Microarea analysis using Auger electrons induced by gallium focused ion beam

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(Received October 12 1998; accepted January 18 1999)

Ion-induced Auger electron (IAE) spectra show different features from those of electron-induced Auger electron (EAE) spectra. Study on IAE emission from light elements, e.g. Al and Si, using a gallium focused ion beam (Ga FIB) has shown that discrete sharp Auger peaks (atomic-like peaks) with high yields can be observed. Since these atomic-like peaks have much higher signal-to-background (S/B) ratios compared with their corresponding EAE signals, elemental analysis with higher sensitivity can be realized using Ga FIB IAE spectroscopy (Ga FIB IAES).

Elemental mapping with Ga FIB has been achieved on an integrated circuit using an ion and electron dual focused beam apparatus developed by our group. elemental maps with high contrast and sub-μm lateral resolution have been achieved. Elemental mapping using Ga FIB IAE has been proved to be applicable to samples with poor electric conductivity. It has also been found that no Auger electrons can be detected from oxides (e.g., SiO_2). This chemical effect is quite different from the enhancement effect in secondary ion mass spectrometry (SIMS).

1. Introduction

It is known that inner-shell electron excitation occurs when energetic ions bombard on Mg, Al and Si targets. Some fractions of the excitations result in intense Auger emission. The ion-induced Auger electron (IAE) emission process is different from that of the conventional electron-induced Auger electron (EAE) emission. In EAE process, an electron beam with energy around a few keV is used to excite the inner shell electrons in direct Coulomb interaction. Ion-induced inner-shell electron excitations originate, however, from violent binary atomic collisions, where core electrons are promoted through crossing of quasi-molecular orbitals formed in a close encounter between projectile and target atoms or target atoms themselves [1]. The consequent decay results in IAE emission. Because of the significant momentum transfer during the ion-solid collisions, some of the excited particles are ejected during the sputtering process. The resulting decay outside the solid exhibits some features in the spectra (peak I, II and III in Fig. 1.). The main features of these atomic-like Auger peaks are narrow widths (typically a few eV) and high signal-to-background (S/B) ratios. Because of the short inelastic mean free path of these Auger electrons (1-8 Å between 20-100 eV), the atomic-like emission occurs in the outermost surface layer and has been shown to be sensitive to surface conditions [2]. So far, ion beams have been used for excitation sources in secondary ion mass spectrometry (SIMS), particle induced X-ray emission (PIXE), and etc. The characteristics on IAE spectra would provide us a new tool for surface analysis. However, most studies have aimed at investigating the mechanisms of core electron excitation and emission processes, although the applicability of IAE spectroscopy (IAES) as a tool for surface analysis have been evaluated on some specific substances [3-5].

Gallium focused ion beam (Ga FIB) technology has been developed rapidly in recently years. It can easily be focused to less than 0.1 μm in diameter with current density of a few A/cm^2. These advantages have been extensively utilized in cross-sectional sample preparation [6] for transmission electron microscopy(TEM) and scanning electron or ion microscopy (SEM or SIM), and in SIMS analysis with sub-μm spatial resolution. We have previously investigated the Ga-FIB-induced Auger electron (Ga FIB IAE) emission from Al and Si [7,8]. Intense IAE emissions were observed from Al and Si under Ga FIB bombardment. The narrow atomic-like peaks (around 5 eV) in the IAE spectra have high S/B ratios and their intensities increase linearly with the incident energy of Ga FIB (between 6-22 keV). It was also found that IAE intensity estimated from $d[E \times N(E)]/dE$ spectra decreases with increasing atomic number of target material.

The purpose of our study is to develop a new microanalysis method with sub-μm lateral resolution by combining the advantages of Ga FIB and Ga FIB IAE . In this paper, elemental mapping with Ga FIB on an integrated circuit (IC) surface is performed and applicability of Ga FIB IAES on sub-μm microanalysis is discussed.

