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Temporal electric conductivity variations of hydrogenated amorphous silicon due to high energy protons

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ABSTRACT

Electric conductivity variations of undoped, n-type and p-type hydrogenated amorphous silicon (a-Si:H) thin films irradiated with various energy protons are systematically investigated. Dark conductivity (DC) and photoconductivity (PC) of the undoped samples increase at first due to proton irradiation and then decrease dramatically with increasing proton fluence. The increase in DC and PC becomes greater with increased proton energy. However, this increase is metastable and gradually decreases with time at room temperature. Similar results are observed in the n-type a-Si:H, whereas only a monotonic decrease is observed in DC and PC for the p-type samples. The increase of both DC and PC due to proton irradiation is attributed to metastable donor center generation. On further irradiation both the DC and PC decrease by the accumulation of radiation-induced defects, which act as deep traps and compensate carriers. The decrease in DC and PC becomes less pronounced as the proton energy increase and can be fitted along a universal line when the proton fluence is converted into displacement per atom (dpa).

1. Introduction

Great progress has been made in the use of hydrogenated amorphous silicon (a-Si:H) for solar cells, various sensors and high resolution imaging devices including copying machines and panel displays in recent decades. In response to the progress of high energy physics and space technologies, a-Si:H semiconductor devices are also expected to be utilized in severe radiation environments such as actual space, nuclear reactors and accelerator facilities because of their high radiation tolerances [1–3]. For example, radiation effects study of solar cells is a crucial issue for space applications since space solar cells are exposed to space radiation (mainly protons and electrons). Radiation degradation of crystalline silicon (c-Si) solar cells has been extensively investigated for many years, and degradation mechanisms are relatively well understood [4–6]. However, the effect of radiation on microcrystalline (μc-Si) or a-Si:H thin film solar cells, which have the potential to decrease the weight of satellite solar paddles, has not been fully elucidated yet although several studies has been reported [7–9]. In particular, it is unclear even which energy deposition type (nuclear or electronic) of ionizing radiation dominates the electrical degradation. Contradictory results have been reported on this issue [10,11].

In order to develop radiation hardened a-Si:H device design, variations of the electrical properties such as electric conductivity and carrier concentration are a primary concern. For this reason, several research groups have investigated these issues [12,13], especially studies concerning the electron irradiation effects [14–16]. They have shown that defects, which are thought to be mainly dangling bonds (DBs), are generated by electron irradiation and the electrical properties degrade since these defects act as carrier traps and recombination centers. However, systematic and comprehensive studies about radiation effects on a-Si:H is hardly reported at present despite being very important to understand the mechanism. Also, knowledge about the radiation effects is reflected on the optimization of radiation hardened a-Si:H device design.

In this paper, we report electric conductivity variations of undoped and doped a-Si:H thin films irradiated with various energy protons using an *in-situ* measurement system. *In-situ* measurement has many advantages compared to *ex-situ* measurement since it avoids sample variations in fluence dependent studies and allows the investigation of metastable phenomena to be observed immediately after irradiation. Also, it is very important to investigate the incident proton energy dependence of conductivity variation since various energy protons, which have various ratios of nuclear to electronic energy deposition (stopping power), give rise to different radiation effects on a-Si:H as shown here.

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2. Experimental

The samples used in this study were intrinsic (undoped), n-type (phosphorous doped) and p-type (boron doped) a-Si:H thin films fabricated on glass or quartz substrates by plasma enhanced chemical vapor deposition (PECVD) at the National Institute of Advanced Industrial Science and Technology (AIST). The excitation frequency was 13.56 MHz. The substrate temperature during deposition and the gas flow rates were 180 °C and $SiH_4/H_2 = 20/100$ sccm for undoped samples, 195 °C and $SiH_4/H_2/PH_3 = 20/80/23$ sccm for n-type samples, and 200 °C and $SiH_4/H_2/B_2H_6 = 10/100/30$ sccm for p-type samples, respectively (PH_3 and B_2H_6 are 5000 ppm mixtures with hydrogen balance gas). The size of the active area was 8.0 mm × 8.0 mm and interdigitated Aluminum Ohmic electrodes were formed on the samples. All the samples were previously light-soaked using a metal halide lamp to stabilize their electrical properties. Typical electrical properties of the samples are listed in Table 1.

The samples were irradiated with 0.10, 1.0, 3.0 and 10 MeV protons at room temperature (RT) and their conductivity variations as a function of proton irradiation fluence were investigated *in-situ* in an irradiation vacuum chamber. Details of the experimental setup are described in Ref. [17]. Proton irradiation was performed at the Takasaki Ion Accelerators of advanced Radiation Application (TIARA), Japan Atomic Energy Agency (JAEA). The projected ranges of all the protons are greater than the a-Si:H film thickness of the samples and deposit their energy almost uniformly through the sample (see Table 2), according to the Monte Carlo simulation code TRIM [18]. Thus, no passivation by the implanted hydrogen atoms of dangling bonds in the a-Si:H films is expected. The current–voltage (*I–V*) characteristics of the samples were measured under dark conditions and AM-0, 1 sun (136.7 mW/cm^2) light illumination. The voltage sweep range was between −10.0 V and +100 V (between −0.500 and +5.00 kV/cm) in the cases of undoped and p-type samples, and between −10.0 V and +50.0 V (between −0.500 and +2.50 kV/cm) in the case of n-type samples. The conductivity was derived from the slope of the *I–V* characteristics. Hereinafter, dark conductivity (DC) is defined as the conductivity measured under dark conditions and photoconductivity (PC) is defined as the difference between the DC and the conductivity under the light illumination. The measurement fluctuations of DC and PC values were estimated to be within ±3% and ±4% respectively, which mainly caused by light intensity and temperature fluctuations. Proton irradiation and conductivity measurements were performed alternately in the chamber. Proton beams were stopped by a shutter during measurement. The errors of the irradiation fluences were estimated to be within ±10% in view of beam uniformity and beam current integration error. Finally, post-irradiation samples were annealed at 150 °C for 4 h under nitrogen gas flow, and both DC and PC were measured again.

