Observation of an energy dependence of the radiation damage on standard and oxygenated silicon diodes by 16, 21, and 27 MeV protons.

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Abstract

First measurement of the energy dependence of the radiation damage induced by low energy protons on standard and oxygen enriched diodes is presented. The current damage constant α is always insensitive to the oxygen content and increases for lower energy protons, whereas the acceptor creation rate β for both types of diodes slowly decreases for lower proton energies, this effect being amplified when the fluences are normalized to their 1-MeV neutron equivalent values. The dependence from the proton energy of the normalized β values is in open disagreement with the currently accepted NIEL hypothesis. Irradiations and measurements have been performed at the INFN Laboratorio Nazionale di Legnaro.

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1 Introduction

Silicon detectors will be operated in the LHC experiments for many years in a quite hostile radiation environment, mostly due to pions, and to a less extent to protons and neutrons [1][2][3]. Therefore the silicon detectors will suffer a significant lattice damage. When the induced damage is electrically active the operation of the detectors will be altered. The most challenging changes are due to an increase of the leakage current and variations in the full depletion voltage. The increase of the leakage current is due to the introduction of generation centers, while the introduction of additional space charge density will change the voltage to achieve full depletion (V_{dep}).

It has been suggested that the formation of V_2O centers after irradiation is the source of the variations of space charge density in the depleted volume responsible for the changes in V_{dep} observed after irradiation [4]. The centers act as deep level acceptors that therefore introduce negative space charge in the depleted silicon. This model predicts partial suppression of V_2O centers in silicon enriched by oxygen, due to the enhanced formation of VO centers, resulting in a lower rate of space charge formation and therefore improved radiation hardness.

Recent results [5] [6] show that the increase of the volumetric leakage current α is insensitive to the oxygen concentration and fabrication process of the diodes. On the contrary, diodes fabricated on oxygenated silicon show effectively a lower increase of N_{eff} after type inversion than the standard ones, the ratio of the N_{eff}s depending of the energy and type of the impinging particles: a factor $\simeq 3$, when irradiated with 24 GeV protons and 300 MeV pions, down to a factor $\simeq 1.2$ with 27 MeV protons, whereas only a small effect is observed with reactor neutrons. The behaviours are probably due to the different interaction mechanisms with the silicon atoms. However a quantitative understanding is made difficult because of the different conditions in which irradiations and measurements are usually performed.

2 The experiment

In this study we compared the electrically active damage induced by 16, 21, and 27 MeV protons [2] on diodes fabricated on FZ substrates with different oxygen concentration (see Table 1) in an attempt to measure the energy dependence of the beneficial effects of oxygen. Irradiations were performed simultaneously and measurements followed the same procedures to avoid any relative systematic error.

[2] These energies are still large enough to garantee an uniform energy loss along the proton path in a $\simeq 300\mu m$ thick silicon diode.

The diodes, provided to us by the ROSE collaboration [7], are PIN structures with 5x5 mm^2 contacts and single guard rings. The wafers were fabricated by Polovodice [8] (PL) and ITME [9] (JO); their bulk was initially n-type with resistivity of 1.3 - 2 kΩcm. The diodes were all processed by ITE [10]. The oxygen was introduced in the JO wafers by a jet of gas during the refining of the FZ process. The concentration of oxygen and carbon was measured by SIMS at EVANS [11]. In the standard silicon material the oxygen concentration is below the background level of 4×10^{16} cm^{-3} and that of carbon $\simeq 9 \times 10^{15}$ cm^{-3}, close to the carbon background concentration. In the oxygen enriched silicon the concentration of oxygen, which is practically uniform in the diode volumes, is $\simeq 2.2 \times 10^{17}$ cm^{-3}.
The experiment was performed at the SIRAD facility of the INFN Legnaro Laboratory. This facility is dedicated to radiation damage studies of semiconductor detectors, electronic devices and systems using proton and ion beams (up to Au) delivered by a 15MV Tandem accelerator. An electrostatic rastering system, made of a pair of vertical and horizontal deflection plates 1 m long, permits to perform uniform irradiations, within a few percent, over a target of fiducial area 5×5 cm^2 positioned 7.5 m downstream. During the proton irradiations the delivered fluence was measured on-line by a square battery of 3-by-3 independent small Faraday cups positioned 10 cm behind the target plane. To accumulate uniformily a fluence of 2×10^{13} prot/cm^2 typically took about 30 minutes, the proton current being limited by the activation of the irradiation chamber. More details can be found in [12].
The diodes were mounted on the sample holder within the fiducial area in three rows. Each row contained 1 standard (PL) and two oxygenated (JO) diodes. The irradiation was performed in a vacuum better than 10^{-6} mbar and at room temperature; no bias voltage was applied during irradiation.
The Tandem delivered a 27 MeV proton beam that was rattled across the samples. Strips of Silica, respectively 1.55 mm and 2.45 mm thick, were placed 5 mm infront of the diodes of the second and third rows to reduce the energy of the protons impinging on them. The proton energy distributions, calculated with the TRIM MonteCarlo [3], are shown in Fig. 1, and their mean values are reported in Tab. 2. The TRIM simulation also shows that the fraction of protons absorbed or deflected by multiple scattering onto a wrong row of diodes by the silica strips is negligibile.

