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In the framework of the LHC project at CERN, the effects of radiation on the electrical characteristics of epitaxial diodes for superconducting magnet protection were studied, the diodes were exposed to an irradiation dose up to 50 kGy and a neutron fluence of 10^{15} n/cm² with intermediate thermal annealing each 10 kGy dose steps in the TUM* reactor at 4.6 K.

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Abstract—In the framework of the LHC project at CERN, the effects of radiation on the electrical characteristics of epitaxial diodes for superconducting magnet protection were studied. The diodes were exposed to an irradiation dose up to 50 kGy and a neutron fluence of 10^{15} n/cm² with intermediate thermal annealing each 10 kGy dose steps in the TUM* reactor at 4.6 K.

I. INTRODUCTION

Essential elements for the protection of the superconducting dipoles and quadrupoles for the future 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. Extrapolation made from existing simulations show that the maximum expected dose will be of about 5 kGy per year and the maximum neutron fluence of 5.10^{13} n/cm² per year.

Irradiation tests at liquid helium temperatures are essential for a decision as to whether the epitaxial diodes can be used for the current by-pass at liquid helium temperature for the LHC-superconducting magnets [1][2].

Our original intention to irradiate full-size (75 mm wafer) diodes of the epitaxial type at liquid helium temperatures in a nuclear reactor has been given up because of the very high cost of adequate cryogenic installations. Indeed, the layout of the irradiation cryostat of the Technical University of Munich (TUM) restricts the sample size to a maximum length of 120 mm and a maximum diameter of $\varnothing_{\max} = 16$ mm. Therefore small diode samples of 10 mm wafer diameter have been irradiated in the nuclear research reactor at Munich (TUM) at liquid helium temperature up to a gamma dose of 50 kGy and up to a neutron fluence of 10^{15} n/cm² ($E > 0.1$ MeV) [3]. All electrical characteristic measurements are performed at 4.6 K.

II - DIODE TYPES AND ELECTRICAL PARAMETERS

The irradiation tests were performed on 10 mm diameter samples manufactured by the same technological process used for the large 75 mm diameter epitaxial diodes [4]. An n-Si epitaxial layer growth is performed over a n-Si substrate up to 37 μ m. Afterwards, a Boron diffusion leads to a 15 μ m p-Si layer with a 22 μ m n-Si epitaxial layer.

Two sets of two diodes were tested. The diodes number E2 and E3 were manufactured by EUPEC. The other two diodes, M13 and M15, were manufactured by PLESSEY.

The diodes were stacked - together with copper disk electrodes between each of the diodes - and clamped under a 1 kN force. Carbon (Allen Bradley) resistors were mounted in the 4.6 K sample holder to measure the temperature during the irradiation. The forward voltage U_f of these diodes, which governs the thermal transient in the diodes during de-excitation of the magnet and the dimensioning of the heat sinks, is the most sensitive parameter affected by irradiation. The forward voltage U_f was measured during current pulsing up to a maximum value of 120 A. The forward voltage is deduced from the current peak level ($dI_f/dt = 0$) as shown in figure 1. The reverse voltage was measured up to 1 mA for PLESSEY diodes only since the rims of EUPEC diodes were not passivated and had disperse reverse current-voltage characteristics.

Fig. 1 : EUPEC diode forward voltage U_f measured through current pulsing.

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TAB. 1 : TEST PROCEDURE AND SPECIFIC DATA. (ELECT. MEAS. : FORWARD AND REVERSE CHARACTERISTICS : $I_F(U_F)$ AND $I_R(U_R)$).

Each step (5 steps)	Temperature of the step [K]	dose/step [kGy]	Neut. Flu/step [n/cm^2]	Step Time [min]	Remarks
Irradiation	4.6	10	2×10^{14}	10	
Elect. Meas.	4.6				$I_F(U_F)$; $I_R(U_R)$
Annealing	300			10	
Elect. Meas.	4.6				$I_F(U_F)$; $I_R(U_R)$

III - IRRADIATION FACILITY AND DOSIMETRY

The low temperature irradiation facility (TTB) at the 4 MW pool-type research reactor in Munich has already been described in a previous report [3][4]. The reactor was used in the same conditions as in the previous tests with a nominal reactor power of 40 kW rather than the available 4 MW.

The 4.6 K temperature was controlled within ± 0.1 K all through the experiment (during irradiation and during measurements). During the 300 K annealing stage, the diodes were warmed up to room temperature for 15 min outside the reactor.

Referring to the analogue experiment in the previous report [4], the gamma dose rate is estimated as 16.7 Gy/s and the neutron flux as $3.3 \times 10^{11} n/cm^2s$ [5].

Table 1 is a summary of the cumulated gamma dose and neutron fluences deposited during each step.

