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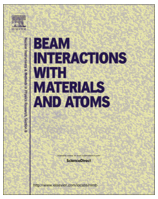

Improvement of depth resolution and detection efficiency by control of secondary-electrons in single-event three-dimensional time-of-flight Rutherford backscattering spectrometry

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ABSTRACT

An improvement of a depth resolution and a detection efficiency in single-event three-dimensional time-of-flight (TOF) Rutherford backscattering spectrometry (RBS) is discussed on both simulation and experiment by control of secondary electron trajectories using sample bias voltage. The secondary electron, used for a start signal in single-event TOF-RBS, flies more directly to a secondary electron detector with the positive sample bias voltage of several tens of volt than that without sample bias voltage in the simulation. The simulated collection efficiency of the secondary electrons also increases with the positive sample bias voltage of several tens of volt. These simulation results indicate the possibility of a smaller depth resolution and a shorter measurement time in single-event TOF-RBS with positive sample bias voltage. The measurement time for the Pt-stripe sample using single-event three-dimensional TOF-RBS with the sample bias voltage of +100 V is 65% shorter than that without sample bias voltage, resulting in a less sample damage by a probe beam. The depth resolution for the Pt stripes under the 50-nm-thick SiO_2 cover-layer with the sample bias voltage of +100 V is 4 nm smaller than that without sample bias voltage. Positive sample bias voltage improves the depth resolution and the detection efficiency in single-event three-dimensional TOF-RBS without an influence on the beam focusing.

1. Introduction

Three-dimensional nano-structures are easily fabricated by electron beam and ion beam induced deposition and etching [1–4]. Buried three-dimensional nano-structures are used in recent and future very large scale integrations (VLSIs), such as metal oxide semiconductor field effect transistors (MOSFETs), interconnects, and via metals [5]. One can analyze a small structure using a destructive technique such as secondary ion mass spectroscopy (SIMS) and atom probe microscopy (APM). However, most of the techniques require a layer removal technique such as sputtering or a special sample preparation [6–8]. A non-destructive analysis technique is required with a shorter measurement time for such a nano-structure. Ion beam analyses (IBAs) based on an elastic scattering, such as Rutherford backscattering spectrometry (RBS) [9–13], medium energy ion scattering (MEIS) [14–16], and elastic recoil detection analysis (ERDA) [9], are the most promising techniques for non-destructive three-dimensional analysis. Some research groups reported the channeling like and the shadow effects in non-destructive three-dimensional analysis using IBA techniques [9–12,14–16]. Dr. R. Huszank et al. reported a non-destructive micro-structure analysis using micro-ERDA, micro-RBS and micro-particle induced X-ray emission (PIXE) techniques with focused ion beam of $1.5 \times 1.5\ \mu m^2$ spot size [13]. In our recent studies, non-destructive analysis techniques for three-dimensional micro-structures using RBS [17] and time-of-flight (TOF) RBS with a start signal from a high speed pulse generator [18–22] were developed with a medium energy focused beryllium beam. The non-destructive analysis technique for three-dimensional nano-structures using single-event TOF-RBS has also been developed [23–26] with a spatial resolution of less than 10 nm. For short time analysis, a secondary electron, emitted by ion incidence to a sample target, was used for a start signal in single-event three-dimensional TOF-RBS. The fluctuation of the secondary-electron trajectories affects the time resolution in single-event three-dimensional TOF-RBS [24]. When a stop signal is detected without a start signal, the stop signal is uncounted to the TOF-RBS data, giving rise to the prolonged measuring time. The time resolution, i.e., depth resolution, and the measurement time should be

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improved by suppression of the fluctuation of the secondary-electron trajectories and by the increase of the collection efficiency of the secondary electrons, respectively.

In this study, the control of the secondary-electron trajectories and the collection efficiency of the secondary electrons using sample bias voltage was discussed on both simulation and experiment for improvement of the time resolution and for realization of the shorter measurement time in single-event three-dimensional TOF-RBS.

2. Experimental conditions

Be ions from a 150 kV focused ion beam (FIB) column were used in single-event three-dimensional TOF-RBS. The typical beam current and the minimum spot size of 150 keV Be^+ were 0.2–3 pA and 10 nm, respectively. The FIB system was described in details elsewhere [23,24]. The start signal in single-event TOF-RBS was a secondary electron emitted from the sample target by an ion incidence. The emitted electron was detected by a secondary electron detector (SED) located at the scattering angle of 100°. The diameter, the decay time and the applied voltage of the scintillator in the SED were 15 mm, 2.3 ns and 10 kV, respectively. The distance from the beam incident position on the sample target to the scintillator of the SED was 69.5 mm. A full width at half maximum (FWHM) of the output signal from the photo multiplier tube (PMT) was 3.5 ns. The outer shield of the scintillator was removed for suppression of the fluctuation of the secondary electron trajectories [24]. The stop signal was a backscattered ion detected by four micro channel plates (MCPs) with the diameter, the flight length, the scattering angle, and the applied voltage of 42 mm, 140 mm, 125° and −1.6 kV, respectively. The probe beam was scanned over the sample target with steps of 10 nm–1 μm. The total dose for each pixel was controlled with the counts of secondary electrons detected at the SED.