[3] In the compound table of TRIM Silica is not present. The simulations were performed on SiO_2 (quartz) setting the density to the Silica value, 2.2 g/cm^3.

3 The measurement

The fluence was delivered in three incremental steps up to a total of 1.16 x 10^{14} protons/cm^2, the partial integrated values being 4.67×10^{13} and $8.12 \times 10^{13} p/cm^2$ respectively. After each fluence increment, the diodes were removed from the chamber and they underwent a fast annealing at 80^o C for 4 minutes. I-V and C-V measurements were then carried out using a microprobe test bench. During the measurements the temperature was recorded using a thermometric probe in direct contact with the chuck of the test bench; the absolute uncertainty was $< 0.5^o$ C.
The I-V characteristics of every diode were measured with a high precision DC source monitor (HP 4142B / HSMU 41423A) with an absolute uncertainty of a few pA. During measurements the guard ring was grounded. The I-V characteristics were used to measure the damage constant α and check the uniformity of the delivered fluence.
In Fig. 2 the leakage current density J measured at $V = V_{dep}$ is shown versus the on-line fluence. We don't notice any difference between oxygenated and standard diodes for any proton energy. Therefore the α value at each energy has been extracted by linear fits to both, standard and oxygenated diodes, data ($J = \alpha\Phi$). The fit to the diodes irradiated with 27 MeV protons also interpolates previous data obtained by us at the same energy [6], thus confirming the goodness of the fluence measurements. The values of α for the three proton energies are reported in Table 2.
The measured damage factors α follow the expected energy dependence although they are systematically $\sim$ 20% lower than values obtained from an extrapolation of proton irradiation measurements in the same energy range [13]. However we recall that comparisons between different experiments are difficult since no standard measurement procedures exist. In fact our value at 27 MeV agrees within 10% with that recently obtained by another group which made use of similar measurement procedures [14].
To set the V_{dep} values, the capacity of the space charge region as a function of the reverse bias voltage (C-V curves) of each diode was measured using a precision LCR meter (HP 4284A). The depletion voltage was calculated at the knee of the 10 kHz CV curve. The HP 4142B was used as V_{bias} generator.
The experimental values of the effective doping concentration N_{eff} [4] for all diodes are reported in Fig. 3 versus the on-line fluence. It has to be noted that the present measurement of β at 27 MeV for the oxygenated diodes [5] is in complete agreement (within 5%) with that we made months ago in a previous irradiation test, so testifying on the goodness of our measurements.

[4] The effective doping concentration $N_{eff} = |N_D - N_{A,n}|$ is evaluated by $N_{eff} = \frac{2\epsilon}{qW^2} V_{dep}$ where V_{dep} is the voltage for full depletion.
[5] Unfortunately the standard diode irradiated with 27 MeV protons broken after the first irradiation step and no measurement was performed on it.

