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AT CRYOGENIC TEMPERATURES IN AN ACCELERATOR ENVIRONMENT

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ABSTRACT

The quench protection diodes for the proposed Large Hadron Collider at CERN will be located inside the He-II vessel of the magnet cryostat, where they could be exposed to a relatively high radiation dose. To determine the correspondence of neutron fluence results, obtained from experiments for the SSC, and the dose in an accelerator environment, several commercially available high current diodes of the DS6000 type from ABB and newly developed diodes of thin base region were irradiated at liquid nitrogen temperature in a target area of the SPS accelerator at CERN. The electrical characteristics of the diodes have been measured as a function of dose up to a maximum of about 600 Gy. After irradiation the diodes were submitted to current pulse annealing and to thermal annealing cycles up to temperatures of about 150 C. The results show that injection annealing alone can extend the service life of irradiated diodes quite substantially. The results are compared with the measurements from irradiation tests on diodes for the SSC, in a research reactor.

INTRODUCTION

Essential elements for the protection of the superconducting dipoles and quadrupoles for the proposed Large Hadron Collider at CERN are high current bypass diodes. In order to reduce the heat-load on the cryogenic system, caused by safety current leads, it is foreseen to mount these diodes inside the He-II vessel at a distance of 10 to 20 cm from the beam axis, where they could be exposed to a relatively high radiation dose. No specific simulation has been made up to now with the exact geometry, but extrapolations made from existing simulations show that a maximum dose of about 5000 Gy per year of LHC operation can be expected¹. In recent experiments made for the SSC², several types of quench protection diodes were irradiated at the Texas NSC Reactor at liquid nitrogen and liquid helium temperatures. They show that the best diodes (DS6000 from ABB) are severely degraded for a neutron fluence of about $5 \cdot 10^{13}$ neutrons/cm². At 4.2 K the forward voltage almost doubles at 6600 A. The increase in forward voltage due to radiation will increase the heat dissipation at the junction during a quench pulse, and diode burn-out might occur before the current pulse - an exponential decay from 15 kA with a time constant of about

100s - is over³. In a first test run, four DS6000 diodes were exposed to a dose of about 600 Gy in a mixed secondary radiation field for about three months downstream of target T4 in the SPS area. Forward characteristic $I_f=f(U_f)$, reverse characteristic $I_r=f(U_r)$, and the zero voltage capacity of the diode were measured versus exposure. After irradiation the diodes were submitted to different type of injection annealing and temperature annealing. A second test run has started on two DS6000 diodes and six newly developed, thin base diodes³ with a wafer of 75 mm diameter downstream target T6 in the SPS area, where a much higher dose is expected and also the different spectrum will be measured. The aim of the second test run - still at liquid nitrogen temperature - is to see, whether it is worthwhile to prepare irradiation tests on the newly developed diodes at liquid helium temperatures in an accelerator environment or at a nuclear reactor. Preliminary results from the second run are also given in this paper.

TEST SET UP

Diode assemblies

The DS6000 diodes were stacked - together with copper disks between each of the diodes acting as heat sinks and electrodes - and clamped under a force of 20 kN applied to the outside of the common holder as shown on the photo in Fig. 1.

The six newly developed diodes were clamped similarly in a separate holder under a force of 42 kN. The diode assemblies were mounted in a low loss cryostat designed to maintain all diodes at the same ambient temperature while permitting all electrical tests on individual diodes via separate leads for current pulsing and coaxial cables for voltage and capacity measurements. The leads for current pulsing were connected to the copper spacers (heat sinks) between each of the diodes and the coaxial cables directly to the anode and cathode of the housing of each diode.

Fig. 1 : Photograph of four DS6000 assembled for irradiation tests

Fig. 2. Forward characteristic $I_f = f(U_f)$ of four DS6000 diodes at 77 K before and after irradiation of about 600 Gy

Current pulse generator and measuring equipment

For measuring the I_f - U_f characteristic a current pulse generator of the LC-oscillator type was used providing a half-sinusoidal pulse of about 200 μ s with peak current levels up to about 16 kA. Thermal model calculations have shown that the temperature rise during the current pulse does not exceed 3 K at 77K starting temperature and 1K at room temperature. A PEARSON current monitor was used to measure the current wave form with a precision of better than 1%. Both the forward voltage U_f and the forward current I_f were recorded with a vertical resolution of 12 bits and a digitizing rate of 0.5 μ s per point. The junction capacitance was measured with an LCR-meter at a frequency of 10 kHz via the coax cable.

