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Radiation Resistant Quench Protection Diodes for the LHC

L. Coull, D. Hagedorn

Abstract

The quench protection diodes for the proposed Large Hadron Collider at CERN will be located inside the He-II vessel of the short straight section of one half cell, where they could be exposed to a radiation dose of about 50 kGy and a total neutron fluence of about 10^{15} n/cm² over 10 years at temperatures of about 2 K. To investigate the influence of irradiation on the electrical characteristics of the diodes, newly developed diodes of thin base region of the diffusion type and of the epitaxial type have been submitted to irradiation tests at liquid nitrogen temperature in a target area of the SPS accelerator at CERN. The degradation of the electrical characteristics of the diodes for a radiation dose up to about 20 kGy and neutron fluence of up to about $5 \cdot 10^{14}$ n/cm² and the effect of carrier injection and thermal annealing after irradiation have been measured. The test results show that only the thin base diodes of the epitaxial type are really radiation resistant. A compromise must be found between required blocking characteristics and radiation resistance. Annealing by carrier injection and occasional warm up to room temperature can extend the service life of irradiated diodes quite substantially.

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RADIATION RESISTANT QUENCH PROTECTION DIODES FOR THE LHC

D. Hagedorn, L. Coull

CERN, European Organization for Nuclear Research
1211 Geneva 23, Switzerland

ABSTRACT

The quench protection diodes for the proposed Large Hadron Collider at CERN will be located inside the He-II vessel of the short straight section of one half cell, where they could be exposed to a radiation dose of about 50 kGy and a total neutron fluence of about 10^{15} n/cm² over 10 years at temperatures of about 2 K. To investigate the influence of irradiation on the electrical characteristics of the diodes, newly developed diodes of thin base region of the diffusion type and of the epitaxial type have been submitted to irradiation tests at liquid nitrogen temperature in a target area of the SPS accelerator at CERN. The degradation of the electrical characteristics of the diodes for a radiation dose up to about 20 kGy and neutron fluence of up to about $5 \cdot 10^{14}$ n/cm² and the effect of carrier injection and thermal annealing after irradiation have been measured. The test results show that only the thin base diodes of the epitaxial type are really radiation resistant. A compromise must be found between required blocking characteristics and radiation resistance. Annealing by carrier injection and occasional warm up to room temperature can extend the service life of irradiated diodes quite substantially.

INTRODUCTION

The quench protection diodes for the proposed Large Hadron Collider (LHC) at CERN will be located inside the He-II vessel of the short straight section of one half cell and be connected across the magnet coils such as to take over the magnet current at quench in one or more magnets of the half cell. These by-pass elements, so-called COLD DIODES, may receive a radiation dose of about 50 kGy and a total neutron fluence of about 10^{15} n/cm² over 10 years at temperatures of about 2 K. To investigate the influence of irradiation on the electrical characteristics of high current diodes several commercially available welding diodes of the DS6000 type, several specially fabricated thin base diodes of the diffusion type, and several

newly developed epitaxial diodes of different base width have been submitted to irradiation tests in an accelerator environment at liquid nitrogen temperature.

Firstly DS6000 diodes were irradiated up to a dose of about 600 Gy.¹ Then the newly developed thin base diodes of 75 mm wafer diameter and two DS6000 diode types were exposed in the target area of the SPS in two different runs up to a radiation load of about 20 kGy each. Detailed results for the first run with two DS6000, three thin base diodes of the diffusion type, and three of the epitaxial type have been given already elsewhere² and are included here in a short form for comparison.

Since only the epitaxial diodes show sufficient radiation resistance, we have concentrated our efforts on this type of diode. The epitaxial diodes of about 10 μm base width tested in the first run were extremely insensitive to irradiation, but showed a rather low reverse voltage blocking capability and relatively high forward voltage drop. New epitaxial diodes of 22 μm base width were developed by the supplier giving increased blocking capability and a lower forward voltage drop but also a noticeably higher sensitivity to radiation.