IV - MEASUREMENTS RESULTS

A. Forward voltage degradation during irradiation

The forward voltage U_F is sensitive to the radiation-induced defects in the silicon. Defects are from different types [6] : ionising radiation, such as gamma-dose, induces electron-hole pairs in the material, the capture (or recombination) time constant of which has a wide range of values. Atomic displacements are associated with the neutron fluence. All of these defects induce a decrease of the carrier life time and of the carrier mobility : the $I_F(U_F)$ slope decreases. Moreover, radiation-induced charges in the Silicon could decrease the effective doping concentration particularly in the low doping epitaxial layer leading to an increase of the forward voltage U_F with radiation dose through the simple relation of the

$$\text{threshold voltage } V_T : V_T = \frac{kT}{q} \ln \left(\frac{N_A^* N_D^*}{n_i^2} \right) \text{ where } N_A^*$$

and N_D^* are ionized doping atoms in the p-Si region and in the epitaxial n-Si layer respectively.

The figures 2 and 3 are typical plots of the forward current-voltage characteristics of EUPEC and

PLESSEY diodes for doses between 0 and 50 kGy. The forward voltage increase is less important for the EUPEC diodes than for the PLESSEY diodes. Even though the wafers are similar, the technological process stages could be different and contribute to differences between EUPEC and PLESSEY diode behaviour under irradiation. Above 40 A for I_F , we notice that the slope of the curves increases : this behaviour is explained by a thermal effect. Indeed, as measurements are performed at 4.6 K, the current induces an increase of the diode temperature. Thus, the forward voltages obtained for current higher than 40 A are lower than the real ones at 4.6 K.

By considering an adiabatic system, the diode temperature increase during current pulsing is related to the thermodynamical relation and is governed in the

$$\text{worst case by : } Q = \int_0^\infty U_F(t) I_F(t) dt = \sum_k m_k \Delta H_k(T)$$

where m_k and $\Delta H_k(T)$ are respectively the weight and the enthalpy variation between $T_0 = 4.6$ K and T of each type of material. In this worst case ($I_{max} = 100$ A and after the maximum dose : see fig. 2 and 3), the diode temperature could increase by about 10 K for EUPEC diodes and 15 K for GEC diodes.

Fig. 2 : EUPEC diode forward voltage U_F measured at 4.6 K after different doses with intermediate accumulated annealing of previous doses.

Fig. 3 : PLESSEY diode forward voltage U_f measured at 4.6 K after different doses with intermediate accumulated annealing of previous doses.

B. Effect of thermal annealing

A thermal annealing at 300 K has been performed after each 10 kGy dose step. It induces a recovery of specific defects. At this temperature, we only expect to anneal defects induced by ionisation [7]. Interface states and atomic displacements due to neutrons can not be annealed at this temperature [8]. An example of the forward voltage recovery is shown in figure 4 where we can observe the degradation after 30 kGy and the improvement due to the following thermal annealing. Figure 5 is a plot of the relative forward voltage degradation as a function of the dose for the EUPEC and PLESSEY diodes at $I_f = 100$ A.

$$\Delta U_f / U_{f0} = \frac{U_f - U_{f0}}{U_{f0}}$$

where U_{f0} is the forward voltage before irradiation.

For each 10 kGy dose step, we notice the large degradation of the PLESSEY diodes compared with the EUPEC ones. Each intermediate annealing gives a recovery in forward voltage. EUPEC and PLESSEY

diodes respectively reach 47% and 175% degradation at 50 kGy total dose. After the last annealing (15 days at 300 K), the residual degradations are of the same order for both EUPEC and PLESSEY diodes : around 20%.

Fig. 4 : PLESSEY and EUPEC forward voltage characteristics before irradiation, after 30 kGy and after the following 300 K thermal annealing.

C. Reverse voltage degradation

The reverse voltage U_r is affected by radiation as typically shown in figure 6 for a PLESSEY diode. Irradiation induces an increase of the reverse voltage which is an advantage for the application in the LHC machine. In these irradiation conditions, the thermal annealing leads to an increase of the reverse voltage. In previous works, for small samples of 10 mm diameter diodes and samples of 75 mm diameter, it has been found that radiation induces an increase of U_r and thermal annealing a reduction of U_r to the initial value [9][10].

Fig. 5 : Relative forward voltage (for $I_f = 100$ A) $\Delta U_f / U_{f0}$ for the EUPEC and PLESSEY diodes.

Fig. 6 : Reverse current-voltage characteristic voltage for different doses and after the last thermal annealing.

DISCUSSION AND CONCLUSION

These two sets of diodes show different behaviours against radiation. They are both epitaxial diodes with the same dimensions of epitaxial layer and p-Si diffusion layer. The real difference is in the doping levels and probably in the technological process which can not be described here. The intermediate annealings lead to a decrease of the maximum relative forward voltage degradation by a factor of more than 3. Final annealing during two weeks at 300 K leads to a residual degradation of around 20%. As a 300 K annealing can only annihilate the effect of the γ radiation, we can assume that the residual degradation is only due to the neutron fluence. Future experiments will be performed to determine the effect of a pure γ -irradiation at cryogenic temperature and thermal annealing at room temperature.

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