Dosimeters

For monitoring the dose during irradiation, several sets of dosimeters of the Alanine and RPL-type were used. One set consisted of 2 Alanine and 3 RPL dosimeters⁴. The dosimeter sets were mounted inside and outside the cryostat in such a way that all dosimeters had the same distance to the particle beam. One pair of dosimeter sets was analyzed after each exposure period and then replaced by new dosimeters for the following exposure. A second pair of dosimeter sets was installed right next to the first pair to integrate the dose of all the exposure periods. The irradiation non-uniformity measured with the dosimeter set outside the cryostat was less than ± 4 %.

TEST PROCEDURE

A variety of electrical tests were performed before and after each irradiation period to monitor performance degradation of the diodes as a function of dose. During the whole irradiation program of three months, the diodes were kept at liquid nitrogen temperature. After each of the six exposure periods the cryostat was removed from the radiation area, the diodes measured at liquid nitrogen temperature, and the cryostat re-installed into the radiation area. During the first test run with DS6000 diodes only, all four diodes were

measured after each irradiation period and self-annealing by carrier injection (induced by the tests themselves) was observed. During the second test run with two DS6000 and six newly developed 75 mm diodes, one DS6000 and two of the other diodes were only measured before and at the end of the total exposure program to minimize the self-annealing effects. Junction capacity and reverse bias measurements were performed before applying high current pulses. The forward voltage U_f was always measured at peak current level ($dI/dt=0$) to avoid inductive contributions. Different current amplitudes up to about 15 kA were applied. After irradiation the four DS6000 diodes were warmed up to room temperature and re-measured at liquid nitrogen temperature before applying thermal cycles above room temperature.

TEST RESULTS ON DS6000 DIODES

Forward Voltage U_f versus Exposure

The increase in forward voltage is a sensitive indicator of radiation damage. Fig.2 shows the I_f - U_f -characteristic of the four DS6000 diodes at 77 K before irradiation and after the total irradiation program. The relative variation in forward voltage $\Delta U_f/U_{f0}$, here called degradation, is given in Fig. 3 for two diodes as function of dose at three different current levels. The degradation $\Delta U_f/U_{f0}$ due to irradiation increases with higher current levels from about 20 % at 0.5 kA to about 60 % at 8 kA indicating that small current pulse level measurements are not sufficient to predict the damage at higher current levels.

The differences among the diodes are less due to radiation non-uniformity than to manufacturing tolerances of the n-base region thickness, which has a strong influence on the forward voltage and is already visible before irradiation. The measured forward voltages are influenced by self annealing effects, so that unmeasured diodes would show a higher degradation.

Fig. 3 Increase in forward voltage on two diodes versus exposure and current level

Fig. 4 Capacitance of four DS6000 versus exposure

Fig. 5 Reverse voltage versus irradiation dose for the DS6000 diodes

Fig. 6 Reduction of degradation $\Delta U_f/U_{f0}$ during current pulsing

Capacitance versus Exposure

The capacitance of the four diodes at zero volt is plotted in Fig. 4 as function of exposure. The relative decrease in capacitance $\Delta C/C_0$ versus dose is almost identical for all four diodes and reaches about -16 %. By measuring the capacitance, before and after the high current pulse tests, we were able to see qualitatively the self annealing. After the last irradiation period a capacitance increase of about 2 nF was observed due to current pulse measurements corresponding to about +5 % for $\Delta C/C_0$.

Reverse Voltage versus Exposure

On each diode the full reverse characteristic $I_r=f(U_r)$ was monitored as a function of exposure covering the I_r -range from about 1 μA to 3 mA. No relevant increase of the reverse leakage current I_r has been observed. The reverse voltage U_r versus exposure for the four DS6000 diodes is shown in Fig. 5. The increase amounts to approximately 3 %, almost identical for all the diodes.

Effect of Current- and Temperature Annealing

Three of the diodes were submitted to carrier injection annealing by applying high current pulses of current amplitudes between 8 kA and 13.6 kA at a rate of about one pulse per minute. The current pulse waveform was of the half sinusoidal type described already above. Fig. 6 shows the reduction of degradation in forward voltage $\Delta U_f/U_{f0}$ for the diode SD42 versus the number of current pulses measured at a forward current $I_f = 8 \text{ kA}$. We have started with annealing current pulses of 8 kA amplitude up to about 120 pulses where the annealing became less efficient and continued with a series of about 100 pulses of 11.5 kA amplitude. After 10 pulses with 13.7 kA the

annealing was stopped due to broken contact of the current leads at the heat sink. By current pulsing only, the initial degradation in forward voltage of 60% could be reduced to about 20 %, and we are sure that a further reduction could have been obtained by continuing with current pulses of higher amplitude. After warming up to room temperature for about 14 days the diodes were measured again at liquid nitrogen temperature and further reduction of degradation down to about 7% has been measured.

