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Characterization of bonding interface prepared by room-temperature Si wafer direct bonding using the surface smoothing effect of a Ne fast atom beam

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ABSTRACT

We performed room-temperature Si wafer direct bonding by surface activation using a Ne fast atom beam (FAB). The bonding energy between Si wafers prepared by Ne FAB etching is equivalent to that of the bulk materials. We also investigated the surface smoothing effect by Ne FAB etching. A rough Si surface with a surface roughness of 0.40 nm rms was etched by Ne FAB, and its surface roughness was decreased down to 0.17 nm rms. For a Si surface etched at a depth of 30 nm by the Ne FAB, the 1D-PSD (1-dimensional power spectrum density) amplitude was decreased in the range of spatial frequencies >10 μm^{-1}. Although the Si wafers with surface roughness of 0.4 nm rms could not be bonded, they were successfully bonded after Ne FAB smoothing of etching depths over 5 nm, and a bonding energy equivalent to that of the bulk materials was attained. We succeeded in dramatically decreasing the local strain at the bonding interface by the Ne FAB smoothing effect.

1. Introduction

For applications such as high-density 3D integration of integrated circuits (ICs) and heterogeneous integration of micro-electro-mechanical systems (MEMS), wafer direct bonding is attractive and has been widely developed [1–7]. In conventional Si-wafer direct bonding, high-temperature annealing around 1100 °C is necessary in order to increase the bonding energy [8,9]. Therefore, applications of wafer direct bonding to micro-devices are limited since the annealing process involves thermal damage to sensitive devices. Moreover, MEMS devices or bonded substrates are distorted due to thermal expansion mismatch between heterogeneous materials. Therefore, several surface treatments have been introduced to achieve strong bonding at lower temperatures. Plasma activation enables a strong bond formation with annealing [10–15]. The best way to package such sensitive devices is room-temperature bonding without any heat treatments [16–19]. Therefore, we have developed surface-activated room-temperature wafer direct bonding. In this method, the surfaces of the specimens are activated by creating dangling bonds by the removal of surface impurity layers using an accelerated inert gas beam in a vacuum. When the activated surfaces are brought into contact with each other, inter-atomic bonds are formed at the bonding interface at room temperature. In this bonding process, not only clean but also atomically smooth surfaces are required to achieve practical bonding strength, i.e., an increase of the surface roughness degrades the bonding quality due to microscopic non-intimate contact at the bonding interface [19]. Therefore the surface roughness is a critical factor in this surface-activated room-temperature wafer bonding process.

An Ar fast atom beam (FAB) as an accelerated inert gas beam has been widely used for surface activation in room-temperature bonding. However, the long-time Ar etching roughens the surface and decreases the bonding strength [19]. In the fabrication of MEMS or ICs, the surface also often becomes rough through dry or wet etching processes. On the other hand, Ziberi et al., reported that the etching by a Ne ion beam does not roughen a Si surface and maintains its smoothness [20]. The roughening mechanism of the ion beam may not be exactly the same as that of the FAB. Therefore, we have recently demonstrated room-temperature wafer direct bonding by using a Ne FAB as the inert gas beam for surface activation [21]. In that work, we reported that the roughness of the surface etched by a Ne FAB was also 0.18 nm rms, which maintained the smoothness of the chemical–mechanical polishing (CMP) finished surface. We also found the smoothing effect of a Si surface by Ne FAB etching. By using the Ne FAB smoothing effect, the bonding energy between Si wafers was successfully improved.

In this paper, more detailed characterizations of the bonding interface prepared by room-temperature wafer direct bonding using the Ne FAB smoothing effect were examined. A Xe FAB was also used for the bonding as a heavier inert gas atom. The influence

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of the atomic weight on both surface roughness and interface structure was investigated. In particular, the surfaces smoothed by Ne FAB treatment were evaluated by performing power spectrum density (PSD) analysis on atomic force microscope (AFM) images. The PSD amplitude decreased for spatial frequencies >10 μm^{-1} by Ne FAB smoothing. From transmission electron microscope (TEM) observation, the local strain at the bonding interface was found to dramatically decrease by Ne FAB smoothing.

2. Experimental

In the experiments, 4-inch, double-side-polished, (100), boron-doped P-type (>1 Ωcm) Si wafers with a thickness of 400 ± 25 μm were used. The FAB 104 (Atom Tech Ltd.) beam sources in the room-temperature wafer bonding apparatus (MWB-12-ST: Mitsubishi Heavy Industries) were used for etching. Before the etching, the background vacuum pressure was about 1×10^{-5} Pa. For the etching, ultrapure Ne, Ar, and Xe gases (>99.999%) were supplied to the FAB sources, respectively. The beam incident angle was about 70°. The applied voltage and plasma current were about 1.8 kV and 100 mA, respectively. The surfaces of Si wafers were observed using an AFM (SII Nano Technology Inc., L-trace) before and after FAB etching. The scan area was 1 μm × 1 μm (256 × 256 pixels). After FAB etching, the surfaces were bonded with an applied load of about 0.4 MPa in vacuum. The crack-opening method [8] was used to measure the average bonding energy of silicon–silicon bonds. Specimens for cross-sectional TEM observation were prepared by the ion thinning technique after cutting them with a diamond saw. The cross-sectional interface structure observations were performed using TEM (HITACHI H-9000NAR) operated at 300 kV.

