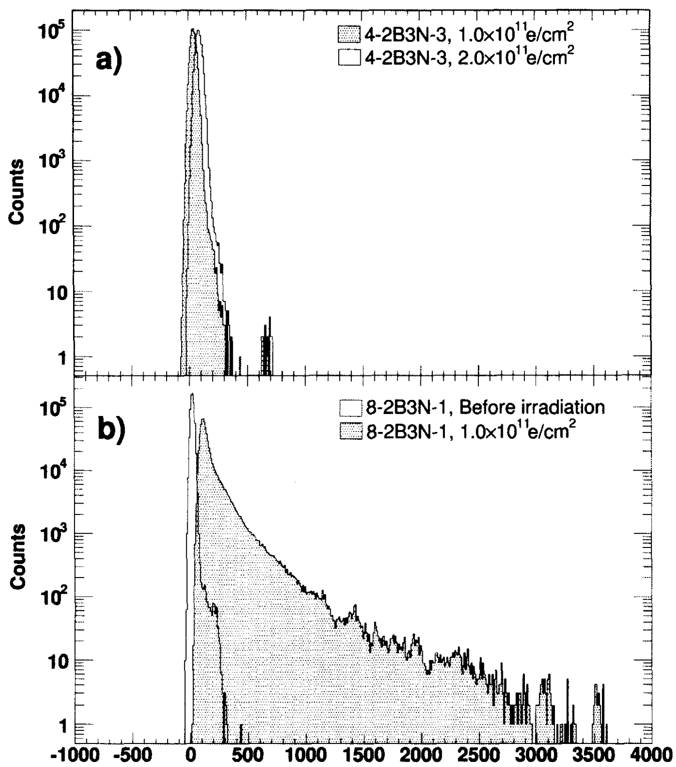

Fig.2. Distribution of dark current of CCDs (a) after irradiation of 1×10^{11}/cm^2 and 2×10^{11}/cm^2 β ray of ^{90}Sr and (b) before and after 1×10^{11}/cm^2 140 MeV electron beam irradiation [8].

energy electrons. In the readout cycle time of 6.7 ms at GLC [1], this dark current is not a problem at all.

We observed a large difference in the distribution of the dark current between the beam-irradiated CCD and the β-ray-irradiated CCD as shown in Fig.2. The beam-irradiated CCD shows a long tail of hot pixels which can not be seen in the β-ray-irradiated one. These hot pixels are presumably due to cluster-defects which cannot be created by low energy β ray [7, 12].

In MPP mode, we observed the spurious dark current, which is generated during clocking and thought to be due to impact ionization by holes trapped in $Si\text{-}SiO_2$ interface levels. The beam-irradiated CCD showed larger spurious dark current than β-ray-irradiated one at higher temperature. For the CCD irradiated with $1 \times 10^{11}/cm^2$ beam electrons, the spurious dark current of about 100 electrons/pixel was observed at 10 °C.

Surface damage of CCDs causes shift of operating voltage (gate clock voltage), called as flat-band voltage shift. The flat-band voltage shift of the sample CCDs is measured as the shift of the transition voltage from normal node to MPP mode. At the dose level of $2 \times 10^{11}/cm^2$, no significant flat-band voltage shift was observed for the sample CCDs.

4.2 Charge transfer inefficiency

The measured CTI in the vertical (parallel) register as a function of temperature is shown in Fig.3 both for the electron-beam irradiated sample and for the β-ray-irradiated sample. From this figure, it can be seen that the high energy electron beam has about 3 times larger effect than β ray of ^{90}Sr in creating the CTI.

The CTI is expected to be reduced by injecting extra charge which fills up trap centers. This technique is called 'fat-zero charge' injection. We have measured the effect of this fat-zero charge injection. The fat-zero charge was injected by illuminating the CCD continuously with LEDs. The CTI with the fat-zero charge injection is also plotted in Fig.3. Suppression of the CTI by the fat-zero charge

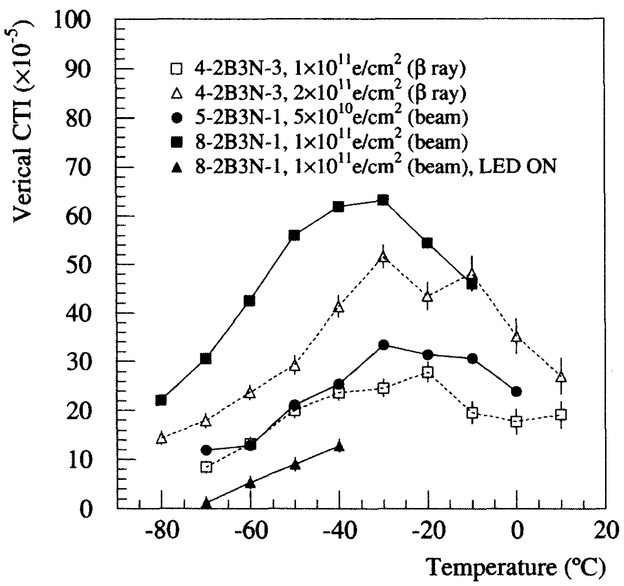

Fig.3. Charge transfer inefficiency (CTI) as a function of temperature. CTI with fat-zero charge injection of ~ 1200 electrons/pixel is also plotted [8].

injection was clearly observed.

In our measurement, the CTI in the horizontal (serial) register was smaller than the sensitivity of the measurement (less than 5×10^{-5} at -60 °C). This is presumably due to the CTI suppression by the large spurious dark current in the horizontal register.

§ 5. Conclusions

We have executed electron irradiation experiment of CCD pixel sensors at LNS in order to study the radiation damage effects expected at the future high energy e^+e^- linear collider experiment. The characteristics of electron-beam irradiated CCDs have been measured and compared with that of ^{90}Sr β-ray-irradiated CCDs. We have observed energy dependence of the radiation effects of CCDs clearly. We found that the 140 MeV electrons create hot pixels which cannot be found in β-ray-irradiated CCDs. No significant flat-band voltage shift was observed up to 2×10^{11} /cm^2 irradiation. The CTI caused by the high energy electron beam was found to be $2-3$ times larger than that caused by the β-ray of ^{90}Sr. Suppression of the CTI by fat-zero charge injection has been demonstrated. The results we have obtained in this work give an important guideline to the design and further R&D of the CCD vertex detector at the linear collider experiment.

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