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Radiation hardness of amorphous silicon particle sensors

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Abstract

Radiation tests of 32 μm thick hydrogenated amorphous silicon n–i–p diodes have been performed using a high-energy 24 GeV proton beam up to fluences of 2×10^{16} protons/cm^2. The results are compared to irradiation of similar 1 μm and 32 μm thick n–i–p diodes using a proton beam of 405 keV at a fluence of 3×10^{13} protons/cm^2. All samples exhibited a drop of the photoconductivity and an increase in the dark leakage current under both high- and low-energy proton irradiation. An almost full recovery of the device performance was observed after a subsequent thermal annealing.
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1. Introduction

Vertical integration of hydrogenated amorphous silicon (a-Si:H) diodes on top of application-specific integrated circuits (ASICs) is an interesting option for the next generation of pixelized detectors for high-energy physics experiments. These innovative sensors offer advantages in terms of radiation hardness, interconnection density, integration and cost. Recently, the authors have successfully developed such sensors, aiming at the detection of single charged particles (β particles and protons) at the minimum ionizing energy [1,2].

Even though a-Si:H has been proven to have an excellent radiation hardness, most experiments have so far been performed in the context of testing the hardness of solar cells for space applications. In thin devices, the effects of proton [3–5], neutron [6] and photon irradiation have all very similar consequences on material and diode properties: metastable deep defects are created than can be annealed out. The process has been very extensively studied for light-soaking but only few experiments have been carried out in the case of irradiation.

In the present work, we first tried to investigate the limits of thick a-Si:H diodes under high-energy proton beams at the fluences that are expected for detectors in future generations of particle colliders. Similar thick diodes as well as thin ones were also degraded using low-energy proton beams and lower fluences as a means of comparison with earlier irradiation experiments published in literature [3].

2. Experimental

The 1.1 and 32.6 μm thick diodes were deposited by very high-frequency plasma-enhanced chemical vapor deposition at 70 MHz and 200 °C at a deposition rate of 15.6 Å/s. Test devices (in the substrate–n–i–p configuration) were evaporated on Cr-coated glass and the pixel area (2×2 or 5×5 mm^2) was defined by a patterned ZnO top contact. More details on the fabrication and properties of the diodes are given in [1,2,7].

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Thick diodes were exposed to a beam of 24 GeV protons with fluxes up to 3×10^{13} protons/(cm^2 h) at the CERN IRRAD1 facility. Note that this rate is about four orders of magnitude higher than the dose rate expected for the large Hardron Collider at CERN. The irradiation followed cycles of 3–4 'spills' (120 ms long periods of 'beam on' with an average fluence of 1.3×10^{11} protons) which were periodically repeated. Diodes were kept under a reverse polarization of 300 V and the currents with the beam on (spill-induced current, SPIC) and off were recorded. Dark $I(V)$ characteristics of the diodes were also measured at various points of the experiment as well as after subsequent annealing steps.

Degradation under low-energy protons was performed using a Van de Graff accelerator with a beam energy of 1.07 MeV, attenuated to 405 keV using a 12 μm Al foil. Under these conditions, an implantation depth for protons of $\geqslant 1.1$ μm into the diode intrinsic layer was estimated using SRIM software [7]. Several thin and thick diodes were irradiated under open-circuit conditions at a fluence of 3×10^{13} protons/cm^2. Dark and illuminated $I(V)$ characteristics, mobility-lifetime product $\mu\tau$ and drift mobility μ for electrons were measured in the initial, irradiated and annealed states.

3. Results

Four samples were irradiated with 24 GeV protons up to fluences of 1.89×10^{16}, 3.52×10^{15}, 7×10^{14} and 2×10^{16} protons/cm^2, respectively. In all experiments, the recorded SPIC exhibited a drop by 50–70% of the initial value followed by a stabilization at fluences $\geqslant 10^{15}$ protons/cm^2. Preliminary results on the first three runs were already published in [8].

During the third irradiation run, the sample was removed from the beam, kept for 20 h in the dark and then irradiated again. In Fig. 1, we can observe a decrease in the SPIC by 50% from the beginning of the degradation to the interruption. The latter allowed the diode to recover to 66% of the initial value, demonstrating an interesting self-annealing effect. The dark leakage current I_{dark} (cf. Fig. 2) increases for higher fluence values and then seems to saturate. A larger effect of irradiation on I_{dark} is observed at lower values of the applied external field. After one year of storage (to allow the radioactivity of the sample to reach an acceptable level), I_{dark} was found to be unchanged. However, most of the effect of irradiation was then reversed after an annealing of 12 h at 100 °C, and completely after 24 h at 100 °C.

