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RADIATION DAMAGE ON HIGH CURRENT BY-PASS DIODES AT CRYOGENIC TEMPERATURES IN AN ACCELERATOR ENVIRONMENT

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ABSTRACT

The quench protection diodes for the proposed Large Hadron Collider at CERN shall be located inside the He-II vessel of the magnet cryostat, where they could be exposed to a radiation dose of about 5 MRad (50 kGy) and a total neutron fluence of about 1.0 10^{15} N/cm^2 over 10 years at temperatures of about 2 K.

To investigate the influence of irradiation on the electrical characteristics of the diodes, several commercially available high current diodes of the DS6000 type from ABB and newly developed diodes of thin base region have been submitted for about 5 months to preliminary 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 versus exposure (up to 20 kGy and 5.0 10^{14} n/cm^2) and the effect of carrier injection and thermal annealing after irradiation has been measured.

The test results show that only the thin base diodes of the epitaxial type seem to be really radiation resistant.

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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1. Introduction

For the quench protection of the superconducting magnets for the proposed Large Hadron Collider LHC at CERN a current by-pass at liquid Helium temperature is foreseen.

This current by-pass will be made of high current diodes housed in the magnet cryostat.[1]

In the LHC environment these diodes will be exposed to a radiation dose of 5 MRad (50 kGy) and a total neutron fluence of about 1.0 E15 N/cm^2 over 10 years at temperatures of about 2 K.

To investigate the influence of irradiation on the electrical characteristics 8 high current diodes have been submitted to preliminary irradiation tests in an accelerator environment for about 5 months at liquid nitrogen temperatures, i.e. T= 77 K.

The degradation of the electrical chracteristics of these diodes versus exposure and the effect of carrier injection and thermal annealing after irradiation has been measured.[2]

The diodes were exposed down stream target T6 in the zone TCC2 of the SPS to the following radiation load:
Ionization Radiation (Dose): 2 Mrad or 20 kGy
Neutron Fluence: 5×10^{14} n/cm2 at 10 keV < E < 3 MeV

2. Diode Types

Three different diode types have been submitted to irradiation, three newly developed high current diodes with thin base width made in the standard diffusion technique (MEDL), three newly developed high current diodes with thin base made in the epitaxial technique (EUPEC), and two diodes of the commercially available DS6000 type (ABB) as a reference. The main dimensions of these diodes are summarized in **Table 1**.

Diode type	Supplier	Wafer diameter (mm)	Substrat thickness (µm)	n-base thickness (µm)
M1A1	MEDL	75	240	> 30 (Diff.)
M2A2	MEDL	75	240	> 30 (Diff.)
M2A3	MEDL	75	240	> 30 (Diff.)
E3	EUPEC	75	525	8.5 (Epitax.)
E4	EUPEC	75	525	8.5 (Epitax.)
E10	EUPEC	75	525	8.5 (Epitax.)
A55(DS6000)	ABB	50	140	40 (Diff.)
A56(DS6000)	ABB	50	140	40 (Diff.)

Table 1: Main dimensions of the 8 irradiated diodes

The six newly developed diodes were stacked - together with copper disks between each of the diodes acting as heat sinks and electrodes - and clamped under a force of 42 kN applied to the outside of the common holder.

The two DS6000 diodes 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.

3. Irradiation Procedure and Electrical Test Procedure

A variety of electrical tests were performed before and after each exposure period to monitor performance degradation of the diodes as a function of dose. During the whole irradiation programme of about 5 months, the diodes were kept at liquid nitrogen temperature.

After the second exposure period - corresponding to a integrated dose of about 330 Gy - it was found that the dose would be too small to see any effect on the thin base diodes of the epitaxial type. For the following exposure periods therefore a concrete shielding block was removed from T6 (TCC2) and the cryostat placed close to the target to obtain a higher dose.

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. On one DS6000 (A56) and two of the other diodes (M2A1, E4) high current pulse measurements were only carried out before and at the end of the total exposure programme to minimize the self-annealing effects by carrier injection (induced by the tests themselves). 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 and before warming up to room temperature all diodes were submitted to carrier injection annealing by applying up to 600 high current pulses of about 15kA amplitude and 200μs duration at a rate of about one pulse per minute. The current pulse generator and details of the measuring equipment are described elsewhere [2].

4. Dosimetry

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 dosimeters. 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 %.

For the evaluation of the integrated dose at liquid nitrogen temperature the RPL-dosimeters only were used , since the behavior of the Alanine dosimeters at low temperature is not well known.

The integrated neutron fluence was evaluated from activation foils at room temperature of the Al,S,Ni,Co-type after the irradiation process.

5. Measurement Results

5.1 Forward voltage U_f versus dose

The increase in forward voltage U_f is a sensitive indicator of radiation damage. **Fig. 1** shows the forward voltage U_f at 15 kA peak current level versus exposure of the five diodes at 77 K. The thin base diodes of the epitaxial type E3, E4, E10 show only very little increase of the forward voltage. The maximum of about 4% for $\Delta U_f/U_{f0}$ was measured on diode E4 which was submitted to current pulse measurements just before and after the irradiation program only, whereas on the diodes E3 and E10 a relative increase in forward voltage $\Delta U_f/U_{f0}$ of about 3% was observed.