All the diodes are type inverted after the first irradiation step and therefore linear fits to the different sets of data provided us with the corresponding β values ($N_{eff} = \beta\Phi$ + const). The obtained β values are reported in Table 2, column 3 and 4, for standard and oxygenated diodes respectively. The βs are systematically lower for the oxygenated diodes, as expected, but in addition they significantly decrease by lowering the proton energy for both oxygenated and standard diodes.
To permit a comparison with other experiments the βs were also extracted after normalization of the delivered fluences to the 1 MeV neutron equivalent values (see Fig. 4). That was done for each energy by multiplying the delivered fluence on-line values by the ratio of the measured current damage factor to that of 1 MeV neutrons (4×10^{-17} A/cm). The normalized β values are reported in Table 2, column 5 and 6, and plotted as a function of the proton energy in Fig. 5. The energy dependence of β is amplified by the normalization for both standard and oxygenated diodes.
The data confirm that oxygenated diodes are less sensitive to the proton damage than the standard ones and that this effect at low proton energies is significantly smaller than that measured with 24 GeV protons[5], as already presented by us in [6]. That can be understood since low energy protons produce a larger vacancy density and therefore the creation of V_2O centers is favoured with respect to the high energy case. However β decreases with lower proton energy in a significant way in spite of the narrowness of the explored energy range, and more than expected from the variation of the vacancy introduction rate in the same range[6] when we normalize the fluences with the relative current damage factors.
In addition β goes down with decreasing proton energy, also for the standard diodes, this effect being even larger than for the oxygenated ones.
This result, which is in clear disagreement with the NIEL hypothesis, could be artificially produced by a non uniformity of the beam rastering. However the uniformity of the irradiation by rastering measured by the battery of Faraday cups is well known [6] and stable (Figures 2 and 3, compare old and new data). On the other hand the effects due to the presence of the silica strips are too small, due to the proximity of the silica to the diodes, to account for the fluence corrections required to eliminate the observed β dependence on proton energy. Moreover, a fractional systematic uncertainty in the delivered fluence would affect both the determinations of α and of the uncorrected β, and, to the extent that the NIEL hypothesis is valid, the normalized β correspondingly remains unaffected by such a systematic[7], if present.
Therefore there is no evidence for a non-uniformity that could lead to a systematic overestimation of the fluence for the lower rows of diodes.

[6] The main value of the vacancy introduction rate varies by less than 10% in this energy range according to TRIM.

[7] After inversion $N_{eff} = \beta\phi_{delivered} = \beta\frac{\alpha_{norm}}{\alpha}\phi_{norm}$ so $\beta_{norm} = \beta\frac{\alpha_{norm}}{\alpha}$

4 Conclusions

We measured that a high concentration of oxygen introduced in the fabrication process of FZ silicon diodes increases their tolerance to irradiation with protons also in the low, 16 - 27 MeV, energy range. Moreover the measurements at different energies having been performed simultaneously, on diodes from the same production batch, in the same experimental conditions and with the same measurement procedures, allowed us to investigate for the first time the possible dependence of the damage factors from energy without relative systematic effects.
As expected, the current damage constant α of diodes is insensitive to the oxygen concentration and the process of fabrication and increases by lowering the proton energy.
Also as expected, the rate of introduction of acceptor like centers β is lower in oxygenated diodes and the mean value of this effect, in the energy interval under study, is only $\simeq 35\%$, well below that observed with 24 GeV protons and 300 MeV pions, but still significantly higher than that observed with reactor neutrons. The oxygenation effect on β is observed to increase by a small but significant amount by varying the proton energy from 16 ti 27 MeV.
However a new and completely unexpected result is found: β goes up by increasing the proton energy not only for the oxygenated diodes but even for the standard ones, this behaviour being amplified after correction by the current damage factor. Therefore the currently accepted NIEL hypothesis appears inadequate to compare among them the radiation damage produced by different particles and different energies.