TESTED DIODE TYPES AND ASSEMBLIES

Four different diode types have been submitted to irradiation: three specially developed diodes with thin base made in the standard diffusion technique, six newly developed high current diodes with thin base made in the epitaxial technique (three diodes of about 10 μm and three diodes of 22 μm base width), and for comparison two commercially available welding diodes of the DS6000 type. The main dimensions of these diodes are summarised in Table 1. The diodes of 75 mm wafer diameter were stacked - together with copper disks between each of the diodes acting as heat sinks and connectors - and clamped with a force of 42 kN applied to the outside of the common holder. The two DS6000 diodes (A55 and A45) were clamped similarly in a separate holder under a force of 20 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.

Table 1. Main wafer dimensions of the irradiated diodes

Diode	Supplier	Wafer diameter [mm]	Substrate width [μm]	n-base width [μm]
M1A1	GEC/Plessey	75	240	> 30 (Diff.)
M2A2	GEC/Plessey	75	240	> 30 (Diff.)
M2A3	GEC/Plessey	75	240	> 30 (Diff.)
E3	EUPEC	75	525	10 (Epitax.)
E4	EUPEC	75	525	10 (Epitax.)
E10	EUPEC	75	525	10 (Epitax.)
E6	EUPEC	75	525	22 (Epitax.)
E13	EUPEC	75	525	22 (Epitax.)
E17	EUPEC	75	525	22 (Epitax.)
A55	ABB	50	140	40 (Diff.)
A56	ABB	50	140	40 (Diff.)

IRRADIATION - AND ELECTRICAL TEST PROCEDURES

Various electrical tests were performed before and after each exposure period to monitor the degradation in performance of the diodes as a function of dose. During the two irradiation runs of about 5 months each the diodes were kept at liquid nitrogen temperature. After each exposure period of about 3-4 weeks the cryostat containing the diodes was removed from the radiation position downstream of target T6 in the zone TCC2 of the SPS, the diodes measured at 77 K, and the cryostat re-installed into the radiation area. On the diodes A56, M2A1, E4, E6, and E13 high current pulse measurements in forward direction were only carried out before and at the end of the total irradiation run, to minimise the self-annealing effects by carrier injection (induced by the tests themselves). Junction capacity- and reverse voltage measurements were performed before applying high current pulses. The forward voltage drop 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 but before warming up to room temperature all diodes were submitted to carrier injection annealing by applying up to 600 high current pulses of about 15 kA amplitude and 200 μ s duration at a rate of about one pulse per minute. The current pulse generator and details of the measuring equipment have already been described elsewhere¹.

At the end of the last exposure period in the second run the automatic liquid nitrogen refilling system failed and the diodes E6, E13, and E17 warmed up to room temperature for some days and were thus already annealed. The measurements after irradiation were carried out after this thermal cycle. The forward current-voltage characteristics at 77 K after the last exposure period (before warming up) were obtained by linear extrapolation from measurement results before the warm-up.

DOSIMETRY

For monitoring the dose during irradiation, several sets of dosimeters of the Alanine - and RPL-type were used. These have already been described in detail elsewhere^{1,2}. For the evaluation of the integrated dose at liquid nitrogen temperature the RPL-dosimeters only were used, since the behaviour of the Alanine dosimeters at low temperature is not well known. In view of the difficulties of precise dose measurements the total doses of 20 kGy for each of the two irradiation runs were measured with a precision of about ± 30 % only. The integrated neutron fluence was evaluated from activation foils at room temperature of the Al,S,Ni,Co-type after the irradiation process.

MEASUREMENT RESULTS

Forward voltage U_f versus dose

The most sensitive indicator for radiation damage is the increase of forward voltage. The forward voltage of the diffusion type diodes increased significantly with radiation load. The diffusion type diodes A55, A56, M2A2, and M2A3 became high ohmic resistors (several k Ω) after a radiation load of less than 1 kGy