The forward voltage U_f of the diffusion type diodes increased significantly. The diodes A55 and M2A2 became high ohmic resistors (several kΩ) after about 4500 Gy and current pulsing had to be stopped on these diodes.

The diode M1A1 was submitted to intermediate annealing by carrier injection - i.e. about 200 pulses of 15 kA peak level were applied - and the forward voltage dropped from about 7 V to about 4.5 V at 15 kA as shown in **Fig. 1**. After the total irradiation program, i.e. after a dose of about 20 kGy, the forward voltage on that diode increased to about 30V at 15 kA. The diodes M2A3 and A56, measured only before and after the total irradiation program, also became high ohmic resistors.

5.2 Reverse voltage versus exposure

The full reverse characteristic $I_r=f(U_r)$ was monitored on each diode as a function of exposure in the I_r-range from about 1μA to 3mA.

The reverse voltage U_r at I_r=1mA versus exposure is shown in **Fig. 2.**

On all diodes the reverse voltage increased with dose except for the diode A55 on which a significant decrease after about 3500 Gy was observed. After 20 kGy the reverse voltage on the diodes A56 and M1A1 has increased by about 60%, whereas on the diodes of the epitaxial type E3,E4,E10 the increase varies quite substantially as shown in **Table 2**.

It seems, that at least for the epitaxial diode types the relative increase in reverse blocking voltage after irradiation is higher for the diodes with initially low reverse voltage.

5.3 Capacitance versus exposure

The decrease of capacitance at zero volt for all diodes is shown in **Fig. 3** versus exposure.

After a dose of about 4000 Gy the capacitance of the diffusion type diodes has dropped to a residual capacitance of about 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 has decreased to about 17% of the original capacitance after a dose of 20k Gy.

These results show, that the reduction in capacitance for the epitaxial diodes does not correspond to the degradation (increase) in forward voltage.

5.4 Annealing

The three diodes of the epitaxial type E3, E4, E10 and the only surviving diode M1A1 of the diffusion type were submitted to annealing by carrier injection at 77 K by applying 15 kA current pulses of half sinusoidal type.[2]

Fig. 4 shows the reduction of forward voltage U_f on diode M1A1 versus the number of current pulses applied on the diode after the total irradiation program. The annealing by carrier injection is very efficient during the first few current pulses when the forward voltage U_f dropped down from originally 30 V to about 12 V, whereas the reduction in forward voltage is relatively small during further pulsing up to 600 pulses.

Annealing by carrier injection applied on the epitaxial diodes E3, E4, E10 showed practically no reduction (less than 0.5 %) in forward voltage at peak current levels above about 10 kA.

After warming up to room temperature for about 3 weeks the diodes E3, E4, E10, and M1A1 were measured again at liquid nitrogen temperature to see the effect of temperature annealing.

Fig. 5 shows the measured I_f-U_f-characteristic at 77 K of the diode M1A1 before and after irradiation and after current pulse annealing (carrier injection) and after one thermal cycle to room temperature.

In **Fig. 6 - 8** the corresponding characteristics for the epitaxial diodes E3, E4, and E10 are presented. The diodes E3 and E10 show an increased forward voltage at currents up to about 5 kA after the irradiation program (post-irrad. 20 kGy). For diode E4 this voltage drop is even higher for currents up to about 10 kA, which can be explained by the fact, that diode E4 was only submitted to current pulse measurements before and after the irradiation program whereas on diodes E3 and E10 current pulse measurements were applied after each of the six irradiation periods. Obviously annealing by carrier injection was induced to the diodes E3 and E10 by the current pulse measurements itself.

The thermal cycle to room temperature has only very little effect (less than 1 %) on the forward voltage characteristic of the epitaxial diodes, whereas for diode M1A1 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 Ir = 1 mA and the diode capacitance C before and after irradiation and after current pulse annealing and after one thermal cycle to 300 K.

DIODE	pre-irradiation		post-irradiation		after current pulsing		after 300K annealing	
	U_{ro} [V]	Co [nF]	U_r [V]	C [nF]	U_r [V]	C [nF]	U_r [V]	C [nF]
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
M1A1	370	116	597	10	595	10	584	11

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

6. Conclusions

The test results show, that only the diodes of the epitaxial type seem to be really radiation resistant. The forward voltage U_f of these diodes, which governs the thermal transient in the diodes during the de-excitation of the magnets and the dimensioning of the heat sink, is only very little affected

up to a dose of 20 kGy. The reverse blocking characteristics improve with irradiation. The diode capacitance cannot be used as indicator of irradiation damage.
Further tests at liquid helium and at liquid nitrogen temperature up to a dose of about 50 kGy should be carried out in order to see whether these diodes can be used for the current by-pass of the LHC-superconducting magnets.

7. Acknowledgements

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8. References

1. D. Hagedorn, W. Nägele, Quench protection diodes for the Large Hadron Collider LHC at CERN, ICMC 1991, Huntsville, Al.

2. D. Hagedorn, W. Nägele, Radiation effects on high current diodes at cryogenic temperatures in an accelerator environment. ICMC 1991, Huntsville, Al.

