ANNEALING OF SUPERCONDUCTING MAGNET PROTECTION DIODES FOR THE LHC AFTER IRRADIATION AT LIQUID HELIUM TEMPERATURES

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ABSTRACT

Within the framework of the collaboration between CERN and the TUM[*], irradiation experiments have been carried out at liquid helium temperatures on epitaxial diodes for the superconducting magnet protection of the future Large Hadron Collider (LHC). Two sets of 10 mm diameter diode samples were submitted to an irradiation of 30 kGy dose and $6*10^{14}$ n/cm^2 neutron fluence at liquid helium temperature. The radiation-induced degradation has been measured by the increase in the forward voltage. Afterwards, one set of diode samples was stepwise warmed up to about 250 K and, at each step, the recovery in forward voltage was monitored to determine the minimum annealing temperature. The second set of diode samples was thermally annealed with different time intervals at about 100 K and 200 K to determine the minimum annealing time.

1 INTRODUCTION

Up to now, irradiation has been performed on diode samples of 10 mm diameter at liquid helium temperature and annealing periods were applied at room temperature [1]. The paper presented here is related to cryogenic temperature irradiation followed by stepwise annealing up to about 250 K, and, on the other hand, followed by increasing time intervals annealing at two temperatures (about 100 K and 200 K). These experiments have been carried out in order to determine the maximum temperature above which there is no more electrical characteristic recovery and, for a fixed temperature, the minimum time interval needed to reach the maximum recovery expected for this temperature.

The following sections describe the components under test, the experimental conditions of irradiation and of annealing, and finally the experimental results are given in the last sections followed by conclusions concerning the LHC application.

2 DEVICES UNDER TEST

The diode samples of 10 mm diameter were cut from the wafers of large power diodes to be used for the quench protection of superconducting magnets. It was not possible to use directly the full-size power diodes because of the limited space in the irradiation facility [2]. Two sets of three diodes each were under test :

- Set 1 : diodes number E6, E13, E16 were submitted to one irradiation dose. Afterwards they were submitted to different increasing temperatures from 75 K to 250 K in steps of 25 K.

- Set 2 : diodes number E14, E15, E18 were submitted to one irradiation dose. And afterwards, they were annealed at 100 K and 200 K during different time intervals.

3 EXPERIMENTAL CONDITIONS

3.1 Irradiation conditions

The irradiation is performed in the nuclear research reactor of the Technical University of Munich (TUM) at Liquid Helium temperature (T = 4.6 K). The irradiation conditions have already been described in a previous paper [2]. The main conditions are the following :

- Temperature during irradiation : 4.6 K
- Dose rate : 1 kGy/min.
- Neutron flux : 2.10^{13} n/cm^2/min.

As the two diode sets are irradiated in one step of about 30 min, the total deposited dose is about 30 kGy and the neutron fluence is 6.10^{14}n/cm^2.

3.2 Electrical measurement conditions

The electrical measurements are principally based on the forward current/voltage characteristics $I_f(U_f)$ and have been described earlier [2]. They are performed at 4.6 K before the irradiation, just after the end of the irradiation period, and then after each step of annealing.

3.3 Annealing conditions

The annealing process was performed in an oven inside a test cryostat placed above the reactor pool. The temperature was controlled by thermocouples in the oven and in the sample holder. Just after the end of the irradiation and when the required annealing temperature was reached in the oven, the diode samples were pulled in. After some waiting time (about 3 minutes) for the samples to reach the required annealing temperature, the

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annealing process was carried out. For the first set of diode samples, the time interval was 15 minutes for all annealing temperatures. For the second set, the time interval was increased at each step of annealing. Table I gives the main steps of the two experiments and the main experimental conditions.

4 EXPERIMENTAL RESULTS

4.1 First set of diodes - Temperature effects

a) Radiation-induced forward voltage degradation

The forward current/voltage characteristic $I_f(U_f)$ was measured at 4.6 K before the irradiation, just after the irradiation, and after each step of annealing by applying fast current pulses up to about 100 A. The increase in forward voltage is a measure of the degradation of the diode due to irradiation. The degradation was defined as follows :

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

,with U_f at a reference current of I_f = 100 A and U_{f0} as reference voltage before irradiation.

