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Oxygen Plasma Activated Silicon Direct Bonding in PECVD Mode

T. H. Kim, M. M. R. Howlader, T. Itoh, T. Suga

Research Center for Advanced Science and Technology (RCAST),
The University of Tokyo, Komaba 4-6-1, Meguro-ku, Tokyo 153-8904 Japan
Phone:+81-03-5452-5180 Fax:+81-03-5452-5184 E-mail:kim@su.rcast.u-tokyo.ac.jp

1. Introduction

Silicon direct bonding is a promising method in the field of vary large scale integration (VLSI), micro electro mechanical systems (MEMS) applications. High bonding strength should be needed to broaden the application of this technology. In order to increase bond strength, a high temperature annealing (higher than 450 ℃) is required [1]. But the high temperature process is harmful for the boding of metallized silicon wafers and for the fabrication of devices which are sensitive to temperature. One of the low temperature bonding techniques is a plasma activation method by which sufficient bonding strength may be achieved without high temperature process [2-4]. Till now most plasma activations have been done in the reactive ion etching (RIE) mode. In the case of RIE mode, the ion energy is so high that silicon surface may be damaged due to the attack of energetic ions [5]. In order to avoid such bombardment effects of energetic ions, dc self-bias voltage should be lowered. For this purpose, we proposed plasma enhanced chemical vapor deposition (PECVD) mode.

In this work we used an oxygen plasma operated in PECVD mode and tried to find an optimized activation condition for bonding. We showed the correlation between bonding strength and plasma exposure time at relatively low temperatures(lower than 450 ℃). The purpose of this work is to develop a low temperature, low damage silicon direct bonding technique.

2. Experiment

We used bare samples of p-Si(100) having dimension of 5x5 mm^2 and 10x10 mm^2 respectively. Since one specimen of them has a mesa structure to avoid the influence of the cutting edge, the actual bonded area of the mating sample is 3x3 mm^2. In order to achieve clean sample surfaces, organic and inorganic contaminants on sample surfaces should be removed. Samples were dipped into boiling H_2SO_4+H_2O_2(4:1), diluted HF(3%) and boiling H_2O+H_2O_2+NH_4OH(5:1:1) solutions. Samples were rinsed using clean water between each wet chemical process. The silicon surfaces were rendered to be clean and hydrophilic through this cleaning process

Fig. 1 shows the parallel plate RF plasma system used in our experiment. The system was operated under the condition of PECVD mode, in which the silicon sample is positioned on the grounded electrode. In this case the incidence energy of ions is relatively low compared with RIE mode since the negative dc self-bias is not developed due to the absence of the blocking capacitor of a matching network [6]. The clean sample surfaces were exposed to the oxygen plasma from 0 sec to 1800 sec in a flow rate 40 sccm at 30 Pa of a operating chamber pressure. Subsequently, the plasma-activated samples were mated together as quickly as possible outside the plasma chamber and were pressed using a pin in order to give some load for initial bonding. The samples were stored for about 12 hours in air. Thereafter the bonded samples were heated for 8 hours at 200 ℃ and 400 ℃, respectively.

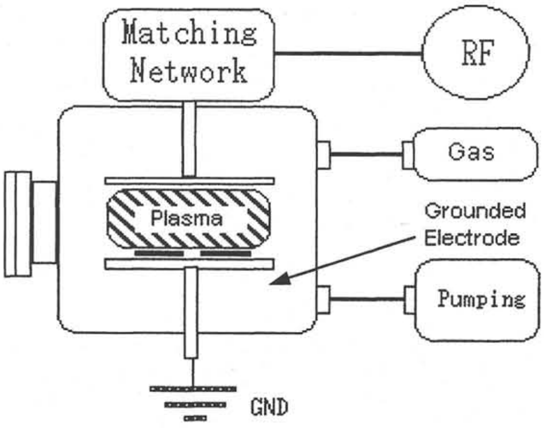

Fig. 1 Parallel plate RF plasma system operated in PECVD mode for silicon surface treatment.

Before tensile tests, current versus voltage (I-V) measurements on the bonded samples were performed to investigate electrical behavior with plasma exposure time. For tensile tests, metal bars of 4x4x20 mm^3 were glued to the smaller sample. Thereafter, the samples were pulled apart by the tensile test machine for the measurement of surface bonding energy.