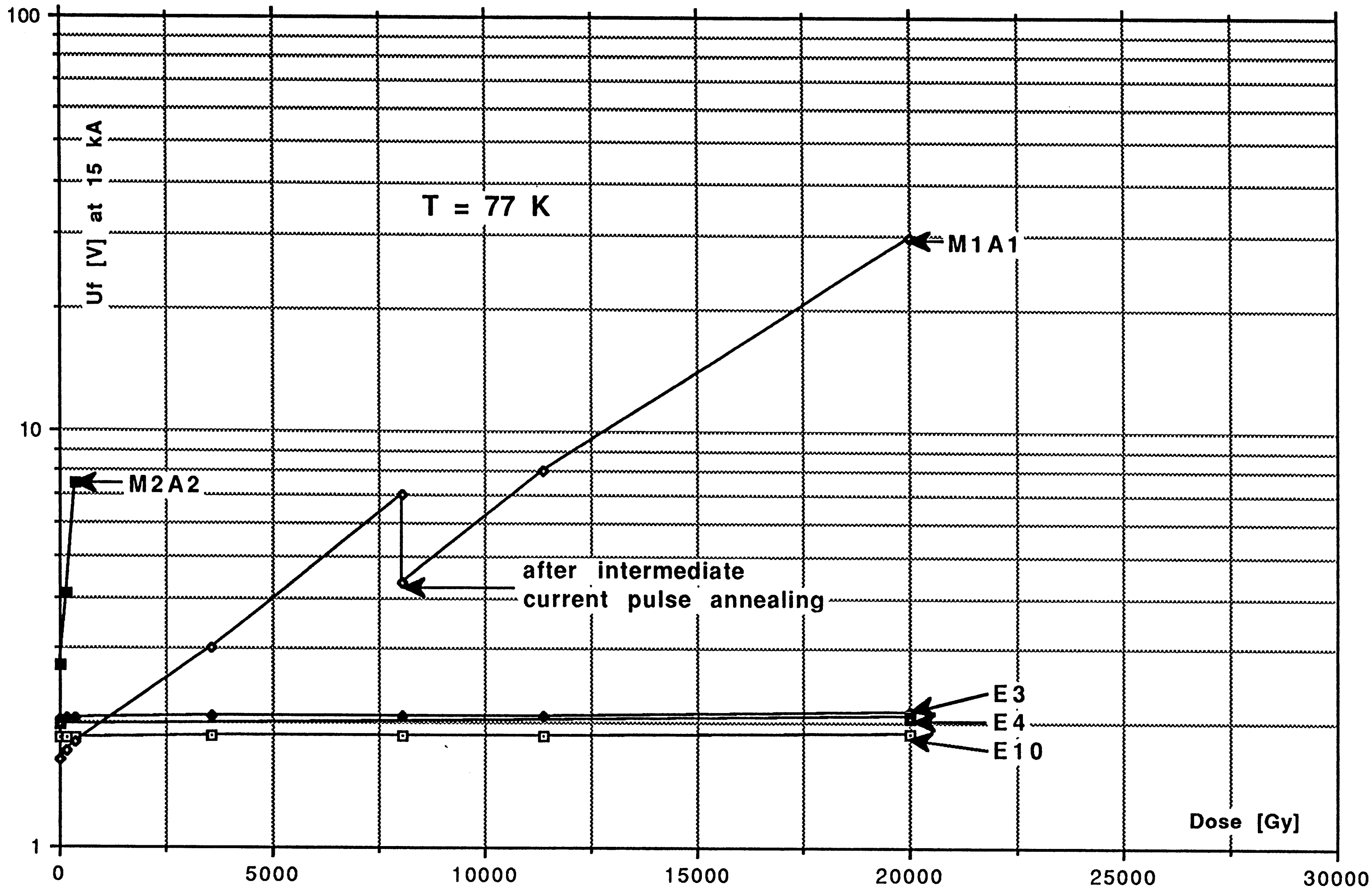

Fig. 1: Forward voltage Uf at 15 kA versus exposure for thin base diodes

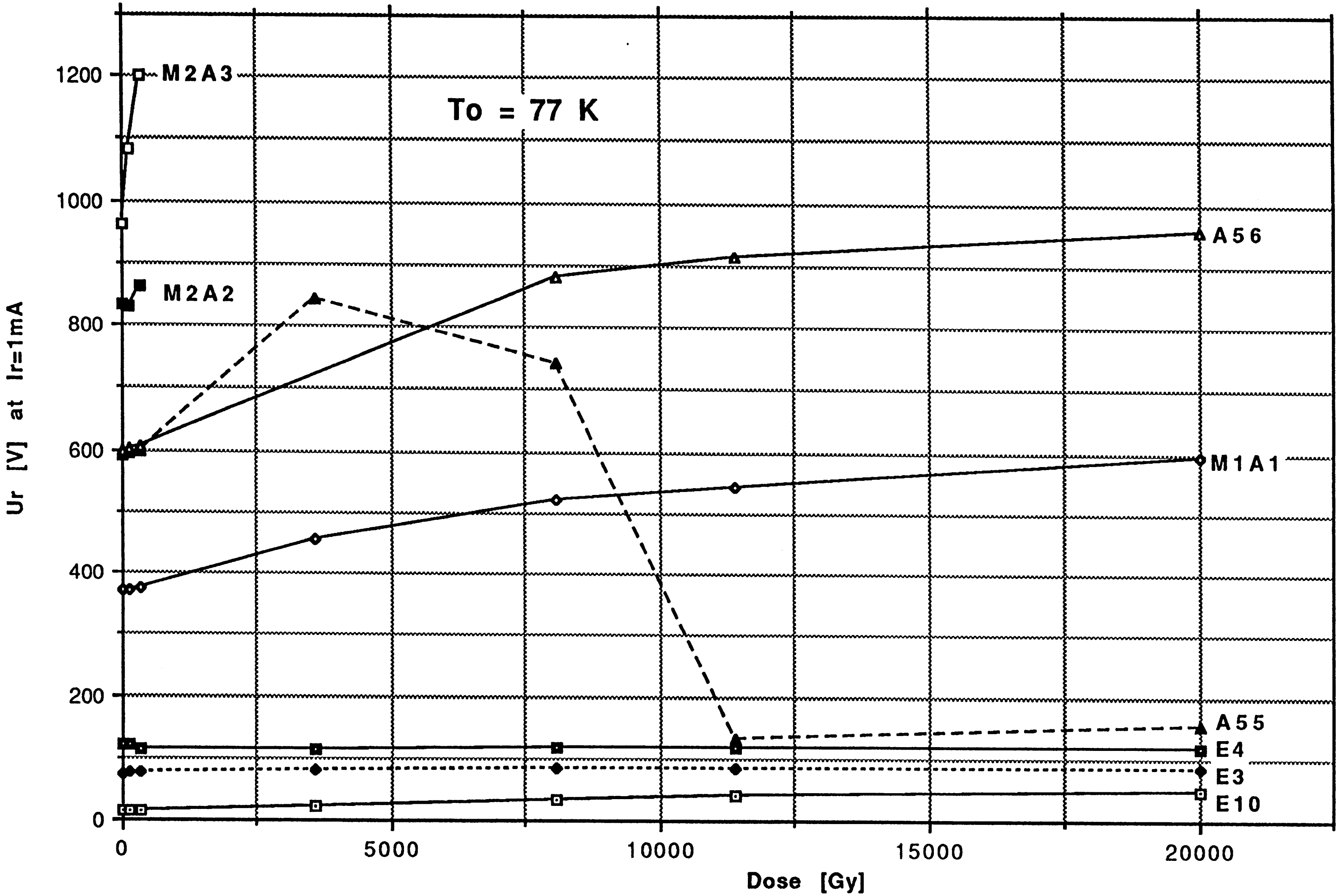