The irradiation induces a relative U_f degradation of about 60 % after 30 kGy and 6.10^{14}n/cm^2. Table II gives the forward voltage of the three diodes of set 1 and their relative U_f degradation after the irradiation. These results show that the degradation is rather uniform for the three samples.

TABLE II : Forward voltage U_f for I_f = 100 A before and after irradiation.

diode number	U_{f0} [V]	U_f aft irr [V]	$\Delta U_f/U_{f0}$ [%]
E6	1.95	3.00	53.85
E13	1.91	3.08	61.25
E16	1.95	3.28	68.21
Average	1.94 ± 2%	3.12 ± 5%	61.1 ± 11%

The effects of thermal annealing are shown in figure 1 where the relative U_f degradation is plotted versus the annealing temperature. Each annealing period was 15 minutes long and the experiment is performed to determine the minimum temperature necessary to anneal the maximum of radiation-induced defaults. The annealing time interval has been chosen according to previous experiments where we had verified that there was no more significant annealing between the first step of 15 min and the long term annealing (several days) [1].

b) Analysis of test results

The results in figure 1 show that the annealing rate is high in the range of 75 K to 175 K. Below 75 K, the annealing effect is negligible, and above 175 K, the annealing effect seems to saturate which does not mean that no more annealing is possible. The saturation value is related to the residual forward voltage degradation attributed to the defects induced by neutron atomic displacement (about 10%). The maximum annealing can be obtained by only going to 200 K instead of room temperature as done in the past.

TABLE I : Experimental conditions of irradiation, electrical measurements and thermal annealing steps for both sets of diodes under tests.

step number	Devices under tests	Conditions	Remarks
Irradiation	E6-E13-E16	T = 4.6 K - Dose = 30 kGy Neutron fluence = 6.10^{14}n/cm^2	Irradiation time : 30 min
Electrical measurements	“	T = 4.6 K Forward $I_f(U_f)$ up to 150 A/cm^2	Just after the irradiation Pulse of 200µs. [2]
Annealing steps	“	From 75 K to 250 K by 25 K steps. Annealing time intervals : 15 min.	Helium gas temperature. Thermocouple temp. sensor.
Electrical meas. after each annealing step	“	T = 4.6 K Forward $I_f(U_f)$ up to 150 A/cm^2	After each step of annealing
Irradiation	E14-E15-E18	T = 4.6 K - Dose = 30 kGy Neutron fluence = 6.10^{14}n/cm^2	Irradiation time : 30 min
Electrical measurements	“	T = 4.6 K Forward $I_f(U_f)$ up to 150 A/cm^2	Just after the irradiation Pulse of 200µs. [2]
Annealing steps	“	T = 100 K during 1, 7, 35 min and T = 200 K during 1, 7, 35 min	Helium gas temperature. Thermocouple temp. sensor.
Electrical meas. after each annealing step	“	T = 4.6 K Forward $I_f(U_f)$ up to 150 A/cm^2	After each step of annealing.

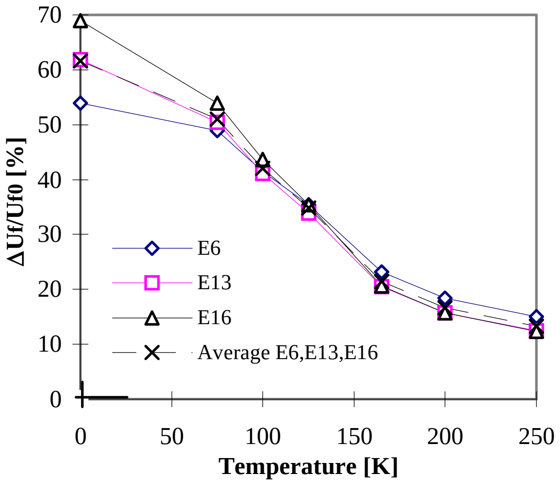

Fig. 1 : Relative forward voltage degradation as a function of the temperature of 15 min time interval.