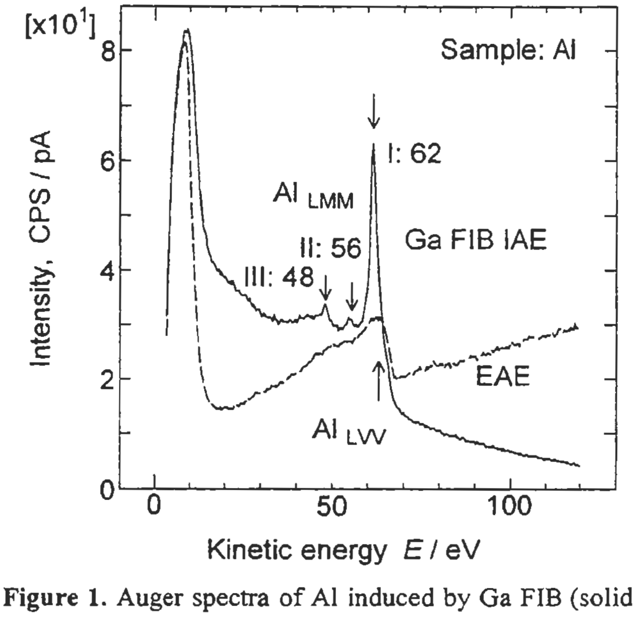

Figure 1. Auger spectra of Al induced by Ga FIB (solid line) and EB (dashed line). The incidence of the two beams are normal to the sample surface. Ga FIB: 20 keV, 1nA. EB: 4keV, 1nA.

2. Experimental

An ion and electron dual focused beam apparatus developed by our group was used in the experiment. Figure 2 shows the interior of the analytical chamber. Details on the apparatus can be found elsewhere [9]. The Ga FIB was accelerated at 20 keV. The beam current was 300 pA. The kinetic energy of the secondary electrons induced by Ga FIB was analyzed by a cylindrical mirror analyzer (CMA). The energy resolution of the CMA was set to 1.2%. The IAE intensity was recorded in pulse counting mode. A 64 Kbit EPROM was used for two dimensional IAE mapping. Since the atomic-like peaks of Si were not observed from protection layer (SiO_2) on the IC surface [7], the surface was pre-sputtered with the Ga FIB before the mapping to remove the SiO_2 layer. One area on the IC surface was further heavily bombarded to expose the Si substrate for mapping. Each secondary electron image was composed of 128×128 pixels and acquired for 301 s.

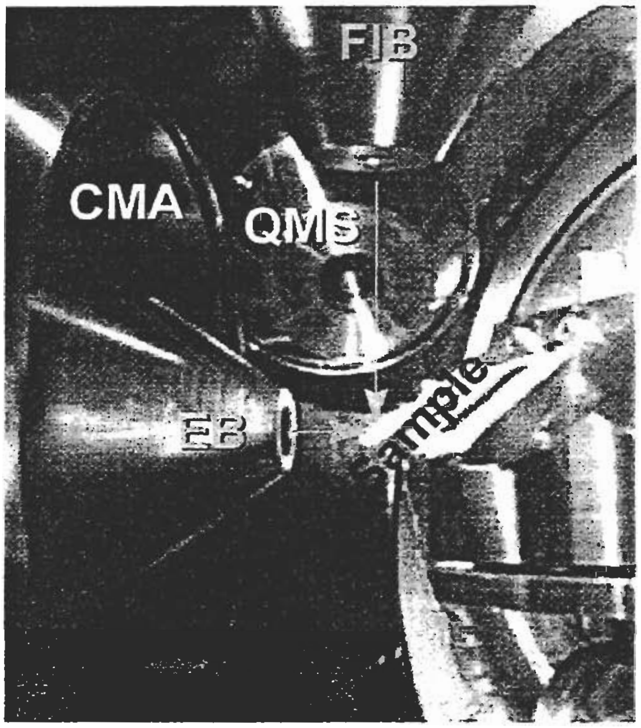

Figure 2. Geometry of the analytical chamber of the ion and electron dual focused beam apparatus.

3. Results and Discussion

Figure 3 shows the Ga-FIB-induced secondary electron image of the area on the IC surface where elemental mapping with Ga FIB IAE was performed. The center square was heavily bombarded with Ga FIB to expose the Si substrate (A in Fig. 3). Figure 4 is the IAE spectrum taken over the whole area shown in Fig. 3. The prominent atomic-like Al_{LMM} and Si_{LMM} peaks can be found at 62.6 eV and

