Application of a Low Energy Ion Gun for High Resolution Depth Profiling

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A low energy ion gun of floating type, which provides primary ions of 50 to 500 eV with high current intensity of ~ 1 μA, has been applied for high resolution depth profiling with considerable success. Depth resolution measured with ISO reference material, GaAs / AlAs super lattice, has attained ~ 1.8 nm and ~ 2.2 nm, for Ar^+ ions of 150 and 300 eV, with sputter-etching rate ~ 1.3 nm/min and ~ 2.7 nm/min, respectively.

Altered layer formation on a GaAs-surface under low energy Ar^+ ion bombardment was discussed in conjunction with cross-sectional observation under transmission electron microscope (TEM), leading to very good agreement between the values of the ultimate resolution assessed from the depth profiling and TEM-observation.

INTRODUCTION

Shallow dopant depth profiling has been becoming one of key techniques for leading-edge semiconductor technology. Depth profiling has been commonly performed by surface analytical techniques, *i.e.* Auger electrons spectroscopy (AES), X-ray photoelectron spectroscopy (XPS) and secondary ion mass spectrometry (SIMS), combined with keV ion sputter-etching.

Sputter-etching with such high energy ions as a few keV causes atomic mixing extending over significantly broader surface region, resulting in the deterioration of depth resolution in the depth profiling. For achieving higher depth resolution, therefore, the use of lower energy ions has recently been approached in practice.

With respect to depth profiling by using the low energy ions, several studies have been already reported. Clegg[1] studied sputtering of silicon by the low energy oxygen ions. He reported the depth resolution of 1.5nm was attained for boron and carbon in silicon by 260 eV O_2^+ (130 eV O^-) ion irradiation, which was estimated from the measured value of the sputtering yield based on the modified Andersen's model[2, 3]. Dowsett et al.[4] also developed a floating type low energy ion gun (FLIG) which produced an ion beam of 0.2 to 1 keV at high ion current intensity and depth resolution of ~ 1nm was achieved for Si/Ge super lattice with 300 eV O_2^+ ion bombardment[5]. In most of these studies, however, the ion gun systems were too large to be attached to conventional surface analytical instruments and development of a more compact ion gun has been required.

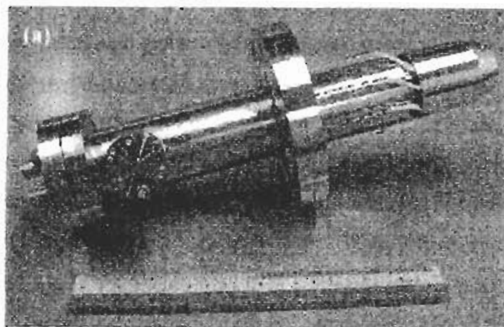
For this we developed a compact-type FLIG as reported in the previous paper[6]. This FLIG was so compactly constructed as ~30 cm long to be easily attached to conventional surface analytical instruments through an ICF 114 conflat frange, even through an ICF 70 conflat frange, if necessary, by slight modification. The Ar^+ ion current density of ~41 μA/cm² was ensured even at such a low energy of 100 eV at working distance 50 mm, enabling depth-profiling with very low energy ions to be performed in practical use.

This paper reports practical applications of the low energy ions for high resolution depth profiling of ISO-reference material, GaAs/AlAs super lattice, and for reduction of altered layer formed on a cross-sectional TEM sample surface.

FLOATING TYPE LOW ENERGY ION GUN

Figures 1(a) and (b) show a photograph and schematic illustration of the FLIG which consists of an ionization cell, extractor and cylindrical immersion lens. A tungsten filament of 0.125 mm ϕ is used for ionization of argon gas by electron bombardment. Reactive ions such as oxygen ions are also produced by replacing the tungsten filament to a rhenium filament[8]. The cylindrical permanent magnet made of Alinico-8 is attached to the ionization cell to increase the ionization efficiency[9 - 11]. An aperture of ionization cell is 1mm ϕ. The ions generated in the ionization cell are first extracted by the negative high voltage, V_{EXT}, at the extractor to ensure high efficiency of the extraction. Then, the ions are decelerated by the retarding field of the cylindrical immersion lens, in which voltages, V_{CL1} and V_{CL2} were supplied for focusing. All the electrodes are electrically floated by the acceleration voltage, V_A, from the ground.

To improve the efficiencies of the extraction and transportation of the primary ions, the lens system was designed so that the lens gap and the lens diameter were designed to be 2 and 18 mm, respectively, which are larger than those of 1 and 12 mm of the previous FLIG[7]. The FLIG was attached to a scanning Auger electron microprobe, JAMP-10(JEOL) through an ICF114 conflat flange. The base pressure in an analysis chamber of the JAMP-10 was ~ 1 x 10^{-7} Pa. The incident angle of ionbeam was 60° from the surface normal. The gas species was argon (4N). The electron bombardment voltage, V_B and current, I_B for ionization were fixed at 200 V and 10 mA, respectively. The voltage applied to the repeller electrode, V_R was set at -15 V. Gas pressure of the ionization cell was monitored by ion current detected with the repeller electrode to ensure the high stability of the ion beam.



(b)

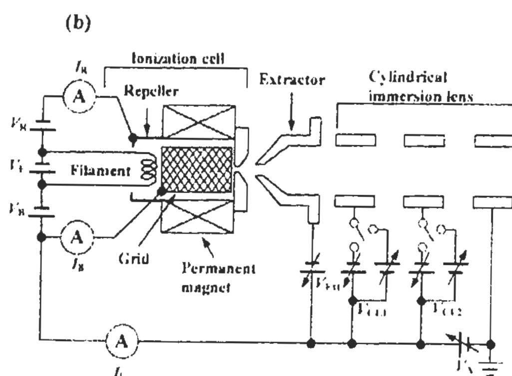


Fig.1. An outer view (a) and schematic diagram (b) of floating type low energy ion gun.

