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Ion-induced changes in semiconductor properties of hydrogenated amorphous silicon

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ABSTRACT

Undoped, phosphorus doped (n-type), and boron doped (p-type) hydrogenated amorphous silicon (a-Si:H) thin films are irradiated with 3.0 MeV protons, 100 keV protons, and 2.8 MeV silicon ions, and the electric conductivity variations as a function of ion fluence are investigated. The Seebeck coefficient variations as a function of ion fluence are also investigated and are compared to the electric conductivity variations. As a result, a systematic interpretation of radiation effects on a-Si:H semiconductors is obtained. In the fluence regime of below 10^{-6} dpa, the increase in electric conductivity and the emergence of negative Seebeck effect are observed in the undoped a-Si:H because of donor-center generation. In the fluence regime from 10^{-6} dpa to 10^{-4} dpa, the decrease in electric conductivity and the decrease in absolute value of Seebeck coefficient are observed in the doped a-Si:H, since the carrier removal effect is caused by radiation defects, which are thought to be mainly dangling bonds. In the fluence regime of above 10^{-4} dpa, the increase in electric conductivity caused by the enhancement of hopping transport via localized states is observed. The absolute value of Seebeck coefficient of doped a-Si:H decreases in this fluence regime, whereas no Seebeck effect is observed in the undoped a-Si:H.

1. Introduction

Because of the development of high energy physics and space technologies, high radiation-tolerance is increasingly required for electronic devices utilized in spacecrafts and nuclear and accelerator facilities [1–5]. Variations of semiconductor properties depending on irradiation fluence are fundamental and important knowledge to understand behavior of electronic devices operated under radiation environments. The knowledge is also essential to design the radiation-hardened devices, and thus variation of electric conductivity of crystalline silicon (c-Si) due to radiation exposure has been extensively studied [6,7]. On the other hand, investigation for radiation effects on amorphous type semiconductors including hydrogenated amorphous silicon (a-Si:H) is insufficient at the present stage, even though a-Si:H semiconductors are utilized as a material of thin-film transistors (TFTs), solar cells, and photo-detectors. Since a-Si:H devices are generally known to have higher radiation-tolerance than c-Si devices [8–10], a-Si:H-based devices are one of the strong candidates of radiation-tolerant photoelectric devices.

Owing to these facts, radiation effects on a-Si:H thin films have been investigated by several research groups [11–14]. However, the details are still unclear. In particular, little is known about variations of semiconductor properties of a-Si:H depending on irradiation fluence even though comprehensive study is required to obtain a systematic interpretation. Accordingly, we have investigated electric conductivity and photoconductivity of a-Si:H irradiated with charged particles and have obtained systematic understandings of the radiation effects on a-Si:H [15,16].

In this paper, electric conductivity and Seebeck coefficient variations of a-Si:H depending on irradiation fluence are comprehensively investigated. Ion fluence and ion species as well as impurity-doping conditions of samples are used as experimental parameters. In particular, continuous variations of Seebeck coefficient of a-Si:H as a function of ion fluence are clarified for the first time. Since the Seebeck coefficient depends on the majority carrier concentration and the electronic transport mechanism, a systematic understanding of radiation effects on semiconductor properties is obtained from the relationship between variations of electric conductivity and Seebeck coefficient.

2. Experimental

The samples used in this study were device-grade undoped, n-type (phosphorous doped) and p-type (boron doped) a-Si:H thin films fabricated on glass substrates by plasma enhanced chemical vapor deposition (PECVD). The excitation frequency was 13.56 MHz. The substrate temperature during deposition and the

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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). Interdigitated type and coplanar type aluminum Ohmic electrodes were formed on the samples for conductivity measurement and for thermoelectric power measurement, respectively. The thicknesses were 0.30 μm for undoped, 0.27 μm for n-type, and 0.21 μm for p-type a-Si:Hs. The majority carrier concentrations of 6.2×10^{17} cm^{-3} for n-type and 6.6×10^{13} cm^{-3} for p-type a-Si:Hs were determined by Hall measurement.

The samples were irradiated with 3.0 MeV protons, 100 keV protons, and 2.8 MeV silicon (Si) ions at room temperature (RT). The electric conductivity variation and the Seebeck coefficient variation as a function of irradiation fluence were investigated *in situ* in an irradiation vacuum chamber. Ion irradiation was performed at the Takasaki Ion Accelerators of advanced Radiation Application (TIARA), Japan Atomic Energy Agency (JAEA). A raster beam scanning system was used for uniform irradiation of the whole area of a sample. The fluctuation of beam uniformity was estimated to be within ±5%. The projected ranges of all the ions used in this study are beyond the thickness of the a-Si:H film and deposit their energy almost uniformly through the film, according to the Monte Carlo simulation code, TRIM [17]. Thus, no passivation by the implanted hydrogen atoms of dangling bonds in the a-Si:H films is expected. Also, a unit of displacement per atom (dpa) was applied in order to compare results in different irradiation conditions. The conversion ratios are 1 dpa = 8.1×10^{19} cm^{-2}, 4.5×10^{18} cm^{-2}, and 9.8×10^{15} cm^{-2} for 3.0 MeV protons, 100 keV protons, and 2.8 MeV Si ions, respectively. In the TRIM calculation, the mass density of 2.3 g/cm^3 and the hydrogen concentration of 11.6% were used for undoped a-Si:H. These values were experimentally determined by using Rutherford backscattering spectroscopy (RBS) and elastic recoil detection analysis (ERDA). The default values of displacement energy installed in TRIM were used: 15 eV for Si and 10 eV for H. The same values were also applied for the analysis of n-type and p-type a-Si:Hs, since the difference was sufficiently small.