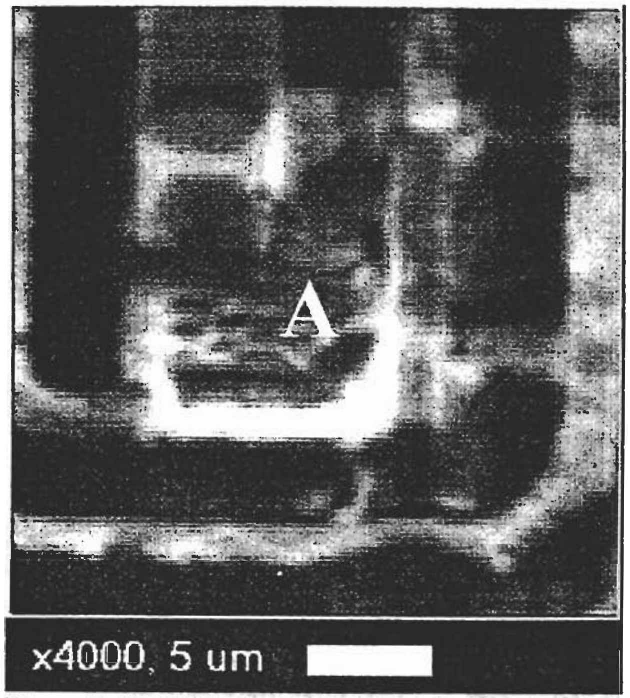

Figure 3. Ga-FIB-induced secondary electron image of the pre-sputtered area on an 64 Kbit EPROM surface, where the elemental mapping of Al and Si with Ga FIB IAE was performed.

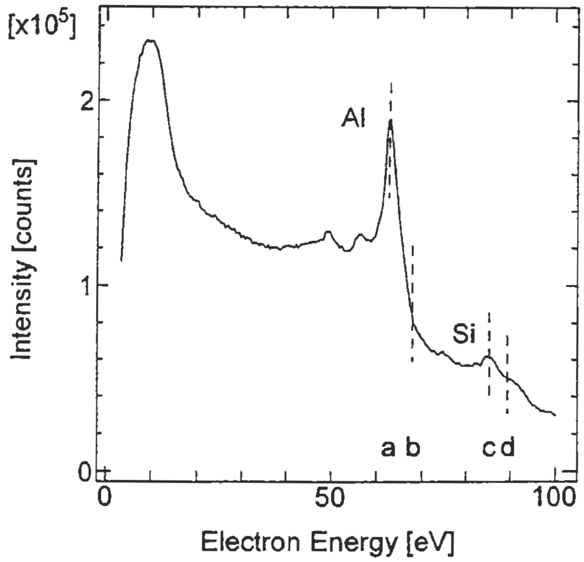

Figure 4. Ga FIB IAE spectrum over the pre-sputtered surface of an 64 Kbit EPROM shown in Fig. 3. Ga FIB: 20keV, 1nA.

85.1 eV, respectively. In order to obtain the $\mathrm{Al_{LMM}}$ map, two secondary electron images were taken at kinetic energies a and b indicated in Fig. 4, respectively. The $\mathrm{Al_{LMM}}$ map was extracted by subtraction of the two images. The $\mathrm{Si_{LMM}}$ map was obtained in the same way. As a result, each map required 602 s for acquisition.

Figure 5 shows the $\mathrm{Al_{LMM}}$ and $\mathrm{Si_{LMM}}$ maps. The maximum intensity in one pixel is 4372 counts in the $\mathrm{Al_{LMM}}$ map and 2116 counts in the $\mathrm{Si_{LMM}}$ map. By assuming there was no complementary elements (Al or Si) in the area, the background noise level was estimated from the pixel count at the dark area in both $\mathrm{Al_{LMM}}$ and $\mathrm{Si_{LMM}}$ maps. It was about 30 counts. These high contrast maps resulted from high S/B ratios of the prominent atomic-like $\mathrm{Al_{LMM}}$ and $\mathrm{Si_{LMM}}$ peaks. Figure 1 shows the Ga FIB IAE and EAE spectra ($\mathrm{Al_{LMM}}$ and $\mathrm{Al_{LVV}}$ lines, respectively). It can be seen that the maximum count rate of peak I is higher than that of $\mathrm{Al_{LVV}}$ peak and its S/B ratio is even much higher. As for other elements, it was reported that the intensity of atomic-like Auger emission decreases with increasing atomic number and the IAE yield for $\mathrm{Ti_{MNN}}$ is about half of that for $\mathrm{Si_{LMM}}$ [8]. It can be concluded that under the same experimental condition, the maximum intensity at a pixel for Ti will reach 1000 counts, which is still enough for elemental mapping. The maps showed that the lateral resolution was around 0.6 μm (16-84% definition). The beam current used in the experiment was 300 pA. However, Ga FIB can be easily focused to less than 0.1 μmϕ if the beam current is reduced to 60 pA. From the count rate in the maps, it is clear that elemental mapping with a 60 pA current, and therefore, even higher lateral resolution can be realized and sample consumption during the mapping can be decreased.

As mentioned above, the acquisition time for each elemental map was only 602 seconds. As a result, the consumption of the sample will not become a serious problem because of the very low dose needed in the IAE mapping (1.8×10^{17} ions/cm^2 in this experiment and can be further reduced with smaller beam current). During microarea mapping with EAE, however, longer acquisition time is required to obtain enough S/N ratio. Besides, charging-up often becomes a problem in EAE analysis of samples with little electric conductivity. However, it is found there was less influence from charging-up during the analysis using Ga FIB. When Ga$^+$ bombarded the sample surface, much less secondary electrons were produced through inelastic collisions.