Fig. 2 Reverse voltage Ur at Ir = 1 mA versus dose measured on the 8 diodes

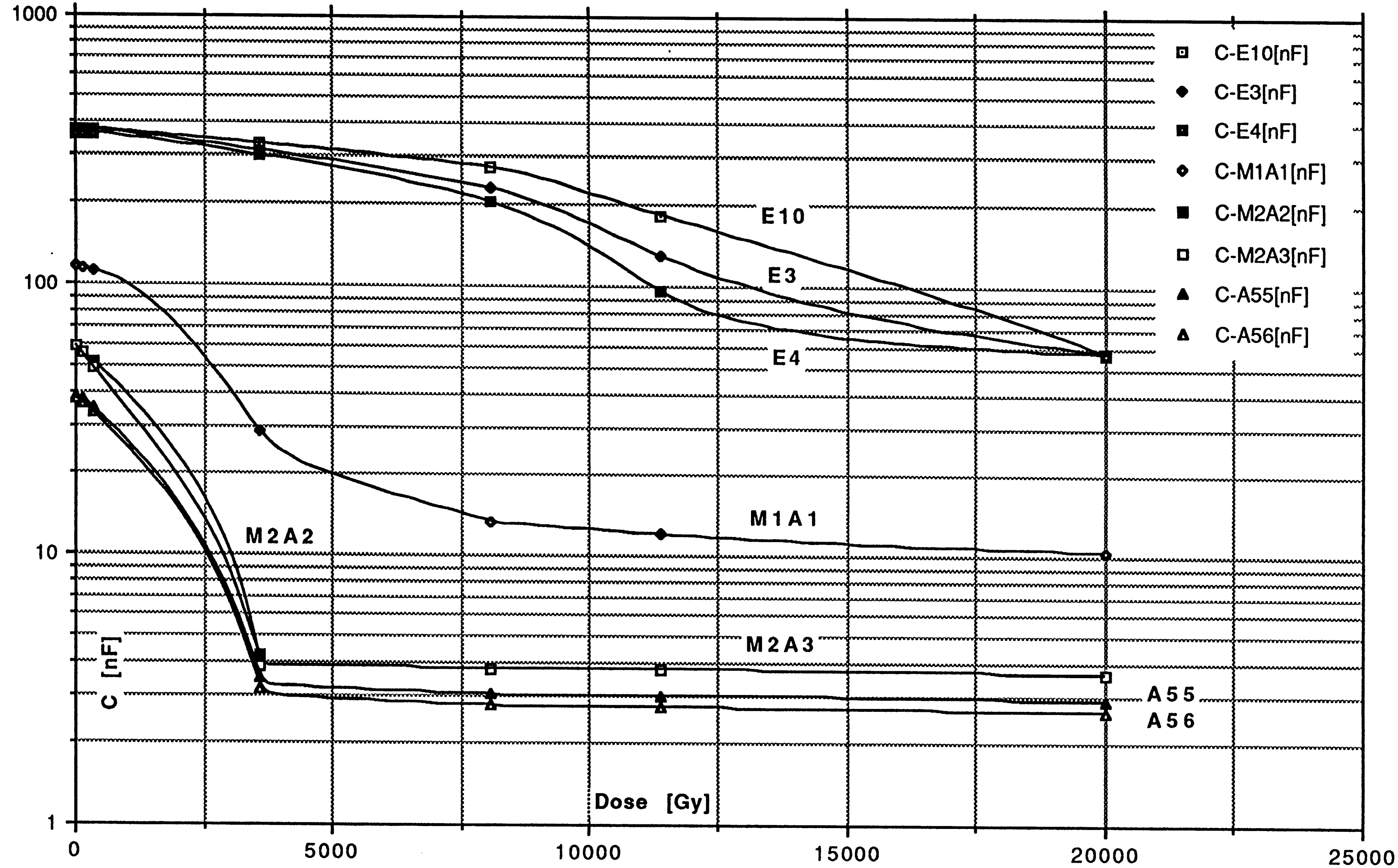

Fig. 3 Decrease of capacitance versus dose measured on the eight diodes