Thin and thick samples were also degraded using a 405 keV proton beam at a fluence of 3×10^{13} protons/cm^2. In the case of thin diodes, protons are passing completely through the diode while in the case of thick diodes, protons are implanted $\geqslant 1.1$ μm below the p–i interface. More defect creation is expected in the latter case, as the protons are releasing all their kinetic energy within the diode.

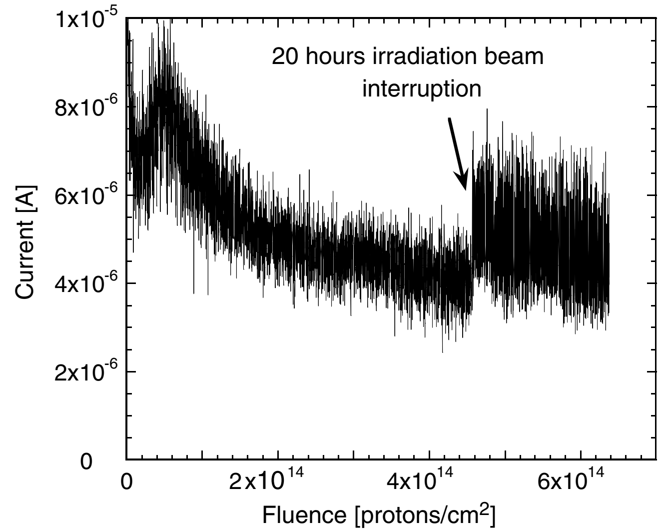

Fig. 1. Irradiation 24 GeV protons: current induced by the proton spills (see text) on a 32.6 μm a-Si:H diode as a function of proton fluence. During the beam interruption at a fluence of 4.5×10^{14} protons/cm^2, the sample was kept under the same reverse bias voltage (300 V). The noise visible during the experiment originates from the variation of the beam intensity from spill to spill.

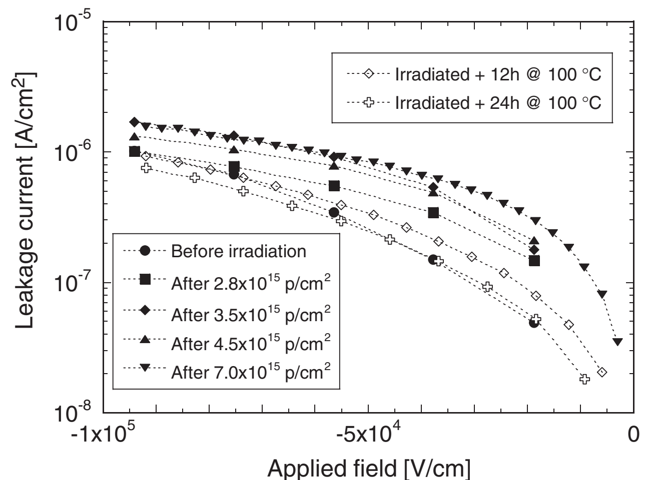

Fig. 2. Irradiation 24 GeV protons: dark (leakage) current I_{dark} as function of the applied electric field for the 32.6 μm thick a-Si:H diode, in various states of irradiation with 24 GeV protons (as plotted in Fig. 1) and annealing.

Current as a function of voltage in the dark is plotted in Fig. 3, for one thin and one thick diodes in the as deposited, irradiated, and after two steps of annealing at 180 °C. For both diodes we observe that the irradiation leads to an increase of I_{dark}, which is recovered to a large extend after 1.5 h of thermal annealing at 180 °C and completely after 4.5 h. The increase in I_{dark} is larger at lower fields where I_{dark} is mainly controlled by thermal generation of carriers from deep defects. At high field values, charge injection and Frenkel–Poole effects become dominant.

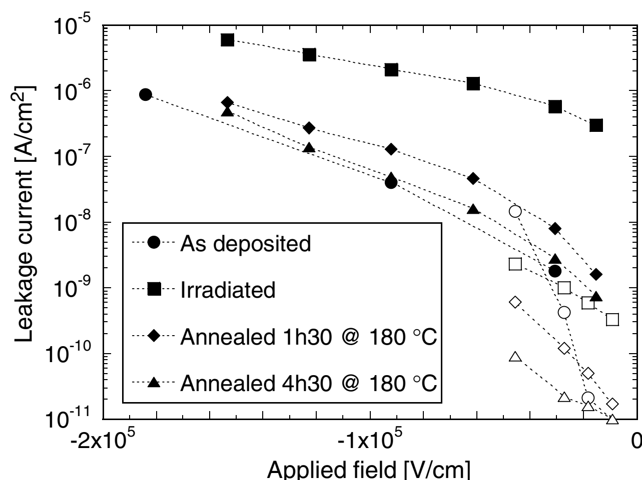

Fig. 3. Irradiation with 405 keV protons: dark (leakage) current density I_{dark} as a function of applied field for a 1.1 μm thick diode (open symbols) and for a 32.6 μm thick diode (full symbols) in the as-deposited, irradiated and annealed states after a 1.5 h at 180 °C and after 4.5 h at 180 °C.