Fig. 1 I_f - U_f -characteristic of the two epitaxial diodes E3 and E13 with 10 μm and 22 μm base width before and after irradiation and after thermal cycling

and current pulsing had to be stopped on these diodes. On the diffusion type diode M1A1 the forward voltage had increased to about 30 V at 15 kA after the end of the first irradiation run, i.e. after a dose of about 20 kGy. For scaling reasons the results on forward voltages for this diffusion type diode are not shown here, they were published elsewhere². Fig. 1 shows as an example the typical forward current-voltage characteristic of the two epitaxial diodes E3 and E13 with 10 μm base width and 22 μm base width respectively before irradiation, after irradiation, and after one thermal cycle to room temperature. The lower forward voltage drop of the 22 μm base diode E13 is mainly due to a higher doping concentration (double compared with E3) in the substrate and improved wafer contacts. The deviation of the current-voltage characteristic of diode E13 at higher current levels towards smaller voltage after longer exposures was also observed on diode E6 and may be due to partial annealing by carrier injection induced to the diodes by the current pulse measurement itself.

Fig. 2 shows the increase of forward voltage U_f at 14 kA peak current level versus exposure of the six epitaxial diodes at 77 K. The 10 μm thin base diodes E3, E4, and E10 show only very little increase in forward voltage. The maximum of about 4 % was measured on diode E4 which was submitted to current pulse measurements just before and after the first irradiation run only, whereas on the diodes E3 and E10 a relative increase in forward voltage $\Delta U_f/U_{f0}$ of about 3 % was observed. As expected the 22 μm base diodes E6, E13, and E17 are much more sensitive to irradiation. The highest increase of about 56 % was measured on the diode E6, which was not submitted to intermediate current pulse annealing. With intermediate current pulse annealing on diode E13 the forward voltage increased by about 47 %. Diode E17 was measured just before and after the second irradiation run (incl. one thermal cycle to room temperature). After one thermal cycle to room temperature a residual increase in forward voltage of about 14 % was observed on all three diodes.

Fig. 2. Relative increase in forward voltage versus dose for the epitaxial diodes

Reverse voltage versus exposure

The full reverse characteristic $I_r = f(U_r)$ was monitored on each diode after each exposure period in the I_r -range from about 1 μ A to about 1 mA. On all diodes the reverse voltage increased with dose except for the diffusion type diode A55 (DS6000) on which a significant decrease after about 3.5 kGy was observed. After 20 kGy the reverse voltage at $I_r = 1$ mA on the diode M1A1 has increased from about 370 V to about 600 V. On the diodes of the epitaxial type the increase varies quite substantially as shown in Fig. 3. The relative change in reverse voltage for the diodes of 10 μ m base width (except for diode E10) is rather small ($< 10\%$) compared to the relative increase in forward voltage for the diodes of 22 μ m base width, which amounts to about 30 % after 20 kGy. It seems, that - generally speaking - the relative increase in reverse voltage goes with the increase in forward voltage versus dose, and thus with the sensitivity to radiation. The relatively high increase in reverse voltage by about 150 % on diode E10 may be related to the very low initial reverse voltage prior to irradiation.

Capacitance versus exposure

The capacitance was measured with 10 kHz with zero bias voltage. Fig. 4 shows the decrease of capacitance of all irradiated diodes versus exposure. After a dose of about 6 kGy the capacitance of all diodes of the diffusion type and of the epitaxial type with 22 μ m base has dropped to a residual capacitance of roughly 8 % of the capacitance before irradiation and varies only very little up to the maximum dose of 20 kGy. The capacitance of the epitaxial diodes of 10 μ m base width has decreased to about 17 % of the original capacitance after a dose 20 kGy and it is not sure if this is already the final residual value. These results show that the degradation (increase) in forward voltage, and thus the degree of damage, cannot be deduced from the reduction in capacitance - at least for the epitaxial diodes.