The current–voltage (*I-V*) characteristics and the thermoelectric power of the samples were measured *in situ* under dark conditions. The conductivity was derived from the slope of *I-V* characteristics and the Seebeck coefficient was derived from the ratio of the thermoelectric power divided by the temperature difference. The uncertainty of obtained data is estimated to be ±3% for electric conductivity and ±10% for Seebeck coefficient, which were mainly due to the uncertainty of temperature. The ion irradiation was paused during measurement and was resumed after completion of the measurement. Details of the experimental procedure are described elsewhere [18,19].

3. Results

Fig. 1 shows the Seebeck coefficient variations of a-Si:H as a function of 3.0 MeV proton fluence. Not observed in the undoped a-Si:H before irradiation, the negative Seebeck effect appeared after the irradiation of 1.0×10^{11} cm^{-2} (1.2×10^{-9} dpa). The absolute value of Seebeck coefficient increased at the fluence of above 10^{13} cm^{-2} and could be observed at the fluence up to 2.0×10^{14} cm^{-2} (2.5×10^{-6} dpa). The absolute value of Seebeck coefficient of n-type a-Si:H similarly increased at the fluence of above 10^{13} cm^{-2} (1.2×10^{-7} dpa). On the other hand, the absolute value of Seebeck coefficient of p-type a-Si:H gradually increased with increasing fluence and could not be observed at the fluence of above 10^{14} cm^{-2} (1.2×10^{-6} dpa).

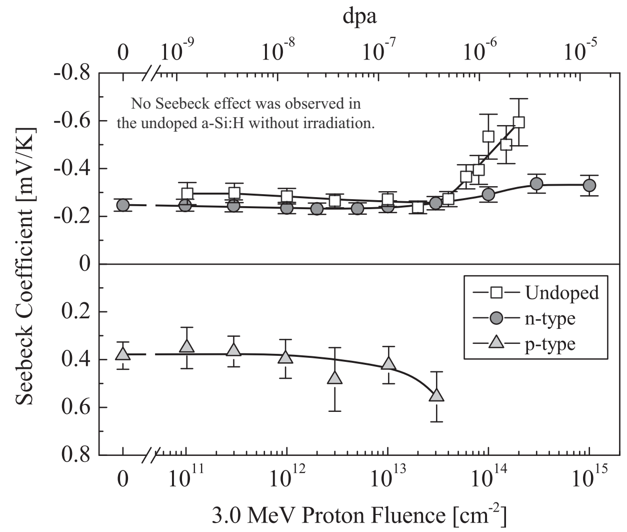

Fig. 1. Seebeck coefficient variations of a-Si:H due to 3.0 MeV proton irradiation. Open squares, shaded circles, and shaded triangles denote the results of undoped, n-type, and p-type a-Si:Hs, respectively. The abscissa axis in the upper part is converted from fluence to a unit of displacement per atom (dpa). Solid lines are to guide the eye.

Comparison between the electric conductivity and the Seebeck coefficient of the undoped a-Si:H irradiated with 3.0 MeV protons are shown in Fig. 2. The electric conductivity drastically increased with increasing fluence and reached 1.5×10^{-5} S/cm at the fluence of 5.0×10^{12} cm^{-2} (6.2×10^{-8} dpa), and after that decreased with further irradiation. However, the electric conductivity even at the fluence of 1.0×10^{14} cm^{-2} (1.2×10^{-6} dpa) was around two hundred times higher than that before irradiation. As shown in Fig. 2, the Seebeck effect was observed in the fluence regime where the electric conductivity was enhanced. The electric conductivity decreased and the absolute value of Seebeck coefficient increased at above 10^{13} cm^{-2} (1.2×10^{-7} dpa). The drastic increase in electric conductivity at the fluence of around 5×10^{12} cm^{-2} was not caused by a charging effect of protons in the sample. The conductivity variation of a dummy sample (glass substrate with

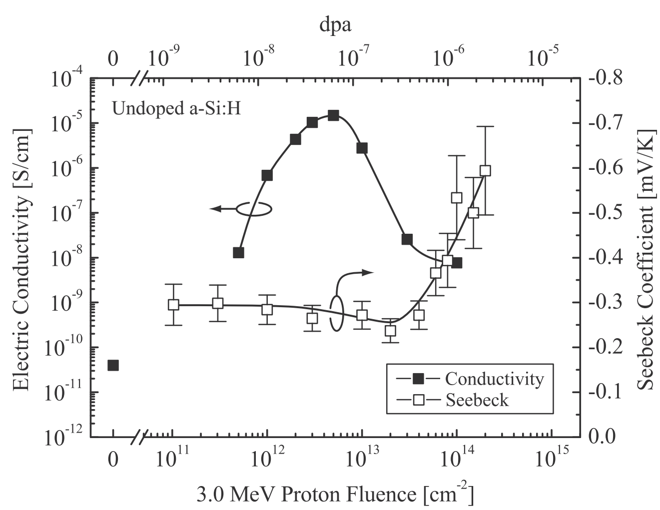

Fig. 2. Variations of electric conductivity (closed squares) and Seebeck coefficient (open squares) of undoped a-Si:H due to 3.0 MeV proton irradiation. Error bars on the data of electric conductivity are not shown since these are sufficiently smaller than the displaying symbol size. The abscissa axis in the upper part is converted from fluence to dpa. Solid lines are to guide the eye. The same is true in Figs. 3–6.