4.2 *Second set of diode samples - Time effects*

The three diodes were subjected to the same irradiation as the previous three (30 kGy + 6.10^{14} n/cm^2). The relative forward voltage degradations are almost identical to the previous ones : about 60 % at I_f = 100 A. According to the results of the first experiment (see Fig. 1), we have chosen T = 100 K since it is at the beginning of the greatest slope of $\Delta U_f/U_{f0}(T)$. Afterwards, we have annealed at T = 200 K since it is in the saturation region of $\Delta U_f/U_{f0}(T)$ (Fig. 1). The time interval of the isothermal annealing experiments are 1, 7 and 35 minutes long. The $\Delta U_f/U_{f0}$ results are plotted on figure 2, where the results for T = 100 K (Fig. 2) and T = 200 K (Fig. 3) are shown.

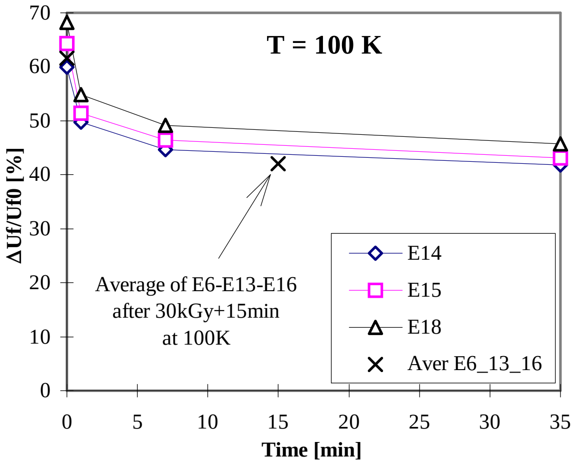

Fig. 2 : Relative forward voltage degradation as a function of thermal annealing time at 100 K.

At both temperatures, 100 K and 200 K, the annealing rate is high in the first 15 minutes. Afterwards, the annealing is rather low. Thus, we can see that, after 15 minutes annealing, there is little time dependence. This is confirmed in figures 2 and 3 by the results of the three diodes of the first experiment in the saturation region of each part (100 K and 200 K). Moreover, we can deduce from this second experiment that annealing at temperatures lower than 100 K for a long time interval (> 30 min) does not improve the residual degradation of the forward voltage.

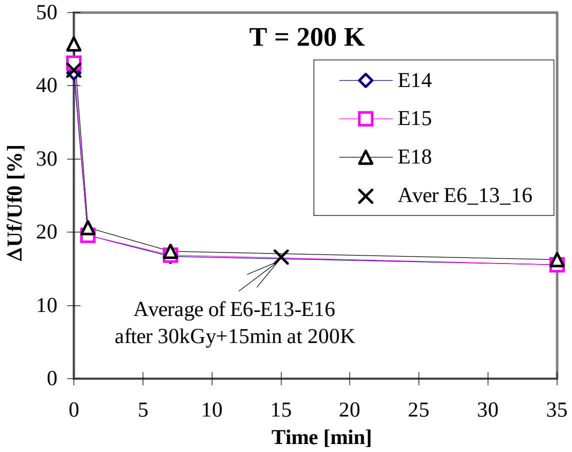

Fig. 3 : Relative forward voltage degradation as a function of thermal annealing time at 200 K.

5 CONCLUSION

The test results show, that an efficient annealing of the irradiated samples at a temperature of about 200 K for a time interval of about 15 min. is largely sufficient. It is not necessary to warm up to 300 K.

Since the same diodes were already partly annealed in the second test at 100 K before annealing at 200 K, a cumulative effect cannot be excluded.

Further annealing tests on irradiated samples at discrete temperatures between 100 K and 200 K are necessary to see if efficient annealing can be carried out even at temperatures below 200 K with longer time intervals, which could be an advantage for cryogenic reasons.

REFERENCES

[1] V.Berland et al., RADECS’95, “*Behaviour of the Future LHC Magnet Protection Diodes Irradiated in a Nuclear Reactor at 4.6 K*”, Proc. of RADECS 95 (Arcachon - France), September 1995.

[2] D. Hagedorn et al., ICMC95, “*Irradiation of Quench Protection Diodes at Cryogenic Temperatures in a Nuclear Research Reactor*”, Columbus USA, June 1995.