DEPTH PROFILING

ISO reference material of GaAs/AlAs super lattice[12], which consists of 4 multi-layers as shown in Table 1, was used as a test-specimen. Depth profiling of the reference material was performed with JAMP-10 by sputter-etching with 150 and 300 eV Ar^+ ions of specimen current intensities ~0.7 μA (150 eV) and ~0.8 μA (300 eV), respectively. Angle of incidence was 60° from surface normal and vacuum was kept remained at ~ 10^{-6} Pa during measurement.

The results are shown in Figs. 2 and 3, in which Al-LVV Auger signal is plotted as a function of sputter-etching time. The sputter-etching was performed by the fixed ion beam mode, not by the raster-scan mode as widely used, simply by the reason to examine the stability of ion beam irradiation over hours. Since the present ion gun is equipped with a deflection system for the raster scan, better depth resolution is, as a matter of course, expected by the use of raster scan. Sputter-etching rate is assessed from the average value of the thicknesses of four layers divided by sputtering time, according to Kajiwara and Kawai[17], as ~1.3 nm/min and ~2.7 nm/min for Ar^+ ions of 150 eV and 300 eV, respectively. These sputter-etching rates are quite high enough for performing the practical depth profiling.

Table.1. GaAs/AlAs super lattice reference material[13].

24.29 ± 0.40	1st Layer (GaAs)	*	(nm)
22.35 ± 0.20	2nd Layer (AlAs)	Certified	(nm)
23.07 ± 0.33	3rd Layer (GaAs)	Certified	(nm)
22.50 ± 0.29	4th Layer (AlAs)	Certified	(nm)

* for reference

Concerning the depth resolution, coarse assessment has led to ~1.8 nm (leading edge) and ~2.2 nm (trailing edge) for 150 eV, and to ~2.2 nm (leading edge) and ~2.5 nm (trailing edge) for 300 eV.

To assess the ultimate resolution of depth profiling with very low energy ions, direct observation under transmission electron microscope (TEM) was performed for the altered layer formed on GaAs-surface under low energy ion bombardment. The result is shown in Fig. 4[14]. Altered layer of ~1.4 nm thick or slightly less was formed on the GaAs surface by ion-etching with 200 eV Ar^+ ions impinging on the surface at angle of incidence 60°. Since the cross-sectioned specimen was once exposed to atmospheric pressure before setting in TEM, the altered layer under observation should get, much or less, influenced by the oxidation and contamination with hydrocarbon adsorption as often reported. However, it has been confirmed

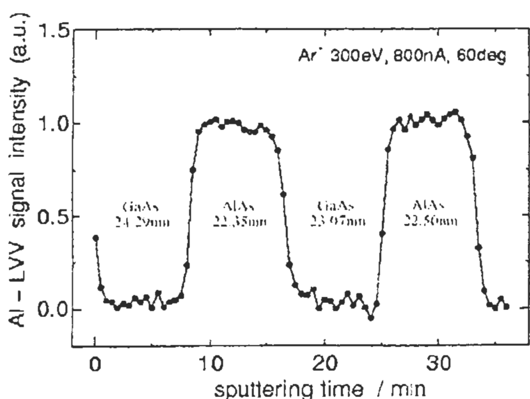


Fig.2. AES depth profile of GaAs/AlAs super lattice reference material. Ar^+ 300 eV with 0.8 μA at incident angle 60° and ~10^{-6} Pa.

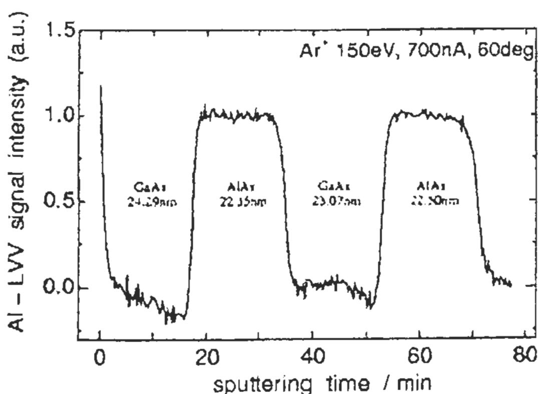


Fig.3. AES depth profile of GaAs/AlAs super lattice reference material. Ar^+150 eV with 0.7μA at incident angle 60° and ~10^{-6} Pa.

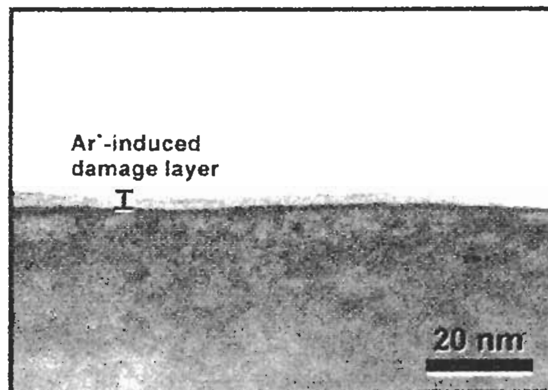


Fig.4. Altered layer formed on a GaAs surface under 200eV Ar^+ ion bombardment at incident angle 60° from surface[14].

that the major part of the altered layer consists of amorphous-like GaAs from electron diffraction pattern.

Taking into account the inelastic mean free path of Al-LVV Auger electrons in GaAs, which is coarsely estimated as ~0.5 nm[15], the ultimate depth resolution assessed from Figs. 2 and 3 agrees very well with that of Fig. 4, leading to the value of ~1.3 nm for 200 eV Ar^+ ions at angle of incidence 45° ~ 60° for GaAs.

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