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Tables

Table 1: The Diodes: Oxygen and Carbon content, thickness.

process	number	**[O] (cm^{-3})**	**[C] (cm^{-3})**	**thickness (μm)**
Polovodice (PL)	3	$<$ 4 x 10^{16}	$\simeq$ 9 x 10^{15}	285
Oxygen Jet (JO)	6	2.1-2.3 x 10^{17}	1 x 10^{16}	307

Table 2: The damage constants: as measured and corrected.

energy (MeV)	α (A/cm)	β_{PL} uncorrected (cm^{-1})	β_{JO} uncorrected (cm^{-1})	β_{PL} normalized (cm^{-1})	β_{JO} normalized (cm^{-1})
27	**8.0 x 10^{-17}**	**0.0492**	**0.0331**	**0.0246**	**0.0166**
20.5	**8.7 x 10^{-17}**	**0.0468**	**0.0291**	**0.0215**	**0.0134**
15.7	**9.9 x 10^{-17}**	**0.0444**	**0.0261**	**0.0180**	**0.0106**

Figure captions

Fig.1: Energy distribution of 27 MeV protons after silica absorbers as calculated with TRIM.

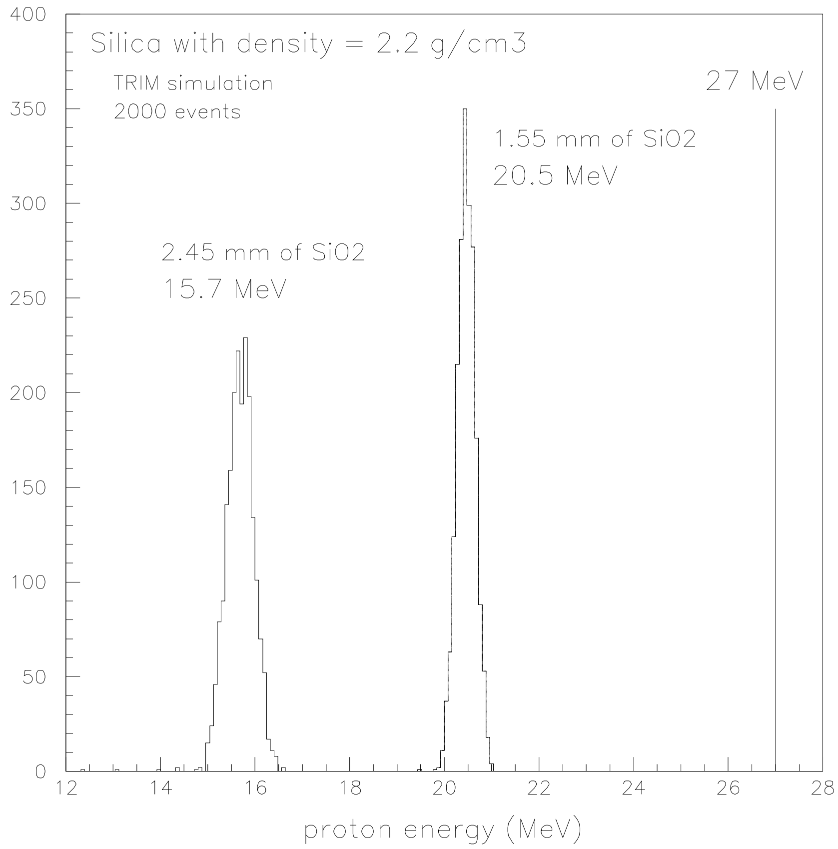
Fig. 2: The leakage current density J versus proton fluence Φ for the different diodes and the different proton energies. The 27 MeV data shown includes data points (small *) from a previous irradiation [6].

Fig. 3: N_{eff} versus the on-line proton fluence Φ for 27 MeV protons for standard (PL) and oxygenated diodes (JO). The line is a linear fit to the previous data on oxygenated diodes.

Fig. 4: N_{eff} versus normalized proton fluence Φ for the standard (PL) and oxygenated (JO) diodes irradiated with different energy protons.

Fig. 5: β values vs the proton energy for standard and oxygenated diodes.

Fig. 6: Ratio of β values of standard to oxygenated diodes vs the proton energy.