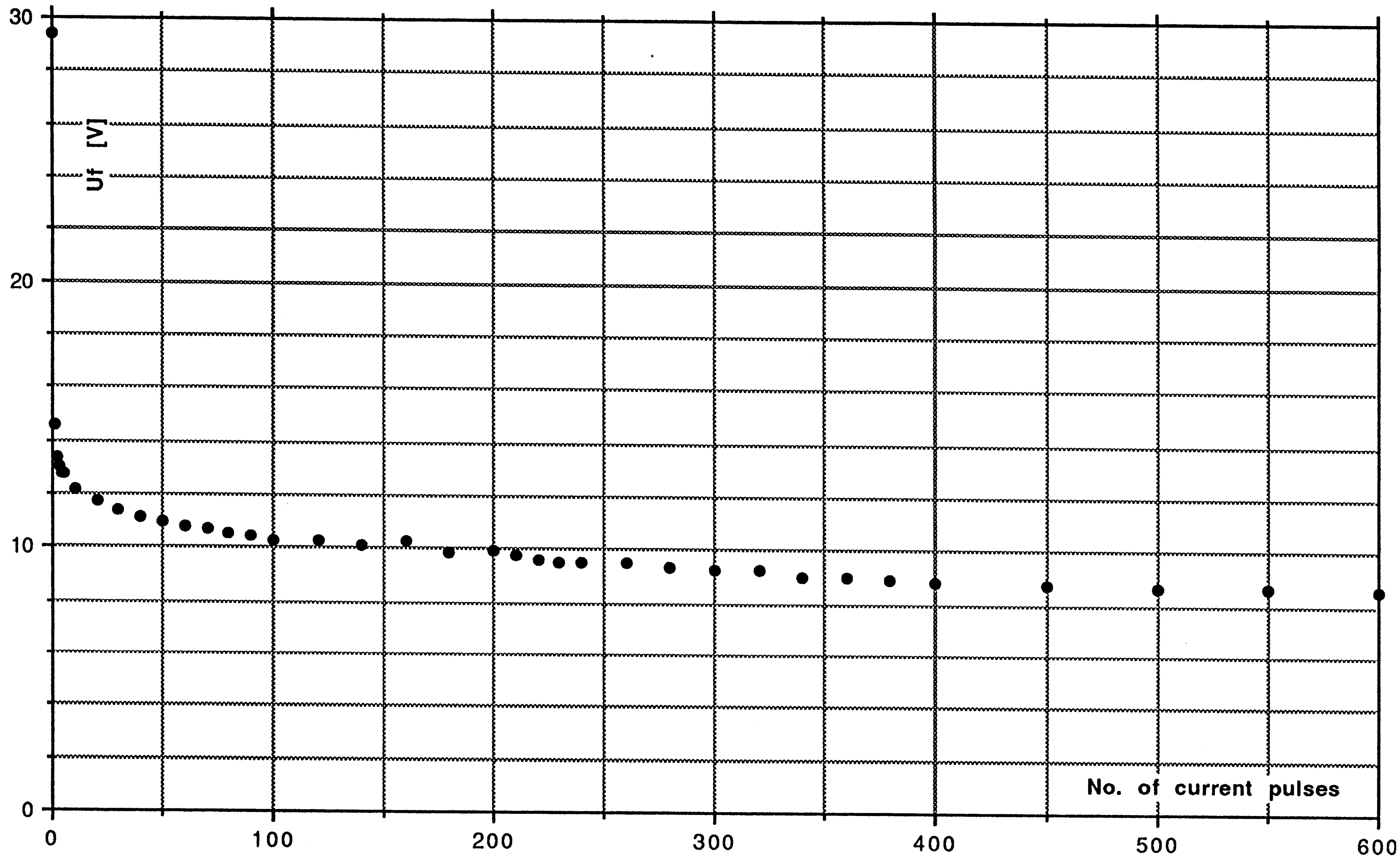

Fig. 4 **Reduction of forward voltage Uf during current pulse annealing on diode M1A1 after irradiation**