4. Discussion

Comparing the results of irradiation with high-energy protons (Fig. 2) and those with low-energy protons (Fig. 3), the increase in I_{dark} strongly appears to depend on the density of absorbed protons and on the energy deposited locally: low-energy proton irradiation on thick diodes results in proton implantation and leads to the highest increase in I_{dark} and the most pronounced creation of deep defects. In order to obtain a value for the density of created defects, charge collection experiments using TOF (time of flight) were performed. Note that these measurements could not be performed on the samples after irradiation with high-energy protons due to the radioactivity of the samples.

Values of $\mu\tau$ and μ of electrons have been analyzed for thin and thick diodes in the as-deposited, irradiated and annealed states; results are given in Table 1. As μ is not affected by irradiation, we conclude that the change in the value of $\mu\tau$ is entirely due to a reduction in deep trapping time by creation of additional defects. The increase by one order of magnitude of the dark current after irradiation is consistent with this change in $\mu\tau$. For thick diodes, the S-shape of the collection curve for electrons (indicating a very defective region close to the p-region [9]) prevented us from extracting $\mu\tau$ values. Nevertheless, from the onset of electron collection for polarization above 150 V and from the proton implantation depth of ≈1.1 μm, we estimated $\mu\tau \leqslant 4 \times 10^{-9}$ cm²/V [8]. This value is consistent with the change in I_{dark} upon irradiation. In all cases, an annealing of 1.5 h at 180 °C is sufficient to recover deep defects created by the irradiation.

In order to check for the presence of additional defects affecting hole transport, $I(V)$ characteristics under white light (AM1.5) were also recorded. For the thin diode, irradiation significantly affects the illuminated $I(V)$, but the characteristics are fully recovered after annealing. No significant change of the open-circuit voltage V_{oc} with irradiation was observed, while fill-factor FF decreased from ≈55% down to less than 30% and fully recovered with annealing. In contrast, irradiation has a much more detrimental effect on the characteristics of thick diodes. The photocurrent in reverse polarization, FF and V_{oc} decreased significantly during irradiation and could not be recovered by annealing the diodes, even after 24 h at 180 °C. Similar observations have been made on microcrystalline silicon solar cells implanted with 405 keV protons [10]. These observations suggest that two types of defects are involved: (a) deep defects affecting electron collection generally created by all irradiation which are easy to be annealed out and (b) probably shallower type of defects affecting hole collection induced by the proton implantation which results in an irreversible damage to the diode properties.

5. Conclusions

Irradiation of thick 32.6 μm a-Si:H diodes with 24 GeV protons has been compared to irradiation of 1.1 μm and 32.6 μm thick a-Si:H diodes with 405 keV protons. Low-energy protons are much more effective in creating defects, especially thin diodes, because these protons are implanted in a-Si:H intrinsic layers leading to defects that cannot be annealed out; the latter mainly affect hole collection. For this reason, the comparison of the radiation hardness of a-Si:H solar cells and of a-Si:H particle detectors is not straightforward. Nevertheless, this reduction in hole collection is not a major drawback for the detection

Table 1
Irradiation with 405 keV protons: average mobility-lifetime products $\mu\tau$ and mobilities μ of electrons for thick and thin diodes in the as-deposited, irradiated and annealed states (1.5 h at 180 °C)

State	1.1 μm thick diodes		32.6 μm thick diodes	
	$\mu\tau$ (cm² V⁻¹)	μ (cm² V⁻¹ s⁻¹)	$\mu\tau$ (cm² V⁻¹)	μ (cm² V⁻¹ s⁻¹)
As deposited	3.5×10^{-8}	0.28	1.6×10^{-7}	0.78
Irradiated	3.5×10^{-9}	0.33	No fit possible	0.81
Annealed (1.5 h)	2×10^{-8}	0.34	1.6×10^{-7}	0.92

The relatively low value of the mobility for thin diodes is due to the large contribution of holes to collection as a consequence of the specific wavelength of 590 nm used for TOF measurement.

of ionizing particles using thick a-Si:H diodes, since it is mainly the electrons that contribute to the measured current [1].

Thick a-Si:H diodes irradiated with 24 GeV protons at fluences in excess of 10^{16} protons/cm^2 show a reduction in proton-beam-induced current by ≈70%. Effects of saturation, relaxation and annealing are observed, and defects created during irradiation (as monitored by the dark current I_{dark} of the diodes) can be annealed out at already 100 °C. The observed high-radiation resistance is remarkable and renders a-Si:H very attractive for experiments in high-energy physics. However, supplementary data on resistance to various other particles (at different energies) and on the reversibility of the defect creation is still needed.

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