Fig. 7 shows the I_f - U_f -characteristic for the diode SD42 before irradiation, after irradiation at about 600 Gy, after current pulse annealing and the thermal cycle at room temperature. Further thermal cycling up to about 450 K did not show any further significant reduction of degradation. On diode SD49, which was not submitted to current pulse annealing, a reduction down to 26 % from originally 61 % has been observed at $I_f = 8$ kA due to thermal cycling at 300 K only. The capacitance showed a similar tendency during annealing by current pulses, but not as significant as the forward voltage. After about 220 current pulses the capacitance of SD42 increased to 35 nF, corresponding to about -11 % for $\Delta C/C_0$ compared with -16 % before annealing.

COMPARISON WITH SSC RESULTS

The comparison of the diode behavior after irradiation in a reactor and after irradiation in an accelerator environment is restricted to a few measurements where the conditions were similar, i.e. current pulses with 500 A amplitude and capacitance measurements at liquid nitrogen temperature. For the extrapolation to liquid helium temperatures care must be taken due to the different current pulse length of 300 μ s, applied during SSC measurements, which certainly results in a higher temperature in the silicon wafer than for our measurements with a pulse length of 200 μ s. In Fig. 8, the relative increase of the forward voltage $\Delta U_f/U_{f0}$ at 500 A and the relative decrease in capacitance $\Delta C/C_0$ are given versus exposure in Neutrons/cm² (from SSC measurements ²) and in Gray respectively. After 600 Gy in an accelerator environment, the relative increase in forward voltage and the relative decrease in capacitance are almost the same,

Fig. 7 I_f - U_f -characteristic of a DS6000 diode before and after irradiation and after current and temperature annealing

Fig. 8 Relative increase of forward voltage $\Delta U_f/U_{fo}$ and decrease of capacitance $\Delta C/C_o$ versus exposure a) in a reactor for SSC and b) in a accelerator environment

i.e. between 16 % and 20 %, whereas after reactor irradiation the relative decrease in capacitance is four times higher than the relative increase in forward voltage. The difference is most probably due to the different radiation field and possibly the different method of capacitance measurement. Additionally, our results are also influenced by the annealing produced by the measurements themselves, since we applied current pulses up to 8 kA compared with 500 A pulses for SSC measurements.

Using the DS6000 diode as damage sensor and assuming that there is no large difference between the diodes of the same type, from Fig. 8, a correlation between reactor irradiation and accelerator irradiation can be derived for the same relative forward voltage increase at 500 A and for the same relative capacitance decrease. From the capacitance measurements we obtain the equivalence of $1.5 \cdot 10^{10}$ Neutrons/cm² per Gray and from the forward voltage measurements about $6 \cdot 10^{10}$ Neutrons/cm² per Gray for the same relative degradation. For the envisaged application of the diode the increase in forward voltage - and not the decrease in capacitance - is the critical indicator in view of radiation damage.

PRELIMINARY RESULTS FROM THIN BASE REGION DIODES

Irradiation tests on six newly developed diodes with thin base region and two reference diodes of the DS6000 type are conducted at the moment and preliminary results after the first two exposure periods can be presented. After exposure to about 340 Gy, on two of the thin base diodes (E3, E10) no increase in forward voltage could be measured, whereas on one diode (M1A1) an increase of the forward voltage by about 9 % was observed as shown in Fig. 9. The DS6000 diode (A55) shows already a significant increase of the forward voltage by about 34 %. The measured capacitances show the expected tendency, i.e. no decrease for E3 and E10, 3 % decrease for M1A1 and 9 % for the DS6000 type M55. These results confirm already the necessity of a thin base region for a diode for use at low temperatures and in a high radiation environment. The present irradiation tests will continue until the end of the annual SPS physics programme with increased radiation level.

Fig. 9 I_f - U_f -characteristic for three thin base diodes E3, E10, M1A1, and one DS6000 diode A55 before and after irradiation of about 340 Gy

After irradiation, all six diodes will be subjected to current pulse annealing and thermal annealing. The results of these tests will influence the decision as to whether further tests on the thin base diodes, such as irradiation tests at liquid helium temperature, should be carried out.

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