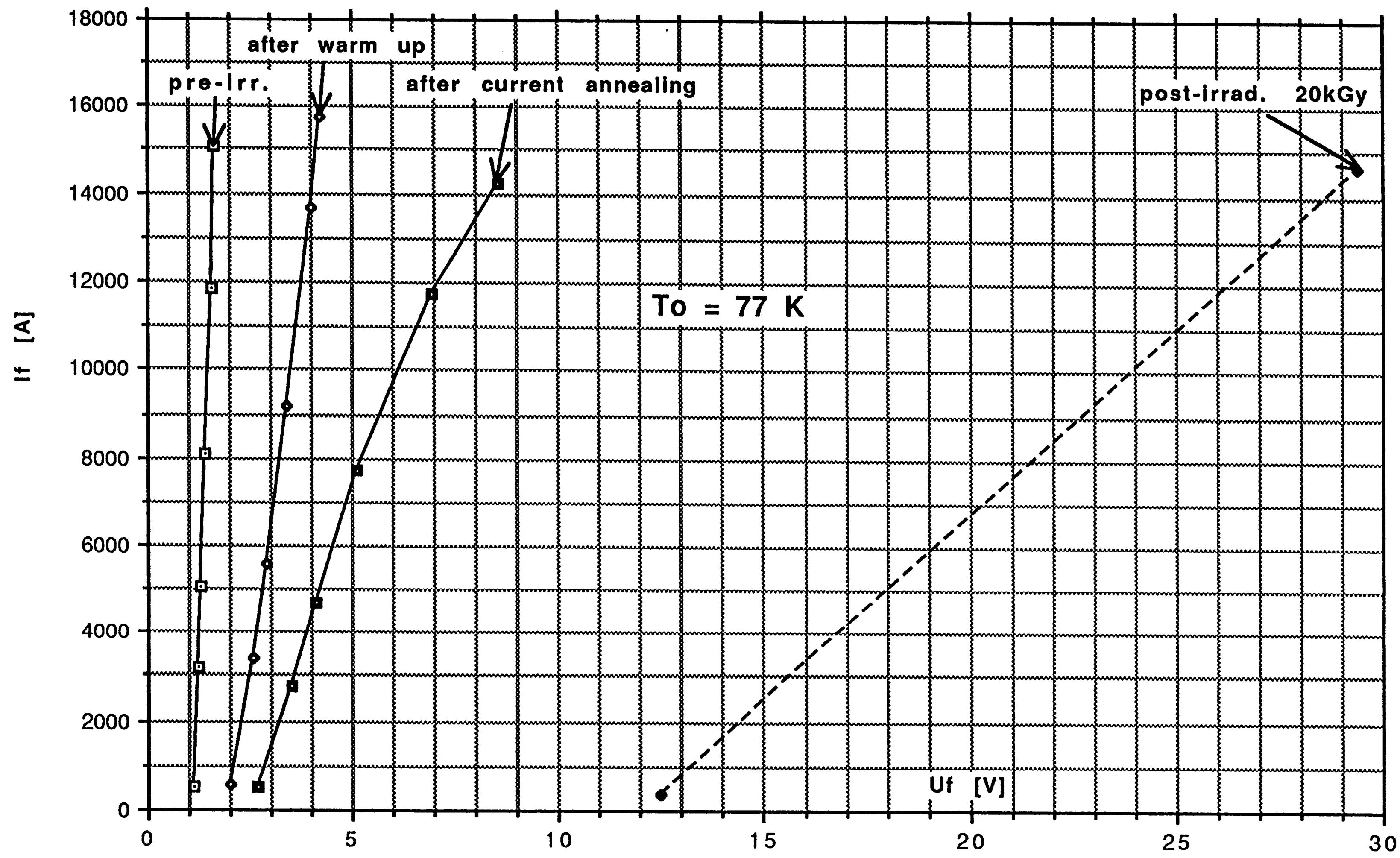

Fig. 5 If-Uf-characteristics of the diode M1A1 before and after irradiation and after current and temperature annealing

