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Comparison of secondary electron emission in helium ion microscope with gallium ion and electron microscopes

K. Ohya [a,*], T. Yamanaka [a], K. Inai [b], T. Ishitani [c]

[a] Institute of Technology and Science, The University of Tokushima, Tokushima 770-8506, Japan
[b] Graduate School of Advance Technology and Science, The University of Tokushima, Tokushima 770-8506, Japan
[c] Research and Development Div., Hitachi High-Technologies Co., 882 Ichige, Hitchinaka, Ibaraki 312-8504, Japan

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ABSTRACT

To evaluate secondary electron (SE) image characteristics in helium ion microscope, Si surfaces with a rod and step structures is scanned by 30 keV He and Ga ion beams and 1 keV electron beam. The topographic sensitivity of He ions is in principle higher than that for scanning electron microscope (SEM) because of the stronger dependency of SE yield versus incident angle for He ions. As shrinking to sub nm patterns, the pseudo-images constructed from line profile of SE intensity by the electron beam lose their sharpness, however, the images for the He and Ga ion beams keep clearness due to darkening the bottom corners of the pattern. Here, the sputter erosion for Ga ions must be considered. Furthermore, trajectories of emitted SEs are simulated for a rectangular Al surface scanned by the beams to study voltage contrast, where positive and negative voltages are applied to the small area of the sample. Both less high energy component in the energy distribution of SEs and dominant contribution of direct SE excitation by a projectile He ion keep a high voltage contrast down to a sub nm sized area positively biased against the zero-potential surroundings.

1. Introduction

Scanning electron microscope (SEM) is used extensively in the semiconductor industry for various applications, including imaging of defects, mask inspection, device metrology and device failure analysis. As their dimensions shrink and the integration schemes grow in complexity, the use of inline SEMs may have limitations moving into sub nm scale patterns due to their spatial resolution and unwilling specimen interaction effects (e.g. surface charging and surface contamination). The interaction of a relatively low-energy He ion in the range of tens of keV with the specimen is mainly confined to the surface of the material. The He ion interaction generates no high energy backscattered electrons, resulting in greater secondary electron (SE) image fidelity as compared to electron beams. Therefore, a scanning ion microscope (SIM) using helium (He) beam might be a new option for such industry applications [1]. Furthermore, the low mass of the He ion does not cause any discernable sample damage or sputtering as opposed to gallium (Ga) ions.

Although the SE excitation mechanism in the He-SIM is similar to that in the SEM, there are differences between the SIM and SEM, which are closely related to resolution and image fidelity, such as the image contrast in specimen material, surface topography, applied voltage, and so on [2,3]. Therefore, an understanding of the mechanisms and modeling of the image formation and its comparison with the SEM images are a key issue for device applications [4]. Recently [5], we performed a Monte Carlo simulation of SE emission from 18 species of metals with atomic numbers of 4–79 by the impact of 10–50 keV He ions. It revealed that the SE excitation volume was narrower for the He ions than for 30 keV Ga ions and 1 keV electrons so that the spatial image resolution in SIM using zero-diameter He beams is prospected to be better than others. In the present study, we focus our attention to the image fidelity, i.e. the topographic contrast of SE images in the He-SIM, the differences from and similarities to the SEM and Ga-SIM, and the voltage contrast. In semiconductor fabrications, especially, the topographic contrast is important for device metrology, such as critical dimension (CD) SEM, whereas the voltage contrast is dominantly used for device failure analysis.

2. Simulation models

2.1. Ion-induced and electron-induced secondary electron emission

When ions bombard a metal surface, SEs are emitted generally by two processes of potential emission and kinetic emission. For

* Corresponding author. Tel./fax: +81 88 656 7444.
E-mail address: ohya@ee.tokushima-u.ac.jp (K. Ohya).

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singly charged ions with the energies of tens of keV or more, the kinetic emission dominates the process, which is very similar to SE emission due to electron impact. In the kinetic emission, SEs are excited not only by kinetic energy of an impinging ion but also of material atoms recoiled by the ion. An electron cascade process initiated by the excited SEs produces additional SEs in the material. The SEs are transported to the surface and a small part of the SEs escapes into the vacuum through a surface potential barrier, conventionally, $E_F + \Phi$; where E_F is the Fermi energy and Φ is the work function of the metal. These processes are simulated using a Monte Carlo technique with given mean free paths for elastic and inelastic collisions of moving particles in the material. For the inelastic collision, the simulation calculation treats only individual excitation of conduction electrons by use of partial wave expansion technique for scattering of the electron by the ion (or recoiled atom) at rest, due to their slow velocity v ($v \ll v_0$, v_0: the Bohr velocity) where both the plasmon and inner-shell excitations are much less contributed [6]. For individual and collective (plasmon) excitations by SEs are treated by using an optical-data model [7]. The advantage of this model is that it includes complicated processes of inter-band, intra-band and some other transition mechanisms automatically along with the experimental complex dielectric constants. The electron cascade simulation is also applied for electron–induced SE emission. The details of the model were presented in previous papers [8,9].

