Nuclear Instruments and Methods in Physics Research B 272 (2012) 206–209

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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

Roughening and smoothing behavior of single crystal Si by low energy Ar$^+$ ion bombardment

S.A. Pahlovy *, S.F. Mahmud, K. Yanagimoto, N. Aikawa, I. Miyamoto

Applied Electronics Department, Tokyo University of Science, Japan

ARTICLE INFO

Article history:
Available online 1 February 2011

Keywords:
Roughening
Smoothing
Si cleaved surface
Ion beam
Sputtering

ABSTRACT

We examined the dependence of smoothing or roughening behavior on the initial surface roughness of single crystal Si. An atomically flat cleaved Si surface of roughness 0.038 nm rms and a Si wafer substrate roughness of 0.12 nm rms were sputtered by 0.2–3 keV Ar$^+$ ion beam at normal ion incidence. Surface morphology was observed by atomic force microscope (AFM) under DFM mode. Result shows that the rough surface (R = 0.12 nm rms) becomes smooth (R = 0.068 nm rms) and the smooth surface (R = 0.038 nm rms) becomes rough (R = 0.068 nm rms) due to low energy Ar$^+$ ion beam sputtering process and both finally saturates at 0.068 nm rms. The saturated roughness R_{sat} depends on ion beam energy and increases with increasing beam energy. To understand the roughening mechanism, we studied the dynamic scaling theory and measured the roughness exponent α and growth exponent β. The values of α = 1.03 and β = 0.28 are in agreement with the Cuerno's one dimensional simulation of the Linear diffusion equation with noise, that corresponds to the initial stage of dynamic scaling of ion bombardment.

1. Introduction

Aspherical mirrors substrate for the projection optics in EUVL lithography are required for surface figure error of 0.20 nm rms or better [1–3]. Today, ion beam-based finishing technologies are well established for shape correction and figuring of high performance optics. Typically, during ion beam sputtering, the surface of solid is far from equilibrium and a variety of atomistic surface processes and mechanism become effective which is the complex interplay of these processes that either tends to roughen (e.g., either by curvature dependent sputtering) or smooth (e.g., by surface diffusion or viscous flow of surface atoms) the surface. Variations on this behavior can be observed depending on the sputtering conditions such as the temperature, ion flux, surface crystal orientation, ion incidence angle and surface initial condition [4]. In the BH model, the initial surface curvature induces the surface roughening. It is considered that the local sputter yield depends on the initial surface curvature so that regions at the tops of hills on the surface sputter more slowly than regions in the valleys. This dissimilar surface sputtering increase the rate of roughening with increasing surface roughness. Mayer et al. observed smooth surface morphology of diamond substrate by 20 keV Ga$^+$ ion beam at ion incidence angle of 40° [5]. Recently Frost et al. reported that Si substrate can be smoothened by low energy ion beam sputtering at incidence angle of 60° [6,7]. Datta et al. stated in his paper that surface can be smoothened if ion incidence angle is below critical angle [8]. A lot of researches have confirmed that ion incidence angle and initial surface conditions are important parameter which induces surface smoothing or roughening. However, there have been no complete reports to understand the smoothing or roughening behavior of an atomically ultra flat Si surface caused by ion beam sputtering. Therefore, we conducted our research to observe the roughening or smoothing behavior of sputtered ultra smooth Si cleaved substrate.

In this paper, we report an atomic force microscopy (AFM) study of surface morphology evaluation of atomically flat cleaved (roughness 0.038 nm rms) Si surface and Si wafer substrate sputtered by 0.2–3 keV Ar$^+$ ions at normal ion incidence. Finally, to understand the roughening or smoothing mechanism, we studied the dynamic scaling theory (DST). We measured the scaling exponents such as roughness exponent α and growth exponent β to characterize the eroding dynamics of the surface. Our measured result is in agreement with the Cuerno's one dimensional simulation of the Linear diffusion equation with noise.

2. Experimental detail

2.1. Sample preparation

The cleaved atomically flat and smooth plane of single crystal Si wafer was obtained by manually cutting vertically against orientation flat of a Si(1 0 0) wafer. The sample was prepared at room

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* Corresponding author. Tel.: +81 4 7124 1501; fax: +81 4 7122 1499.
E-mail address: pahlovy@te.noda.tus.ac.jp (S.A. Pahlovy).

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doi:10.1016/j.nimb.2011.01.066

temperature without pre-treatment and the dimension of the prepared sample was 8 × 0.70 mm.