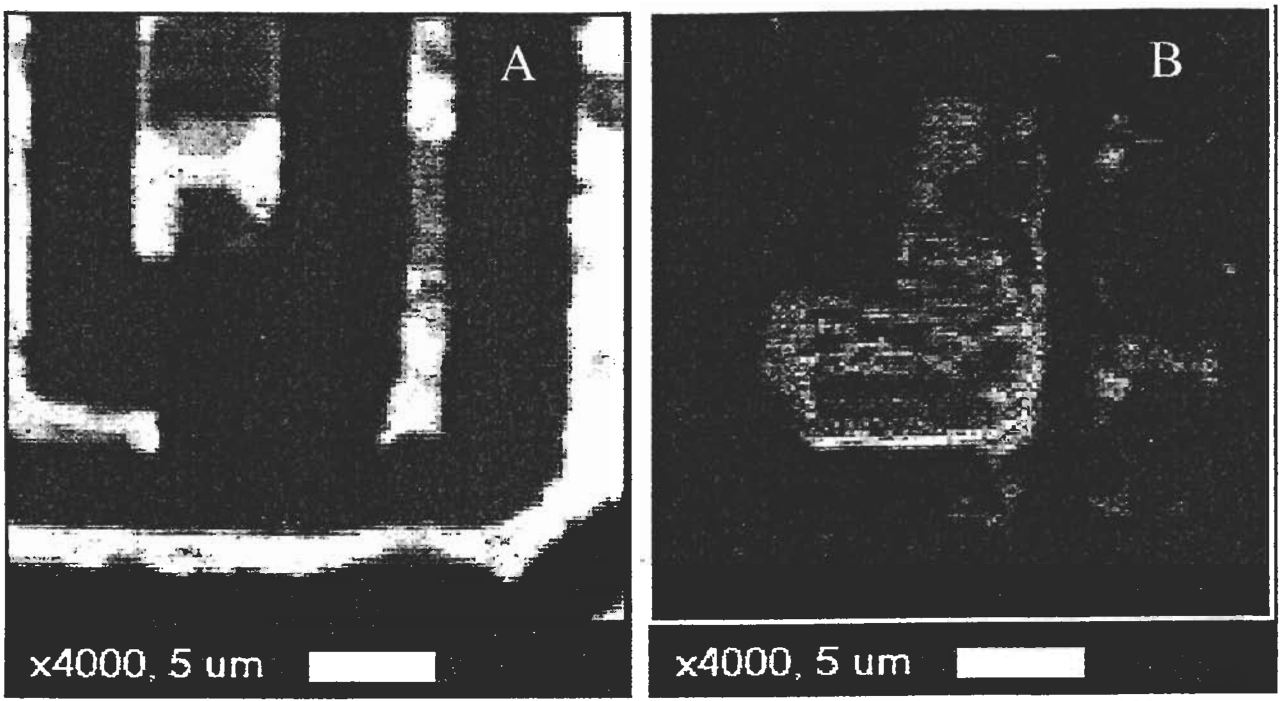

Figure 5. Al_{LMM}(A) and Si_{LMM}(B) maps of the surface area on the IC shown in Fig. 3. Ga FIB: 20keV, 300pA, Incidence angle: 45degrees from the surface normal.

Dark areas in both Al_{LMM} and Si_{LMM} maps are SiO_2 layer. It has been found no Ga-FIB-induced Si_{LMM} emission can be observed from SiO_2 [7]. This is at least one of the chemical effects, which is far different from the enhancement effect in SIMS for oxidized samples [10]. It is worth noting that the final states of the species corresponding to peak I's for Al and Si, for example, are singly charged ions, which are used in SIMS analysis. So Ga FIB IAES may provide a new way in studying the formation of secondary ions during ion bombardment.

Comparing with other major analysis methods, fundamental studies concerning the IAE processes are still necessary. For example, behavior of Ga FIB IAE emission from various elemental combinations, which determines quantification of the method, is worth studying.

4. Conclusions

Ga FIB IAES was applied to two dimensional elemental mapping on a 64 Kbit EPROM surface. Al_{LMM} and Si_{LMM} maps with high contrasts within 602 s, respectively, were achieved. Study on the elemental maps showed that Ti_{MNN} IAE electrons induced by Ga FIB will be used for elemental mapping with sub-μm lateral resolution.

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