Fig. 3. Reverse voltage ($I_r = 1 \text{ mA}$) versus dose for two different epitaxial diodes

Annealing

The epitaxial diode E13 and the only surviving diode M1A1 of the diffusion type were submitted to intermediate carrier injection annealing by applying 15 kA current pulses of half sinusoidal type. Up to 200 current pulses were applied to diode M1A1 and up to 130 current pulses to diode E13. The result of this intermediate current pulse annealing to diode E3 is shown in Fig. 1. For diode M1A1 the forward voltage dropped from 7 V to about 3 V at 15 kA. Diode M1A1 and the epitaxial diodes of 10 μm base width were submitted to a final current pulse annealing after the irradiation run prior to warm up. The forward voltage on diode M1A1 dropped from 30 V to about 12 V at 15 kA during the first few pulses and to about 9 V after 600 current pulses. Practically no reduction - less than 0.5 % - in forward voltage was observed on the epitaxial diodes E3, E4, and E10

Fig. 4. Reverse current-voltage characteristics $I_r(U_r)$ for two epitaxial diodes of different base width

Fig. 5. Decrease of capacitance versus dose for diffusion and epitaxial diode types

after final current pulse annealing. The effect of current pulse annealing on the diode capacitance and on the reverse voltage is usually less than 2 %. No final current pulsing could be applied to the epitaxial diodes E6, E13, and E17 due to the unforeseen warm-up at the end of the last exposure period.

After warming up to room temperature for about 3 weeks the diodes were re-measured at 77 K to see the effect of temperature annealing. The effect of thermal annealing by one cycle to room temperature are shown in Fig. 1 and Fig. 2 for the epitaxial diodes. The forward voltage for diode M1A1 dropped from about 9 V to about 4 V at 15 kA. The thermal cycle to room temperature has only very little effect on the forward voltage characteristic of the epitaxial diodes of 10 μm base width, whereas for the epitaxial diodes of 22 μm base width the annealing effect - reduction in U_f - by warming up to 300 K is quite significant. Table 2 shows the reverse voltage U_r at $I_r = 1$ mA and the diode capacitance C before and after irradiation and after current pulse annealing and after one cycle to 300 K for the diffusion type diode M1A1 and for the epitaxial diodes.

Table 2. Reverse voltage U_r and capacitance C of the diodes before and after irradiation and after current pulse and thermal annealing.

DIODE	pre-irradiation		post-irradiation		after current pulsing		after 300K annealing	
	U_{r0} [V]	C_0 [nF]	U_r [V]	C [nF]	U_r [V]	C [nF]	U_r [V]	C [nF]
M1A1	370	116	597	10	595	10	584	11
E3	75	367	84	58	81	59	79	84
E4	121	356	117	57	117	58	116	71
E10	15	371	48	58	48	60	43	107
E6	160	254	-	-	-	-	197	30
E13	153	272	-	-	-	-	204	30
E17	158	265	-	-	-	-	205	30

IRRADIATION AT LIQUID HELIUM IN A NUCLEAR REACTOR

Irradiation tests at liquid helium temperatures -at least at 4.2 K- are essential for a decision as to whether these diodes can be used for the current by-pass at superfluid helium temperatures for the LHC-superconducting magnets. More damage may occur at these temperatures and the character of damage may also change.

Our original intention to irradiate full size (75 mm wafer) diodes of the epitaxial type at liquid helium temperatures in a nuclear reactor had to be given up because of the very high costs for adequate cryogenic installations. Instead, small diode samples of 10 mm wafer diameter of the same wafer material used for the 75 mm diameter wafers will be irradiated in the nuclear research reactor at Munich³ at liquid helium temperature, and also at liquid nitrogen temperature for comparison, up to doses of 50 kGy and neutron fluences up to 10^{15} N/cm².

For the evaluation of size effects and in view of the uncertainty in relating reactor neutron damage to damage from beamline radiation these small diode samples will be also irradiated in the accelerator environment at 77 K here at CERN as described above.

CONCLUSIONS

The test results show that only the diodes of the epitaxial type seem to be really radiation resistant. A compromise must be found between the required blocking characteristics of the diode and radiation resistance. Annealing by carrier injection (high current pulsing) and occasional warm up to room temperature can extend the service life of irradiated diodes quite substantially.

The forward voltage drop U_f of these diodes, which governs the thermal transient in the diodes during de-excitation of the magnets and the dimensioning of the heat sinks, can be kept small by a high doping concentration in the substrate. The reverse blocking characteristics improve considerably with radiation dose. At least for the epitaxial diodes the decrease of junction capacitance cannot be used as indicator for radiation damage.

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