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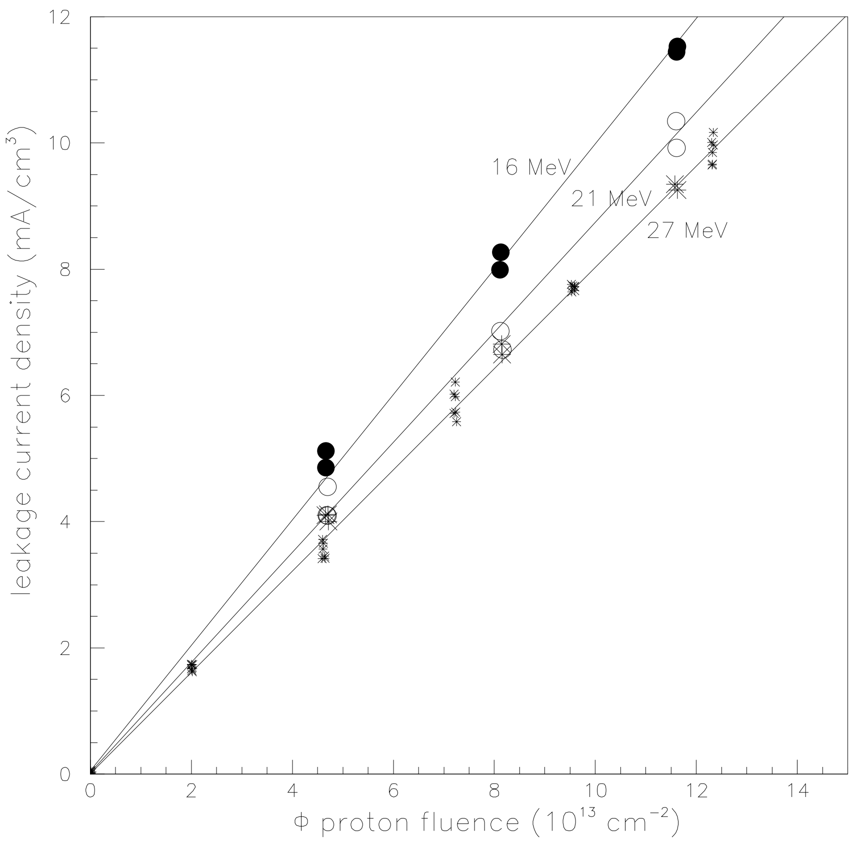

Fig. 2. The leakage current density J versus proton fluence Φ for the different diodes and the different proton energies. The 27 MeV data shown includes data points (small *) from a previous irradiation [6].