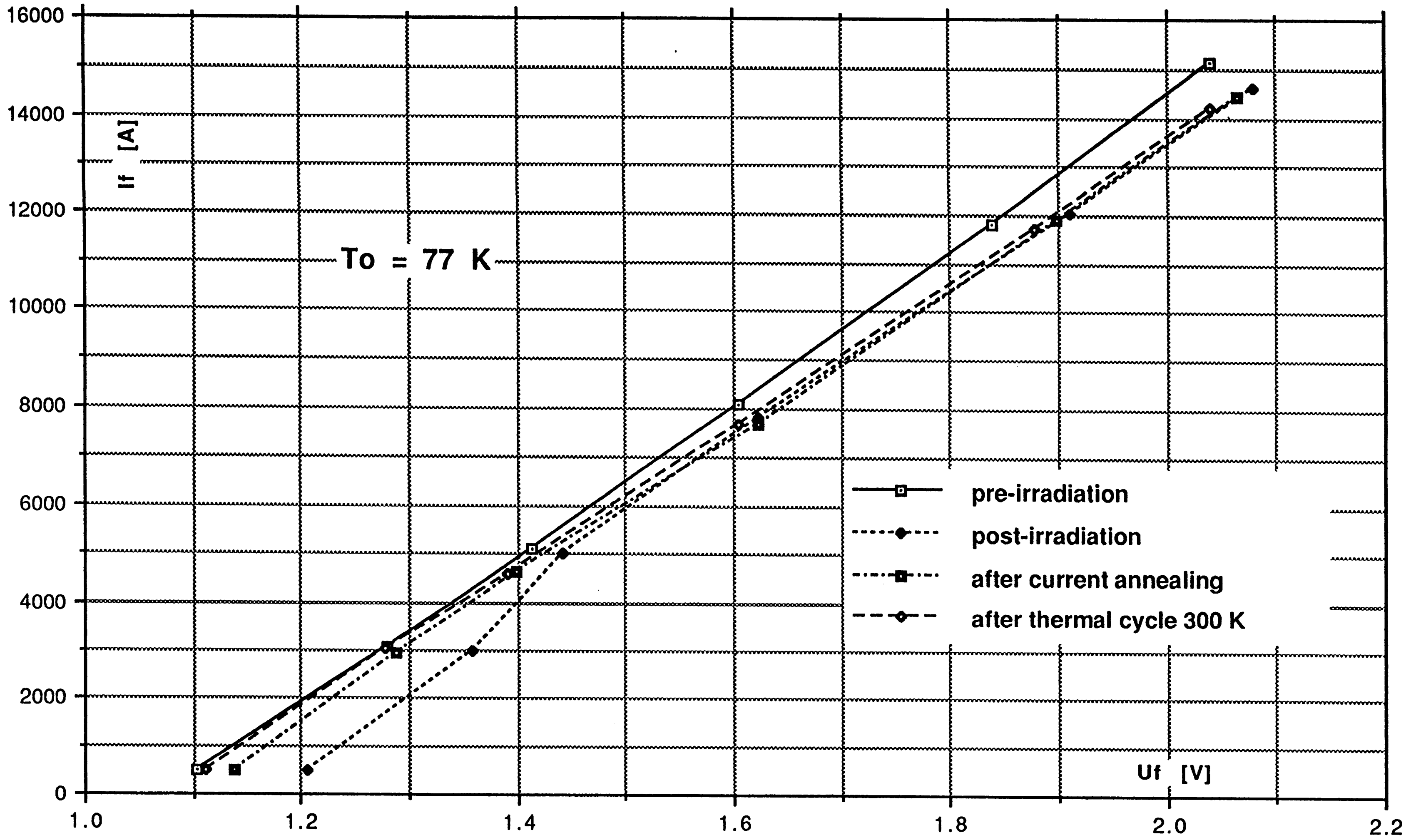

Fig. 6 If-Uf-characteristic of the diode E3 before and after irradiation and after current and temperature annealing

