Vacuum 110 (2014) 228–231

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Development of focused ion beam system attached to floating type low energy ion gun for surface finishing

Takaomi Matsutani [a,*], Tadahiro Kawasaki [b], Tetsuji Kodama [c], Masaki Hisaka [d], Yoshizo Takai [e], Takashi Ikuta [f]

[a] Department of Electric & Electronic Engineering, Kindai University, 3-4-1 Kowakae, Higashi-osaka, Osaka 577-8502, Japan
[b] Graduate School of Engineering, Nagoya Univiersity, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
[c] Department of Electrical & Electronic Engineering, Meijo University, 1-501 Shiogamaguchi, Tenhaku, Nagoya 468-8502, Japan
[d] Department of Biomedical Engineering, Osaka Electro-Communication University, 1130-7 Kiyotaki, Shijyonawate, Osaka 575-0063, Japan
[e] Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
[f] Department of Electronic Engineering, Osaka Electro-Communication University, 18-8 Hatsucho, Neyagawa, Osaka 572-8530, Japan

A R T I C L E I N F O

Article history:
Received 18 December 2013
Received in revised form
2 July 2014
Accepted 13 July 2014
Available online 19 July 2014

Keywords:
Low-energy ion gun
Electron impact ionization cell
Floating source
Retarding immersion lens
Focused ion beam
Damage removal

A B S T R A C T

Ion beams of several tens of keV are widely used for the analysis and materials processing, but the occurrence of damage to the surface is of concern. For surface treatment of the ion beam processed sample to remove the damaged layer, a floating-type low-energy ion gun (FLIG) producing 100–500 eV ions at a high current intensity has been developed. This ion gun consists of a permanent magnet-aided electron impact-type ionization cell, an extractor, and a cylindrical retarding immersion lens. The gun produced current intensities of order 1.81 μA (current density of 7.9 μA/cm^2) for 100 eV ions. The entire system has been compactly constructed with an ionization cell that has an outer diameter of less than 3.3 cm and a lens system that has a length of 24 cm. In addition, a focused ion beam (FIB) system attached to the FLIG has been developed to remove damaged layers formed by previous high energy etching. The thickness of the damaged layer induced on a GaAs (111) surface by 25 kV Ga^+ ions was of order 24 nm, assessed using a transmission electron microscope (TEM). This damaged layer was reduced to ~2.6 nm by subsequent bombardment by low energy 200 eV Ar^+ ions.

Published by Elsevier Ltd.

1. Introduction

The focused ion beam (FIB) technique has come into wide use as an effective tool for micromachining three-dimensional structures and for preparing cross-sectional specimens for observation under a transmission electron microscope (TEM) [1]. An advantage of using the FIB technique to fabricate TEM specimens is that preparation can be restricted to a specific selected area of sub-micron size for such analysis of a failed part in a semiconductor device. However, it is reported that bombardment by a high energy FIB induces the formation of a thick damaged layer on the specimen [2]. To reduce the thickness of the damaged layer, the use of incident ions of a lower energy has often been attempted [3,4]. Practically, sputter etching with lower energy ions requires a longer processing time because of the lower sputter rate. Therefore, development of a low energy ion gun that provides high ion current intensity to ensure a high ion etching rate is essential to reduce the thickness of the damaged surface layer.

This paper presents an FIB system attached to a floating-type low-energy ion gun (FLIG) system, which has been developed to remove an FIB-induced damaged layer from a specimen. Using this present system, the thinning and finishing processes of TEM specimen fabrication can be made without exposure to air. The one of the advantages offered by the use of this system compared with chemical etching is the suppression of impurities resulting from the chemical reaction. This system has enabled the thickness of damaged layers on GaAs surfaces to be reduced by one order of magnitude, thereby approaching the preparation of a damage-free specimen for TEM observation.

2. Experimental procedure

2.1. Development of FIB-FLIG apparatus

A schematic of the FIB-FLIG apparatus is shown Fig. 1. The FIB column consists of a Ga liquid metal ion source and two

* Corresponding author. Tel.: +81 6 6721 2332; fax: +81 6 6727 4301.
E-mail address: matutani@ele.kindai.ac.jp (T. Matsutani).

http://dx.doi.org/10.1016/j.vacuum.2014.07.020
0042-207X/Published by Elsevier Ltd.

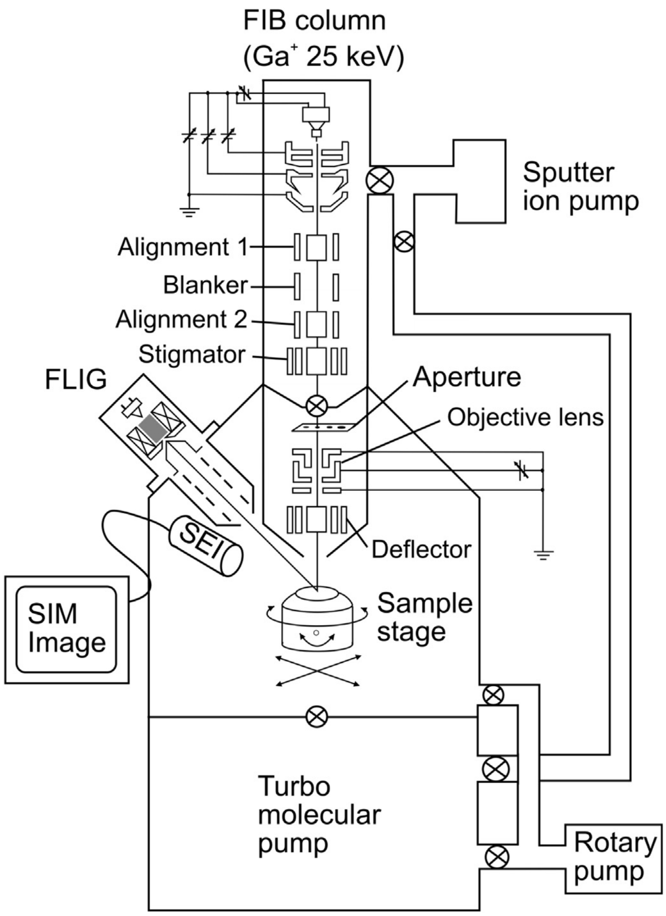

Fig. 1. Schematics of FIB-FLIG apparatus for TEM specimen fabrication.

