Wafer-Scale Surface Activated Bonding of Silicon, Silicon Oxide and Copper at Low Temperature

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Wafer direct bonding of silicon-based materials and metals is useful technology for the application of silicon on insulator (SOI) material, micro electro mechanical systems (MEMS) device packaging and optoelectronic integrated circuit (OEIC) device fabrications. During bonding process, high annealing temperature requires to increase surface energy in the conventional wafer bonding, which should be decreased to expand the application of the wafer bonding technology. Bonding at low temperatures is indispensable in terms of application since most microelectronic devices have temperature-sensitive structures. In addition, in the case of bonding between dissimilar materials, high temperature annealing may cause bonding failure during heating process because of thermal expansion mismatch between two wafers. Therefore, high temperature during bonding should be lowered. In the work, surface-activated bonding (SAB) method using argon fast atom beam (Ar-FAB) irradiation was used as a surface pretreatment for direct bonding at low temperatures [1]. In addition, argon ion beam and oxygen plasma was also used for wafer surface treatment before bonding to increase bonding strength of bonded wafer interface.

8-inch wafers of (100) oriented p-type silicon, thermally grown silicon oxide and copper thin film of 80 nm coated on Si with some diffusion barrier layers ($Si/SiO_2/SiN/TaN/Ta/Cu$) were used in the bonding experiment. For silicon-silicon bonding, Ar-FAB and ion beam were used. Fig. 1 represents the silicon spectrum taken by the Auger electron spectroscopy as a function Ar-FAB process time, where the gun was operated at 2-kV accelerating voltage and 40-mA current. The signals for oxygen and carbon on silicon surface are effectively removed by 20 min Ar-FAB irradiation. This means that the surface of silicon is clean enough for direct bonding. Atomically clean silicon wafers obtained by Ar-FAB were brought into contact and pressed by rolling with 1000-kg load for intimate contact in high vacuum of 10^{-8}torr. The bonded wafers were subsequently annealed at 150℃ for 8 hours. The bonding was successful and the bonding strength is higher than about 10 MPa. In the case of short time process, the bonding was not so strong that wafer pairs were debonded during sawing process. To obtain a reasonable bonding strength, annealing at 150℃ and sufficient Ar-FAB process time, at least 20 min, was necessary.

For bonding of silicon oxide and copper-coated silicon wafer, argon ion beam and oxygen plasma activation was used. Copper-silicon oxide system may have potential advantages since copper is the most prospective candidate for conducting material in the field of interconnections and silicon oxide is the most widely used insulating material in microelectronics. However, it has been assumed that copper is not so adhesive to silicon oxide. To join these two materials, oxygen plasma activated method was used in addition to SAB process. Till now, oxygen plasma activation method has been studied by many research-groups for silicon direct bonding [2]. It has been reported that oxygen plasma-treated silicon with highly hydrophilic surface could enhance mechanical bonding strength at low temperatures. The mechanism of the oxygen plasma activation is still under debate. In this work, two step surface cleaning process was adopted to join copper and silicon oxide. Firstly, copper was exposed to 40-100 eV argon ion beam for 60 sec and silicon oxide was exposed to oxygen plasma for 60 sec, respectively. The secondly, the oxygen plasma-treated silicon oxide is subsequently bombarded by Ar ion beam for 10 sec prior to bonding. The two heterogeneously treated copper and silicon oxide surfaces were successfully bonded. Fig. 2. shows the tensile test results. As shown in the figure, the bonding strength at room temperature is comparably low but the strength abruptly increases with annealing. The mechanism of the increased strength is underway.

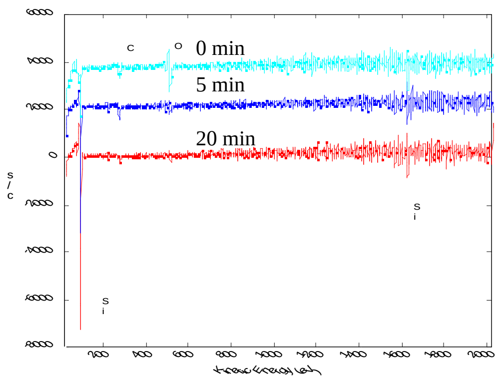

Fig. 1. AES spectrum of silicon surface before and after Ar-FAB irradiation.

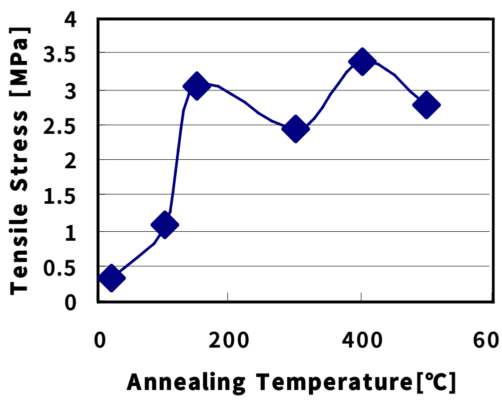

Fig. 2. Bonding strength of 8 hrs annealed copper-silicon oxide interface as a function of annealing temperatures.

[1] H. Takagi, K. Kikuchi, T. R. Chung, and T. Suga, Appl. Phys. Lett. **68**, 2222 (1996).

[2] D. Pasquariello, M. Lindeberg, C. Hedlund, K. Hjort, Sensor Actuat A-Phys **82**,239(2000).