For understanding the differences of the SE image contrast in He-SIM from that in SEM (also Ga-SIM), a specimen surface is scanned by the beam and the SEs generated at each point of the surface are sampled, so that the line profile of the SE intensity is calculated as a function of the scanning beam position. Aluminum (Al) and silicon (Si) are chosen as specimen materials and zero-sized beams of 30 keV He ions, 30 keV Ga ions, and 10 keV and 1 keV (low-energy) electrons are considered in the simulations. Recently, in order to reduce the SE component produced by backscattered electrons, which lowers spatial resolution in SEM, the use of low-energy electron beams with the energy of 1 keV or less are tried for the semiconductor industry applications, such as CD-SEM.

2.2. Topographic contrast

Two types of surface topographies, which were used for a previous study on Ga-SIM [10], are modeled here as shown in Fig. 1(a). One is a rod with semicircular cross-section with different diameters of 1 μm and 10 nm, placed on a perfectly flat surface. The other is a step in the substrate with different heights of 1 μm and 10 nm and wall angle of 1° from the vertical. The former is employed to study the differences in the incident angle dependence of the SE yield between SIM and SEM, whereas the latter is employed to discuss the differences in the edge contrast which is important in the critical dimension (CD) analysis in device metrology as observed in the conventional CD-SEM [11]. The calculation takes re-entrances of re-emitted (or backscattered) primaries and SEs into account. Furthermore, the pseudo-SE-images in 255 gray levels are constructed from a line profile of SE yields normalized by using the yield of an infinite flat surface. In this simulation, the image intensities are not biased to make interpretation of the SE images simple. Since SEs emitted in the vacuum are collected by a relatively large solid angle detector in usual SEMs, all SEs, excluding the re-entered SEs, are accounted for the images without energy filtering.

2.3. Voltage contrast

For the voltage contrast in the SE images, a cubic volume above part of a specimen surface with the side from 1 μm to 10 nm is the simulation volume as shown in Fig. 1(b). The specimen surface is divided into 20×20 segments and a constant voltage of +10 V or −10 V is applied only to 7×7 segments in the center region. For simplicity, both the biased area and the surroundings are assumed to be the same material (in this study, aluminum) as each other. The calculation starts from the bombardment of a center position in each segment with an ion (or electron) beam. Then, after the calculation of the secondary electron emission described before, trajectories of emitted SEs are followed in the simulation volume. This sequence is performed at 20 segments along the dotted line in the figure. Trajectories of SEs emitted from the surface in the vacuum are influenced by an electric field distributed above the surface, which is created by the voltage localized in a small area on the bottom surface; the electric field bends the SE trajectories. If the applied voltage is positive, some SEs are drawn back to the surface and rebound on it. These SEs are unable to produce a tertiary emission and the net effect is a reduction of the SE yield. As a result, the net SE yield is changed with the beam-scanned position and the applied voltage. This is the voltage contrast mechanism in the SE image in both SIM and SEM.

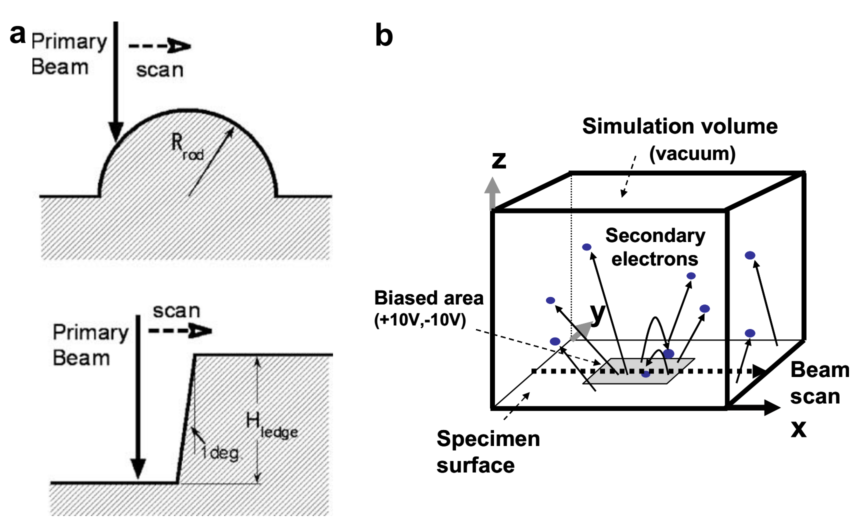

Fig. 1. (a) Models of semicircular rod and step structures for surface topography and (b) model for trajectory simulation of SEs emitted from a rectangular pattern with small area applied positive and negative voltages.