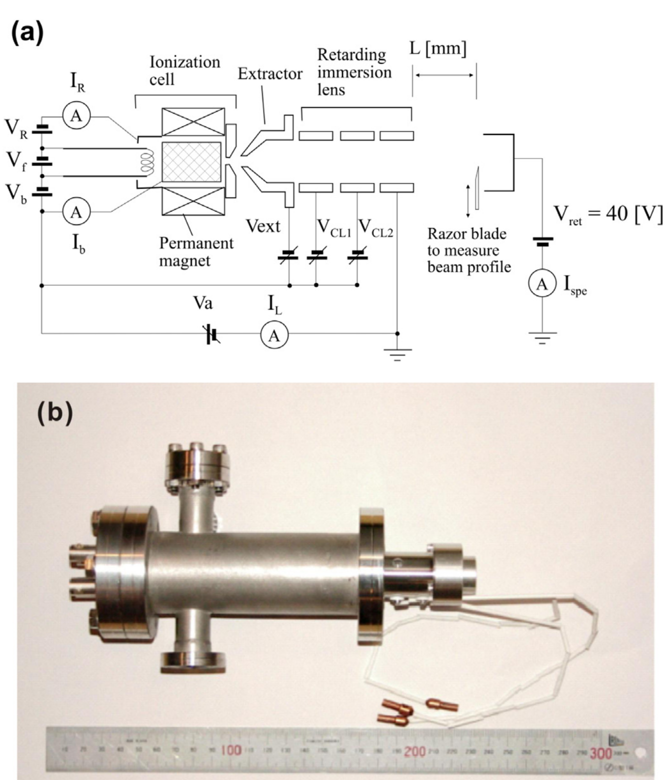

Fig. 2. Schematic of developed compact FLIG (a) and its outer view (b).

electrostatic lens systems. The details of the FIB system have already been described elsewhere [5].

The FLIG system consists of a permanent magnet aided electron impact type ionization cell, an extractor and a cylindrical retarding immersion lens system (Fig. 2(a)). The length of the ion gun is 24 cm. An Alnico-8 permanent magnet with an inner diameter of 12 mm, outer diameter of 26 mm, and a length of 24 mm was mounted in the ionization cell, increasing the ionization efficiency by two orders of magnitude in comparison with that for same ion gun without a permanent magnet. The magnetic field of the central axis is ~0.2 T, two times greater than that of an earlier device [6–8]. A rhenium-filament is used as the electron source to generate reactive ions (e.g., oxygen ions) for reactive ion etching. In this study, however, we simply used Ar for practical assessment of performance. As a means of obtaining a high beam current density at a low acceleration voltage, the ions generated in the cell are first extracted by an electrostatic potential ranging from −0.1 to −6 kV, then decelerated through the cylindrical immersion lenses. The entire system is so compact that it can easily be attached to conventional surface analytical instruments through an ICF-70 Conflat flange (Fig. 2(b)).

2.2. Surface treatment by sputter-etching using FIB-FLIG apparatus

To evaluate an effect of low energy ion etching, a GaAs-specimen was cleaved to form a tiny piece of triangular shape and this piece was mounted on an FIB/TEM specimen stage [5] and thinned using a 25 keV Ga^+ FIB as shown in Fig. 3. The thin-sectioned area was then sputter-etched with low energy Ar^+ ions to remove the FIB-induced damage layer. The finishing was performed at an incident angle of 30° to the sample surface. After the finishing process, the sample was transferred from the FIB-FLIG apparatus to a 200 kV TEM with exposure to the atmosphere and the edge part of the thin-sectioned area was observed from the side direction. The damaged layer formed on GaAs surface can be seen at the edge area in a profile view mode. All TEM photographs were taken at direct magnification of 4×10^5.

3. Results and discussion

3.1. Performance of FLIG apparatus

Fig. 4 shows the relationship between ion beam current, I_{spe}, and extraction voltage, V_{ext}, for acceleration voltages, V_a, ranging from 100 to 500 V. The maximum ion beam current at $V_a = 100–500$ V was found to be 1.81–1.91 μA at the optimized V_{ext}. Under these conditions, the load current, I_L, remained at about 2.20 μA. These results indicate that the ion gun enables ions generated in the ionization cell to be extracted to the specimen surface at high

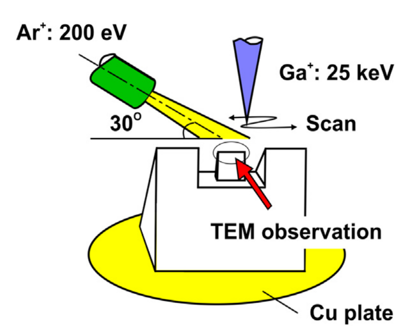

Fig. 3. Schematic illustration of FIB fabrication process and a finishing process with low energy ion beam for TEM specimen preparation.