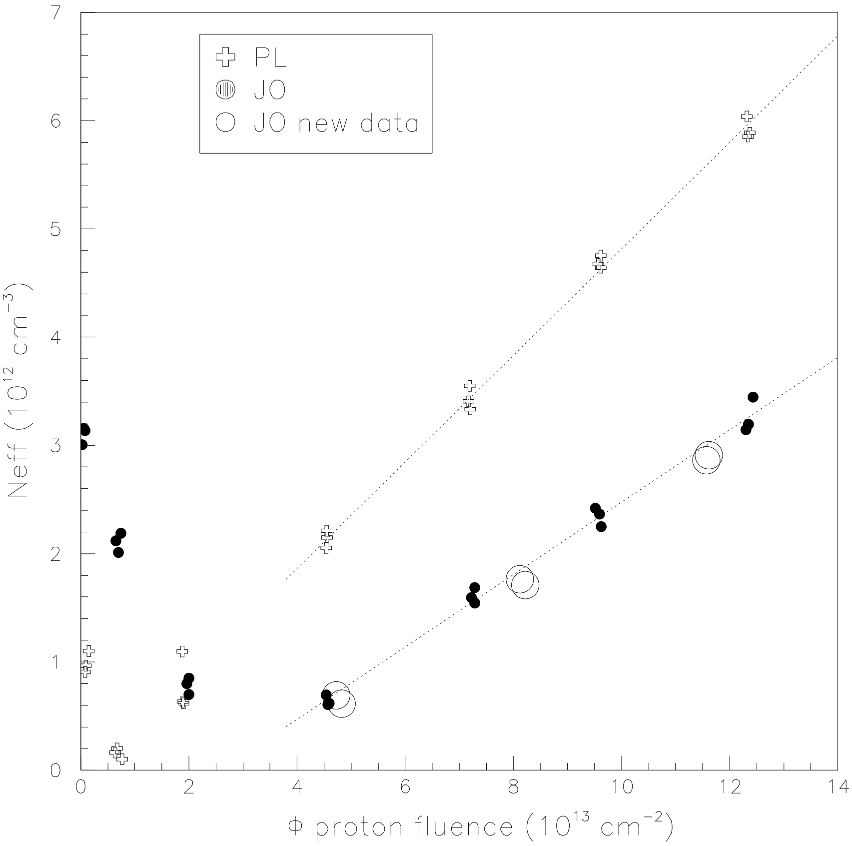

Fig. 3. N_{eff} versus the on-line proton fluence Φ for 27 MeV protons for standard (PL) and oxygenated diodes (JO). The line is a linear fit to the previous data on oxygenated diodes.

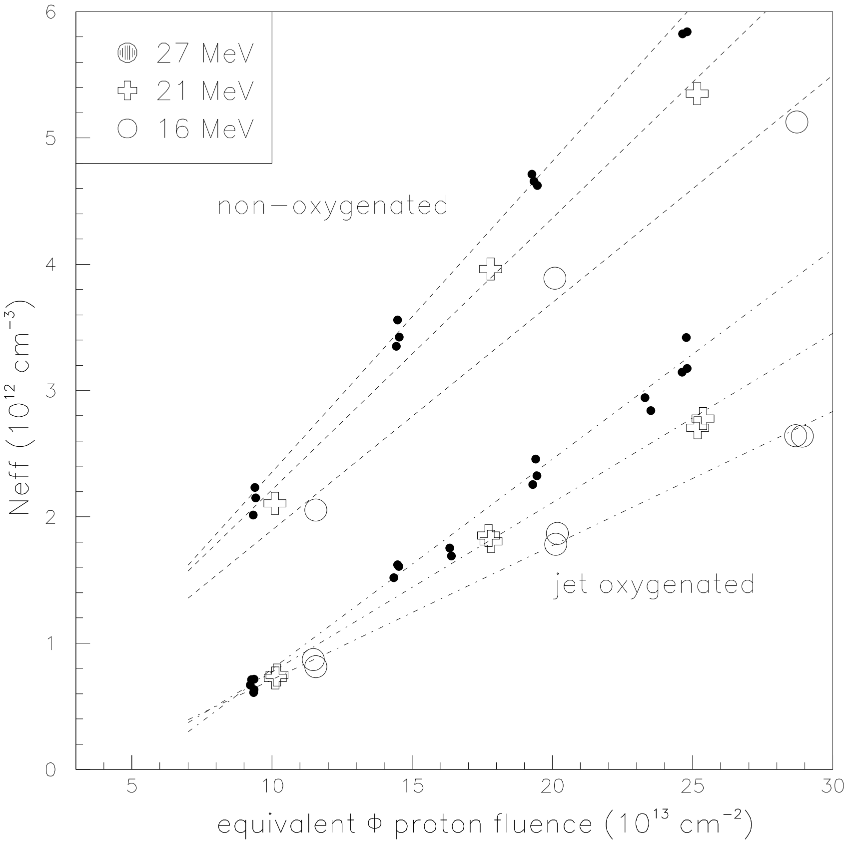

Fig. 4. N_{eff} versus normalized proton fluence Φ for the standard (PL) and oxygenated (JO) diodes irradiated with different energy protons.