3. Results

Fig. 1(a) and (b) shows DC and PC variations of the undoped a-Si:H as a function of irradiated proton fluence. In the case of 3.0 MeV and 10 MeV proton irradiation, both DC and PC increased at first due to proton irradiation peaked at the same fluence and then decreased dramatically with increasing proton fluence. Being below the detection limit in the low fluence regime, the DC values increased dramatically when the proton fluence exceeded 3.0×10^{11}/cm^2 in the case of 3.0 MeV proton irradiation. The DC value had a peak at a fluence of 5.0×10^{12}/cm^2 and then decreased dramatically, dropping below the detection limit at fluences around 1×10^{14}/cm^2. The DC peak obtained with 10 MeV proton irradiation shifted to higher fluence side (1.5×10^{13}/cm^2) compared to that of 3.0 MeV proton irradiation. As for the 0.10 MeV proton irradiation results, the same trend was also observed and the PC value increased by 1.4 times at the fluence of 2.0–5.0×10^{11}/cm^2. The temperature increase due to the proton irradiation in this fluence regime was below 1 K and the conductivity increase due to temperature increase was estimated to be +0.9% at the highest. Hence, the conductivity increase observed in 0.10 MeV proton irradiation is also attributed to the effects of proton irradiation. This is true for all samples studied in this work. The PC variations followed the DC variations and this fact suggests that both have the same origin. Also, a drastic decrease in PC and DC was observed in the high fluence regime particularly for the 0.10 MeV irradiation.

Conductivity variations of the n-type a-Si:H are shown in Fig. 1(c) and (d). In any energy of protons, both the DC and PC values slightly increased at first due to proton irradiation and then decreased with increasing the proton fluence for all proton energies used. The increase in DC and PC was less obvious compared to the results of the undoped a-Si:H. For instance, the DC value at 1.5×10^{13}/cm^2 was 1.6 times larger than that before irradiation in the case of 10 MeV protons. Fig. 2 shows the behavior of the DC increase of the n-type a-Si:H in the low fluence regime. The peak fluences corresponded with the results of the undoped a-Si:H. This indicates that the DC increase observed in both the undoped and the n-type a-Si:H have the same origin. In addition, both the DC and PC behavior in the high fluence regimes is similar to that of the undoped a-Si:H. Fig. 1(e) and (f) show DC and PC variations of p-type a-Si:H. In contrast to the undoped and n-type samples, a monotonic decrease was observed with increasing proton fluences in the DC and PC for all proton energies employed. Again, the greater decrease was observed for the 0.10 MeV protons.

Finally, the post-irradiation samples were thermally annealed and were light-soaked after the annealing. As a result, both DC and PC of all the samples were substantially recovered and the recovery ratios were above 75%. However, only the PC of the undoped sample irradiated with 0.10 MeV protons at 1.0×10^{15}/cm^2 did scarcely recover (7%). This is because 0.10 MeV proton irradiation fluence of this sample was 5.3 times higher and thus the radiation induced damage was much higher than that of the n-type or p-type samples. These results indicate that thermally stable defects are generated by proton irradiation and that the radiation-induced degradation is irreversible by thermal annealing. Therefore, radiation-induced degradation of a-Si:H is very different from the light-induced degradation since light-induced defects can be completely annihilated with thermal annealing [19].

Table 1
Typical values of dark conductivity (DC), photoconductivity (PC), carrier concentration (N) and mobility (μ) of the samples used in this study. Values of N and μ were derived from Hall measurement results. Hall effect of the undoped samples could not be observed because of low conductivity.

Sample	Thickness [μm]	DC [S/cm]	PC [S/cm]	N [/cm^3]	μ [cm^2/Vs]
Undoped	0.30	4.0×10^{-11}	9.3×10^{-6}	N.A.	N.A.
n-Type (P doped)	0.27	3.7×10^{-3}	1.0×10^{-3}	6.2×10^{17}	0.055
p-Type (B doped)	0.21	2.2×10^{-6}	3.9×10^{-6}	6.6×10^{13}	0.077

Table 2
Electronic energy deposition (S_e), Nuclear energy deposition (S_n), S_n/S_e, fluence per dpa (ϕ_{dpa}), and projected range (R) of protons in the undoped a-Si:H from the calculation results of TRIM. Values of S_e, S_n and dpa shown here are average values along to the depth direction.

Proton energy [MeV]	S_e [eV/nm]	S_n [eV/nm]	S_n/S_e	ϕ_{dpa} [/cm^2]	R [μm]
0.10	1.1×10^2	0.16	1.5×10^{-3}	4.5×10^{18}	0.89
1.0	38	1.7×10^{-2}	4.4×10^{-4}	3.2×10^{19}	15
3.0	20	7.0×10^{-3}	3.5×10^{-4}	8.1×10^{19}	85
10	7.4	1.5×10^{-2}	2.1×10^{-4}	4.6×10^{20}	6.6×10^2

4. Discussion

Generally, when semiconductor materials are exposed to ionizing radiation, carrier lifetimes decrease due to the accumulation of