Abstract  Immediately after the GeV-implantation of $^{57}$Mn nuclei produced by the RIKEN-RIBF facility, $^{57}$Mn/$^{57}$Fe Mössbauer spectra in Si-solar cells are measured under light illumination. Comparing with the spectrum of p-type multi-crystalline-Si, the broad spectra of the solar cell under operation can be analyzed as a superposition of interstitial and substitutional Fe components with different charge states. The charge states of Fe impurities are created by the excess carrier injection followed by a directional carrier flow in the p-n junction. The present results provide us a possibility to clarify the carrier trapping process at the Fe impurities in Si-solar cells.

Keywords  $^{57}$Mn/$^{57}$Fe implantation Mössbauer spectroscopy · Si solar cell · Fe impurity · Carrier trapping · Energy conversion efficiency

1 Introduction

Iron impurities in Si have been intensively investigated for more than 50 years by different experimental techniques [1] including $^{57}$Fe Mössbauer spectroscopy [2–9], because Fe impurities can be easily incorporated into the Si matrix during...
the processes, and even an extremely low Fe concentration of $10^{11}/\text{cm}^3$ can degrade seriously the electronic properties of silicon-based devices and solar cells. This is due to the deep levels formed in the Si band gap, producing strong trapping centres for the carriers in the devices.Interstitial Fe$_i$ is well known to form an acceptor level at 0.39 eV from the valence band edge, while substitutional Fe$_s$ is expected to form a donor level of 0.69 eV from the first principle calculation [10]. Although interstitial and substitutional Fe appeared as spectral components in $^{57}$Fe Mössbauer experiments [2–9], the charge states could not be identified in terms of different isomer shifts of Mössbauer spectrum experimentally in comparison with the values calculated theoretically.

The present investigation is carried out to observe directly the charge states of Fe atoms in multi-crystalline Si solar cells under light illumination, which will shift the Fermi level by injecting excess carriers, and consequently the different charge states of interstitial and substitutional Fe are expected to appear in the spectrum. In order to study Fe impurities existing inside of a Si solar cell, however, we have to realize a well isolated $^{57}$Fe probe with an extremely low concentration, and the probes must be introduced into a region where the carrier trapping processes are occurring during solar cell operation, i.e. light illumination. At the RI-beam facility in RIKEN we have been developing a novel technique of projectile fragmentation combined with $^{57}$Mn/$^{57}$Fe implantation Mössbauer spectroscopy. The probes are deeply implanted into mc-Si solar cell, and Mössbauer spectra can be measured under operation immediately after each implantation of $^{57}$Mn. This is possible because of the extremely high implantation energy of GeV, providing an implantation depth of 100 μm with a stragglng of 50 μm.

In the present paper the first Mössbauer spectra of $^{57}$Fe in mc-Si solar cell are reported in different conditions for excess carrier injection and subsequent carrier flow by light illumination. The results are compared with the spectrum measured in the same p-type mc-Si wafer.

2 Experimental procedure

Radioactive isotopes of $^{57}$Mn ($\tau_{1/2} = 1.45 \text{ m}$) were produced by the nuclear projectile fragmentation of $^{58}$Fe$^{21+}$ primary beam ($E = 63 \text{ MeV/nucleon}$) with a Be target, and were subsequently separated as a secondary beam by an on-line isotope separator, RIPS at the RIKEN RI-beam facility. Mössbauer spectra of $^{57}$Mn/$^{57}$Fe in p-type multi-crystalline-Si as well as in Si-solar cells were measured at 300 K and 400 K under Xe lamp illumination immediately after the implantation of $^{57}$Mn with energy of GeV. The implantation was performed through an aluminum foil degrader with a thickness of 200 μm, so that the $^{57}$Mn probes stopped at approximately 100 μm from the surface of the sample. The total fluence of $^{57}$Mn was $2 \times 10^{12}$ $^{57}$Mn/cm$^2$ typically for one spectrum, requiring a measurement time for 4 h per spectrum.

3 Results and discussions

The mc-Si solar cell is covered with Ag electrode lines and a Si-N layer on the top, and Ag electrode layer at the bottom. The $^{57}$Mn implantation was performed through