3. Results and discussion

3.1. Applicability evaluation of Ne and Xe FABs for surface activation of Si room temperature direct bonding

Fig. 1 shows the bonding energies depending on the depth of etching by Ne, Ar, and Xe FABs respectively. The etching rate of Si was about 1.5 nm/min for the Ne FAB, while the etching rate of Si was about 3 nm/min for the Ar and Xe FABs. For each etching condition, a bonded pair of Si wafers was used to measure the bonding energy. Crack lengths at four positions on the edge of the bonded Si wafer pair were measured by an infrared transmission camera in the case of Ne and Ar beam. On the other hand, crack lengths could be measured only at two positions on the edge in the case of Xe FAB because of its weak bonding strength. In case that Si wafers were broken in the crack opening method, the bonding energy could be considered as same as surface energy of Si bulk materials. Surface energy of Si bulk materials for (100) surface is about 2.5 J/m^2, reported by Messmer et al. [22]. Therefore bonding energies were plotted on a graph as 2.5 J/m^2 in the case. In the case of the Ne and Ar FABs, a bonding energy equivalent to that of the bulk materials was attained with an etching depth over 1.5 nm. On the other hand, the bonding energies between Si surfaces activated by the Xe FAB were extremely low.

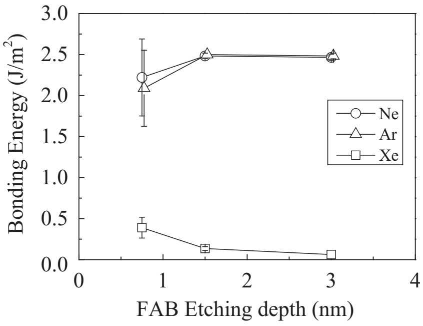

Fig. 1. Bonding energies between the Si surfaces activated by Ne, Ar, and Xe FABs.

In order to investigate what caused this low bonding energy between Si surfaces activated by Xe FAB etching, the Si surfaces were observed by AFM after about 30 nm of etching by each FAB. Fig. 2(a) shows an AFM image of the unprocessed Si surface finished by CMP, while Fig. 2(b)–(d) show the AFM images of the Si surface after about 30 nm of etching by the Ne, Ar, and Xe FABs, respectively. The roughness of the unprocessed surface is 0.18 nm rms. The roughness of the surface etched by the Ne FAB is also 0.18 nm rms, as shown in Fig. 2(b), which maintains the roughness of the unprocessed surface. The surface roughness etched by the Ar FAB slightly increased to 0.33 nm rms, as shown in Fig. 2(c). The surface roughness increased largely to 1.26 nm rms after etching by Xe FAB, as shown in Fig. 2(d). Moreover, corrugations perpendicular to the Xe FAB direction formed on the Si surface. The wavelength of the periodic rippled structures is about 30 nm. This rippled structure formed by Xe FAB etching has been often reported in the past [20,23]. The low bonding energy of the surfaces bonded with the Xe FAB is thought to be due to the roughening of the surface by Xe FAB etching.

In surface-activated room-temperature wafer direct bonding, an amorphous layer is formed by atom implantation of FAB. Amorphous thin layers formed by Ar FAB etching have been often observed in high-resolution TEM images of the interface [24]. In this experiment, we evaluated the microstructure of amorphous thin layers formed by FAB etching using different ion species. Fig. 3(a)–(c) show high-resolution TEM images of the bonding interface after surface activation using the Ne, Ar, and Xe FABs respectively. Fig. 3(a) and (b) show the bonded interfaces after the Ne and Ar FABs etching of 3 nm in depth. On the other hand, Fig. 3(c) shows the interface bonded after the Xe FAB etching of mere 0.8 nm, because the specimens could not be bonded after the Xe FABs etching of 3 nm in depth. No voids or delaminations at the bonded interface were observed in the etching of any of the kinds of FABs. The thicknesses of the amorphous intermediate layer of the bonded interface after etching with Ne, Ar, and Xe FABs were 7.5, 6.2, and 4.5 nm, respectively. The thickness of the amorphous layer decreased with increasing atomic number. The reason for this is thought to be that the lighter atoms were deeply implanted into the Si. In spite of the fact that the bonding energies between the Si surfaces bonded by the Xe FAB are low, the thickness of the amorphous layer for Xe FAB shows thinnest in those for other FAB etching.

3.2. Characterization of bonding interface of Si surfaces smoothed by Ne FAB surface treatment

From the applicability evaluation of a Ne FAB for surface activation at room-temperature bonding, we found that the surface etched by the Ne FAB maintains the roughness of the CMP-finished surface. As a next step, we evaluated the smoothing effect of the Ne FAB surface treatment on Si surfaces. To prepare the rough surfaces, the Si wafers were etched by the Xe FAB etching at a depth of 3 nm in the above-mentioned apparatus. Fig. 4(a) shows an AFM image of the surface etched by the Xe FAB etching at a depth of 3 nm. The surface roughing by Xe ion beam bombardment has been reported before [15,17]. After the Xe FAB etching, the rough Si surface was irradiated with a Ne FAB at a maximum depth of 30 nm. Fig. 4(b)–(d) show AFM images of the Si surface etched at depths of 5, 8, and 30 nm by the Ne FAB after the Xe FAB irradiation. In these AFM images, the surfaces etched by the Ne FAB