2.2. Apparatus and procedure

The experiments were conducted in an ion beam machining apparatus with an electron cyclotron resonance (ECR) type ion source (ELIONIX Inc. EIS-200ER) in order to generate Ar^+ ion with beam energy less than 3 keV. During ion beam machining, the pressures of the plasma generation chamber was 1.2×10^{-2} Pa. The sample was bombarded by Ar^+ ion beam at normal ion incidence. Machining to different depths was accomplished by adjusting the current value and processing time using experimentally obtained sputter rate of the Si substrate. To evaluate the high spatial frequency roughness (HSFR) quantitatively, irradiated surfaces having an area of $1 \times 1\ \mu m^2$ were observed by atomic force microscope (AFM) (SII nanotechnology Inc., SPI3800N). To achieve the high accuracy while measuring the shape of the surface, 512 pixels were obtained by scanning the AFM probe at a line-scan rate of 1 Hz in the scanning direction of the surface [9]. For calculating HSFR, the noise was not eliminated from these images in order to precisely evaluate the surface shape in this report. The ion range was calculated to understand the thickness of amorphous layer by TRIM simulation software and the obtained value was 35 Å. Fig. 1 shows the schematic view of ECR type ion beam apparatus. As shown in Fig. 1, an aluminum made sample holder was specially designed (blunt edge) to minimize the aluminum atom deposition on Si cleaved surface. We observed the sputtered surface by SEM-EDX to check whether any Al atom was deposited on Si substrate. In our present case, we did not find Al atom on Si substrate. However, very little amount of Al atom might be deposited on Si surface during experiment which we could not control and could not trace by SEM-EDX.

Table 1
Dynamic scaling exponent's value for noise-induced roughening due to ion bombardment.

Scaling regime	Roughness exponent α	Growth exponent β
Linear diffusion $\partial h(r,t)/\partial t = -\kappa\nabla^4 h + \eta$	1.0	0.25
Edwards–Wilkinson $\partial h(r,t)/\partial t = \nu\nabla^2 h + \eta$	0	0
Kardar–Parisi–Zhang $\partial h(r,t)/\partial t = \nu\nabla^2 h + (\lambda/2)(\nabla h)^2 + \eta$	0.38	0.24
Kuramoto–Sivashinsky with noise $\partial h(r,t)/\partial t = -\nu\nabla^2 h - \kappa\nabla^4 h + (\lambda/2)(\nabla h)^2 + \eta$	0.38	0.24

3. Results and discussions

3.1. Results

A Si cleaved surface and a Si wafer were sputtered by Ar^+ ion beam and the sputtered surfaces at different machined depth were analyzed by AFM are shown in Fig. 2. As shown in Fig. 2a and b, a roughening behavior was observed due to ion beam sputtering therefore, the atomically flat cleaved Si surface with roughness of 0.038 nm rms becomes rough with roughness of 0.068 nm rms. The Height profiles are included in Fig. 2 to understand the morphology of the substrate.

Fig. 2c and d shows the AFM image of an un-sputtered rough Si substrate with roughness of 0.12 nm rms and a sputtered Si substrate with roughness of 0.68 nm rms. As shown in the figure, a smoothing behavior of Si wafer substrate caused by 500 eV Ar^+ ion bombardment is observed.

Fig. 3 shows the roughening and smoothing behavior of sputtered Si substrate by 500 eV Ar^+ ion beam at different machine depth. As shown in the figure, surface smoothing or roughening depends on the initial surface roughness. When the initial surface roughness is high, then the roughness decreases with increasing machine depth or ion doses and finally become saturated. On the other hand, when the surface roughness is very smooth ($R = 0.038$ nm rms), the surface roughness increases with increasing the machine depth or ion doses and finally become saturated. The saturated roughness for both cases are measured and obtained value is $R_{sat} = 0.068$ nm rms. We also observed the same tendency of curve with respect to R_{sat} for 1, 3 and 10 keV Ar^+ ion beam energy. In the second stage, we investigated the saturated roughness dependence on ion beam energy. Fig. 4 shows the saturated roughness (R_{sat}) dependence on ion beam energy at machine depth of 50 nm. As shown in the figure, the R_{sat} increases with increasing beam energy. To understand the phenomena, we calculated the ion range by SRIM simulation software and found that the range of ion at higher energy is higher than that of low energy ion. Therefore, the irradiation effect and damage increase with increasing the ion beam energy and the surface become rough. In the following section we will discuss the dynamic scaling theory to understand the roughening mechanism due to ion beam sputtering.

3.2. Discussion

The scaling behavior determine the morphology of growing surface and by studying scaling exponents one can learn the dominant processes involved. The roughness exponent α and growth exponent β can be determined by studying the height–height correlation function $[G(r,t)]$ or power spectral density (PSD) of the

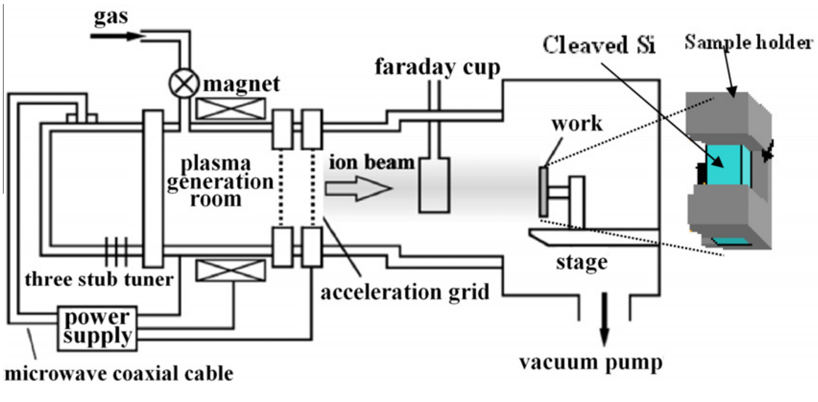

Fig. 1. Schematic view of ECR type ion beam apparatus.