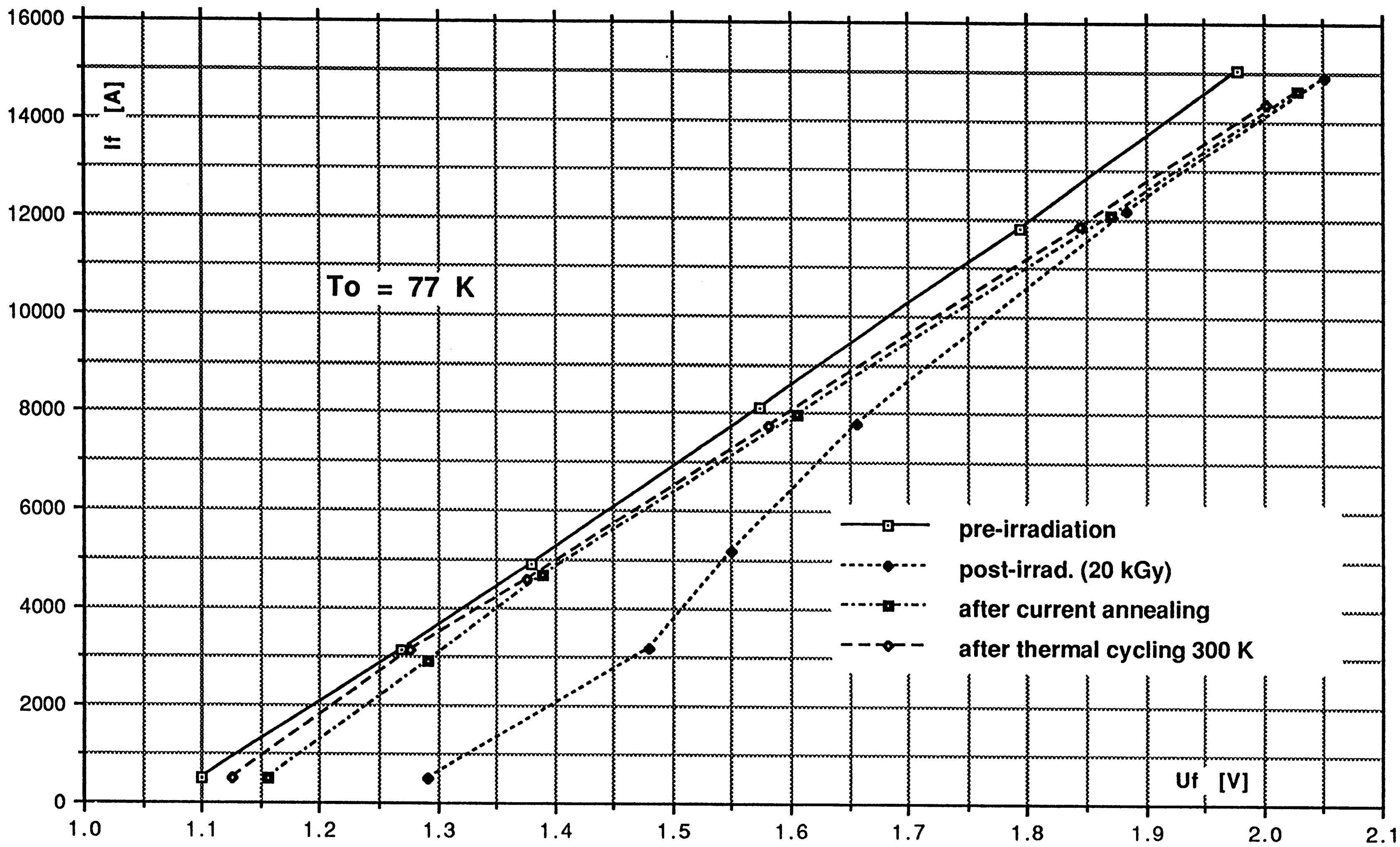

Fig. 7 If-Uf-characteristic of the diode E4 before and after irradiation and after current and temperature annealing

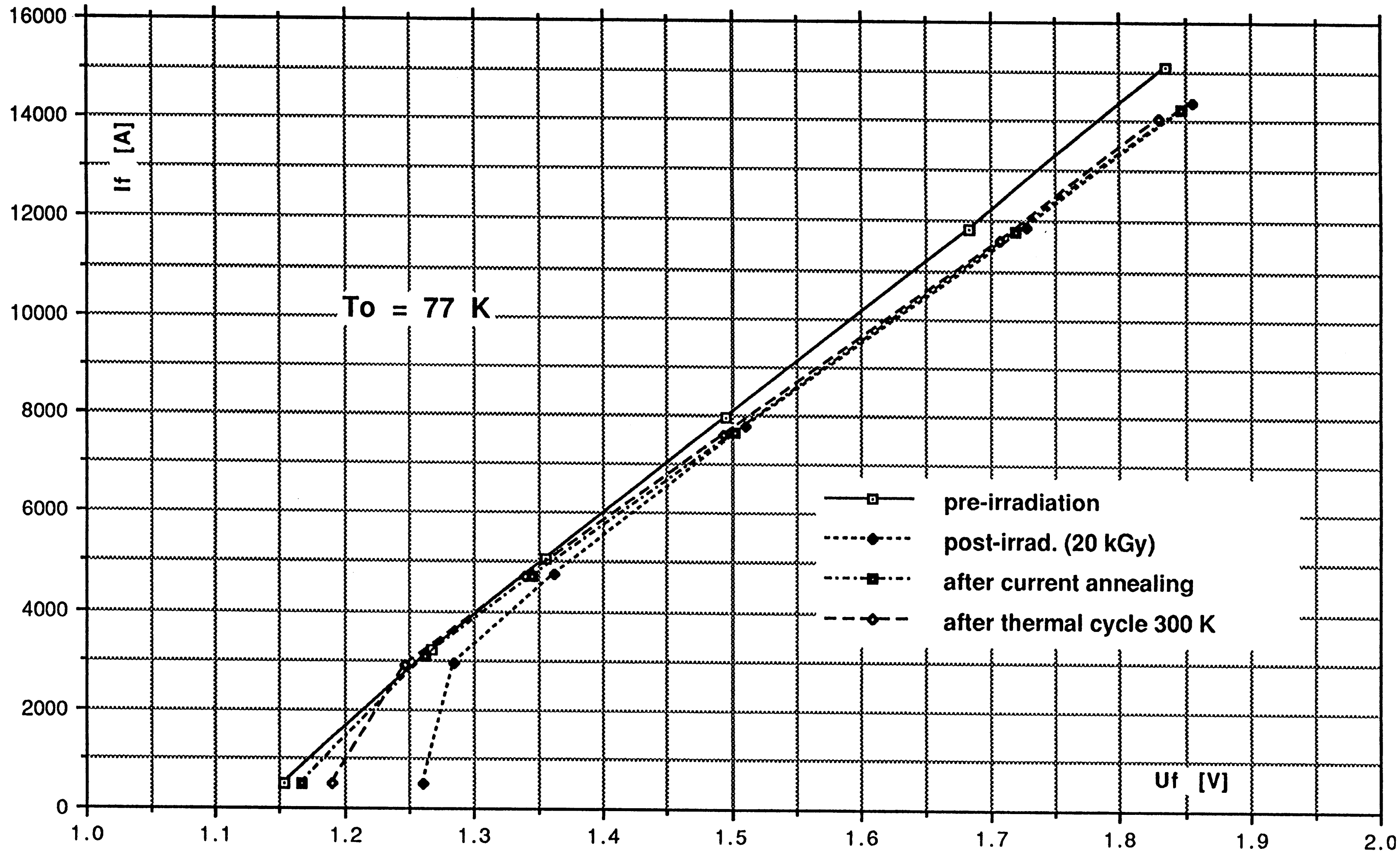

Fig. 8 If-Uf-characteristic of the diode E10 before and after irradiation and after current and temperature annealing