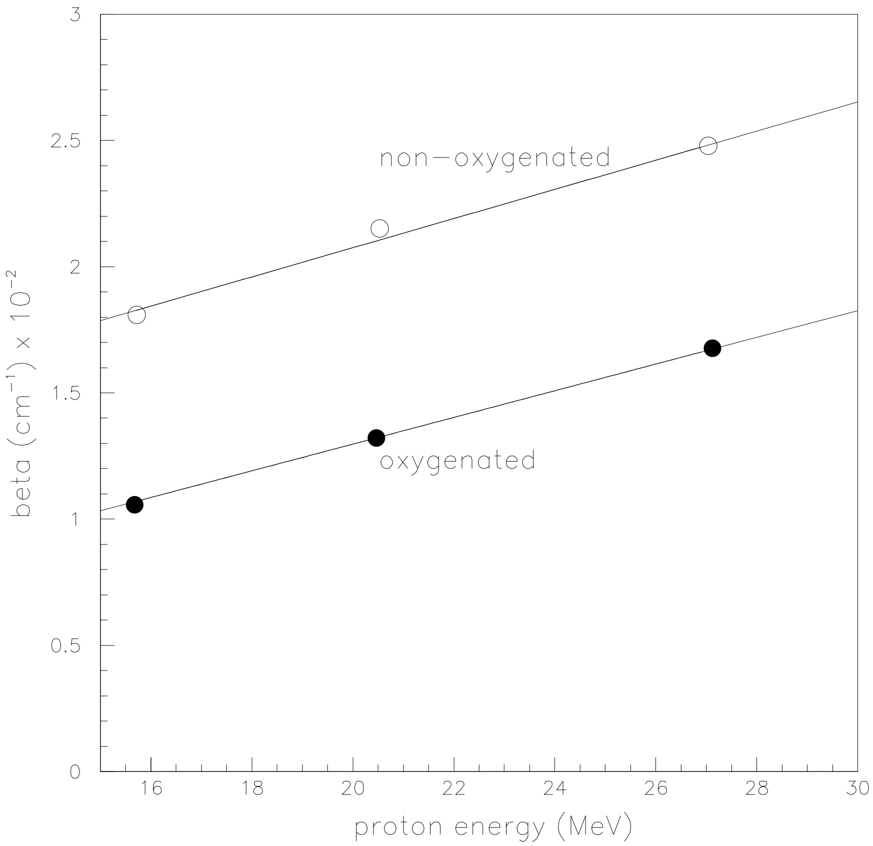

Fig. 5. β values vs the proton energy for standard and oxygenated diodes.

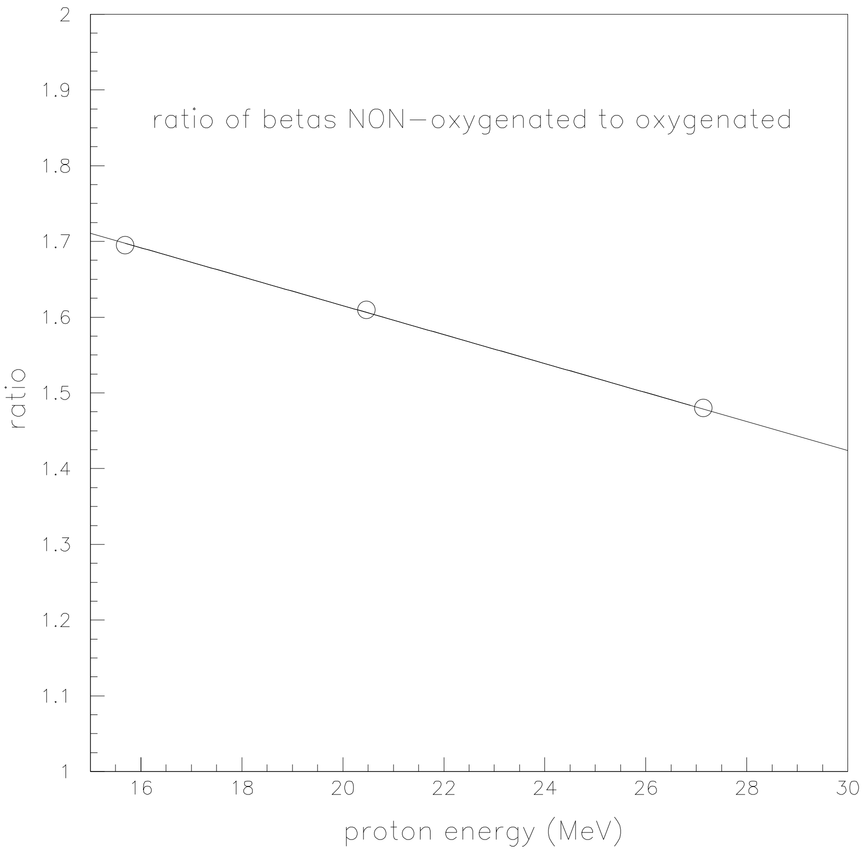

Fig. 6. Ratio of β values of standard to oxygenated diodes vs the proton energy