3. Results and Discussion

Fig. 2 shows the plasma exposure time dependence of the bonding strength at room temperature, 200 ℃ and 400 ℃ respectively. In the case 400 ℃, all samples are as strong as bulk fracture level. But in the case of 200 ℃, samples were fractured from the bonded surface with out plasma treatment. Even in the case of room temperature, the bonding is strong enough so that the bulk fracture is achieved by the oxygen plasma activation when the plasma exposure time is 10 sec and 120 sec respectively. This result means that oxygen plasma in PECVD mode can effectively activate the silicon surface with low ion energy and enables the high-quality bonding to be done at room temperature. It was impossible to carry out tensile tests in the case of long plasma exposure (360-1800 sec) since bonding of the sample pairs was not strong to withstand external stresses resulting in debonding during handling samples for tensile tests. This implies that long plasma exposure may cause damages on silicon surface resulting in low surface bond energy. From this result, it is seen that the plasma bonding may be optimized by rather short time exposure in PECVD mode for low damage plasma activation process.

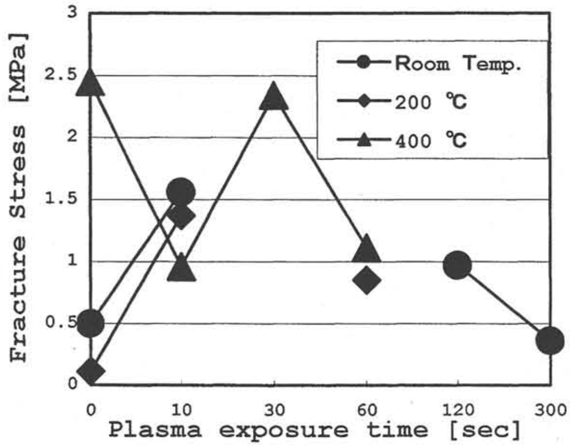

Fig. 2 Relation between surface energy and plasma exposure time.

Fig. 3 shows the I-V characteristic curves of the bonded unipolar silicon-silicon samples in the case of plasma activation without thermal annealing. It is seen that the long exposure time of plasma limits the current across the bonded surface. This may be explained by the fact that longer plasma exposure causes a higher potential barrier. During plasma process, various defects and oxide charges may increase on silicon surface resulting in formation of interface states in the band gap of silicon. These interface states induce potential barriers that limit the current flow [7,8].

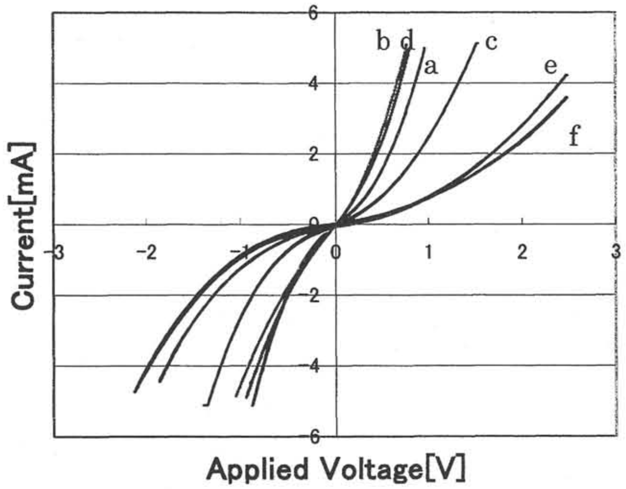

Fig. 3 The I-V characteristics of bonded samples at room temperature in plasma exposure time for (a) 0 sec, (b) 10 sec, (c) 30 sec, (d) 60 sec, (e) 120 sec, (f) 360 sec.

In addition, the oxide layers increase with increasing plasma exposure time and limit the tunneling current of the interface. Therefore, the long plasma exposure seems to degrade I-V characteristics of the bonded samples. As a result, by exposing silicon surface to oxygen plasma in PECVD mode for rather shorter time, we can obtain strong bonding at low temperatures. Short plasma exposure may cause relatively low damage on silicon surface and operation in PECVD mode does not so highly accelerate ions in the plasma sheath to give severe damage on silicon surface. Therefore, it is believed that well-activated surface having low damage may be obtained by this plasma treatment condition. This may be the reason why strong bonding was obtained using the plasma activation at low temperatures.

4. **Conclusions**

Silicon direct bonding at low temperatures was investigated using oxygen plasma operated in PECVD mode. In the mode, oxygen plasma can effectively activate silicon surfaces resulting in strong bonding at low temperatures. Moreover, silicon direct bonding at room temperature was so strong that bulk fracture was achieved by short PECVD plasma treatment

The results from the tensile tests and I-V curves suggest that 10 sec plasma exposure is the optimum condition for silicon direct bonding.

Acknowledgments

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