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Ion Mass Dependence of Surface Planarization by Photoemission-Assisted Plasma Ion Source with He^+, Ar^+ and Kr^+

光電子制御プラズマイオンソースによる基板表面平坦化処理効果のイオン質量種依存性

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To investigate the ion mass dependence of surface planarization by photoemission-assisted (PA) Townsend plasma, Cu thin films deposited on the Si rare surface were irradiated by He, Ar, and Kr PA plasma, respectively. The value of root mean square of surface roughness measured by atomic force microscopy was decreased more than 43% by irradiation of Ar^+ ions but not by He^+ and Kr^+ ions. The mass of Ar^+ ions is the nearest from Cu atoms among three ions, therefore this result indicates the momentum transfer from ions to Cu atoms plays an important role in surface planarization

1. Introduction

The production of atomically smooth and uniform surface has attracted the interest of various research groups because of the critical applications in fabricating CMOS and optoelectronic devices [1, 2, 3]. Thus, surface planarization is of practical importance to these applications. To achieve the plane surface by dry and non-contact smoothing processes with energetic ion, some methods have been proposed such as fast atom beam (FAB) and gas cluster ion beam (GCIB). However, metal contaminates result from FAB irradiation of sample holder and chamber wall becomes critical problem and it is difficult to smooth a large structure or a wide curvature by GCIB.

To overcome these obstacles, we have developed a surface planarization process by means of a photoemission-assisted plasma ion source (PAP) [4-6]. In Ar^+-PAP processing, the UV light is used to irradiate a substrate surface, which is negatively biased, resulting photoelectrons emitted from the substrate surface and accelerated with applying a positive potential to the counter electrode. Such accelerated electrons play as a trigger role in generating DC discharge plasma of as gas over the UV-irradiated surface area, which can lead to generate uniform plasma above the surface. At the meantime, Ar^+ ions in the PAP impinge on the substrate surface after the acceleration. In our previous work, the surface planarization can be produced by Ar^+-PAP treatments on the mechanically grinded Al and Cu surfaces with an initial surface roughness in root mean square (RMS(0)) of a few hundred nanometers, has been reported [6, 7]. To achieve much smaller RMS roughness of metal surfaces, the planarization mechanism using PAP treatment must be clarified. In this study, in order to investigate the ion mass dependences for surface planarization, three kinds of noble gases, He (Z = 2), Ar (Z = 18) and Kr (Z = 36) was used for treating Cu-deposited Si substrate with initial RMS(0) of ~70 nm to clarify the surface flattening mechanism based on the interaction between impinging ion species and Cu atoms.

2. Experiments

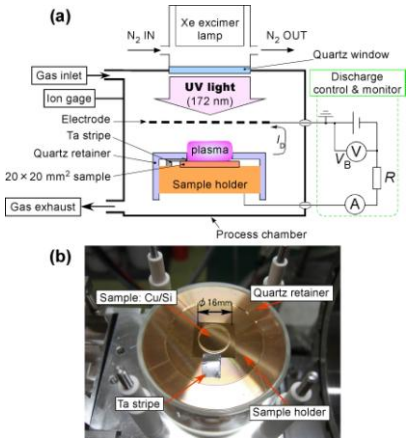

Fig.1(a) Schematic diagram of the PAP apparatus and (b) Photograph of a Cu(200 nm)/Si sample placed on the Cu sample holder with a quarts retainer, which restrains the treated area to 16 mm in diameter.

Figure 1(a) shows the photoemission-assisted plasma apparatus, which is composed of a process chamber, UV light source, two inch sample stage, DC plasma electrical circuit, gas exhaust and gas inlet lines. The UV light source was a Xe eximer lamp (UER20H-172A, USHIO) emitting 172 nm (7.2 eV) in wavelength.

Figure 1(b) shows the sample on the sample holder. The samples were prepared by rf magnetron

sputtering deposition of Cu thin film on a 2 inch Si rear surface (Cu (200 nm)/Si). The initial surface RMS(0) roughness is about ~70 nm, and cut size of substrate as 20×20 mm^2 were used for PAP irradiation. During irradiation, the sample was set at the sample holder and covered with a quartz retainer to restrict the UV-irradiated sample area.

Ar^+-, He^+-, and Kr^+-PA plasma was irradiated the samples. The plasma irradiation time dependences of the surface roughness were investigated. To compare the irradiation time with difference discharge conditions of each gases, the irradiation charge (irradiation time × discharge current) was employed. Discharge conditions are summarized in Table I. The kinetic energy of ions E_k is calculated obtained from ion sheath voltage and mean free path. The surface topography was measured by atomic force microscopy (NPX200 SII) with operating in contact mode in air.

Table I. Experimental designation and parameters used in the experiments.

Gas	Pressure (Pa)	Bias (V)	E_k (eV)
He	500	160	1.6
Ar	300	180	0.8
Kr	300	180	0.6

3. Results and discussion

Figure 2(a) shows the RMS surface roughness before and after irradiation (Ar^+-PAP irradiation). RMS before PAP irradiation (R_{bef}) is almost constant. On the other hand, RMS after irradiation (R_{aft}) decreases with increasing irradiation charge. To understand the RMS changes more clearly, changes ratio ((R_{bef}-R_{aft})/R_{bef}) was calculated. Figure 2(b) shows the dependence of changes of RMS surface roughness on the irradiation charge. According to E_k as shown in Table I and the momentum transfer effect, it was considered that Ar^+-PAP has more effective on the Cu substrate smoothing in this case. As shown in Fig. 2(b), the Ar^+-PAP irradiation had the maximum RMS surface roughness reduction 43% by ion irradiation of 1.7 C. It has no significant surface smoothing effect in the case of He^+-PAP irradiation whose mass (Z = 2) is lighter than Cu atom (Z = 29). In the case of Kr which is heavier than Cu, improvement of surface roughness reduction was not observed. From these results, it is found that the effective momentum transfer from ions to substrate atoms is important factor to reduce the surface roughness. On the other hand, the heavy mass ions are effective for sputtering the substrate using high kinetic energy ion radiation such as FAB. Therefore, surface planarization using PAP is achieved by not sputtering but surface migration of substrate atoms. From these results, it is concluded that the mass matching is most important for surface planarization using PA plasma with low kinetic energy of ions.

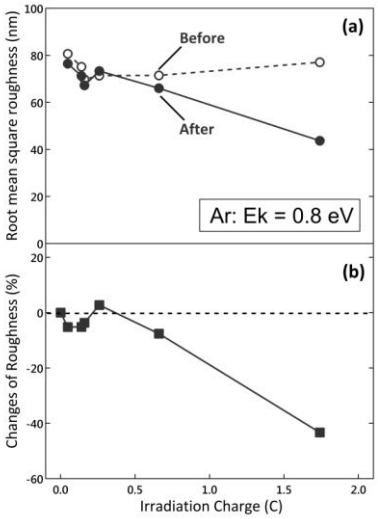

Fig.1(a) RMS surface roughness before and after plasma irradiation. (b) Irradiation charge dependence of changes of RMS surface roughness.

4. Conclusion

The surface planarization effects of He^+, Ar^+ and Kr^+ PAP process were comparatively investigated for the Cu-deposited Si substrates. The Cu surface RMS roughness was flattened by a maximum of -43% with the Ar^+-PAP, but no significant improvement of RMS were observed for both He^+ and Kr^+-PAP irradiation. The momentum transfer plays important role for surface planarization using PAP.

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