2.1. Simulation of secondary-electron trajectory

The electric field and the secondary-electron trajectories in a vacuum chamber were calculated by an original program using a boundary element method. In the simulation, the secondary-electron position and the velocity were calculated by solving the Newton equation at every 0.1 mm steps. Fig. 1 shows the alignments of the SED, the MCPs, the bottom part of the FIB column and the sample target used in the simulation, which structures were the same as those used in the experiment. The structures and alignments of the other detectors and the goniometers were not included in the simulation since a real vacuum chamber was very complicated. However, the tendency of the secondary electron behavior can be discussed with the simulation results. The applied voltages for the SED and the MCPs were the same as those used in the experiment. The sample bias voltages applied in the simulation were ranging from −200 to 200 V. The secondary electrons started from the center of the sample target with the size of 2.0 × 2.0 cm^2. The number of the simulated secondary electrons was 20,000. The initial angles of each secondary electron were randomly selected within all directions. The initial energies of each secondary electron had a Poisson distribution with a peak energy of 5 eV [27]. The collection efficiency, which was the ratio of the number of the detected electrons by the SED to those of the emitted electrons from the sample target, was calculated in the simulation.

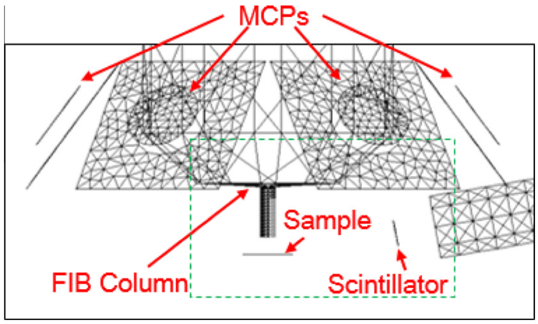
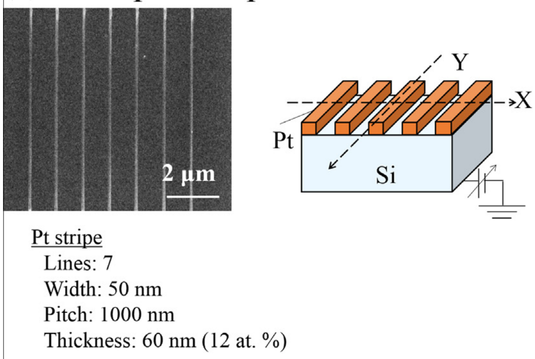


Fig. 1. Alignment of the SED, the MCPs, the bottom part of the FIB column, and the sample target used in the simulation of the secondary electron trajectories. The applied voltages of the scintillator and the MCPs were 10 and −1.6 kV, respectively. The FIB column was grounded. The green dashed line indicates the region used in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Experiment of single-event three-dimensional TOF-RBS

After the simulation, simple standard samples of Pt stripes with (Fig. 2(b)) and without (Fig. 2(a)) a SiO_2 cover-layer on a phosphor doped *n*-Si substrate were measured by single-event three-dimensional TOF-RBS and their results were compared each other for evaluation of the depth resolution and the measurement time. The resistivity and the thickness of the *n*-Si substrate were 3.28–4.94 Ω cm and 525 μm, respectively. The Pt stripes and the SiO_2 cover-layer were fabricated by electron beam induced deposition. The width and the pitch of the Pt stripes were 50 and 1500 nm, respectively. The thicknesses of the Pt stripes were 100 and 60 nm with and without the SiO_2 cover-layer, respectively, with the Pt concentration of 12 at% which was determined using energy dispersive X-ray spectroscopy (EDX). The apparent and effective

(a) Pt stripes sample



(b) SiO_2/Pt stripes sample

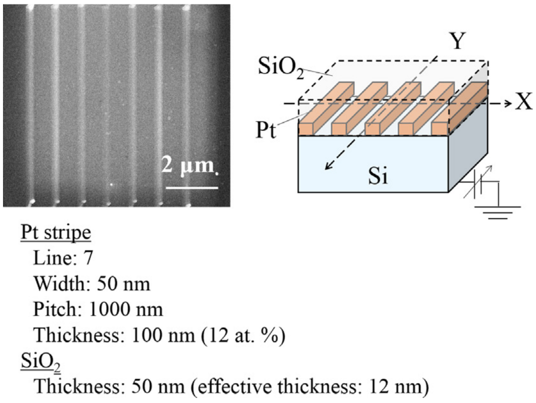


Fig. 2. Scanning electron microscopy images and schematic diagrams of the Pt-stripe samples (a) without the SiO_2 cover-layer and (b) with the SiO_2 cover-layer.