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Si on SiO_2 by Solid-State Diffusion Bonding (SSDB) Technology

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A high quality Si on SiO_2 substrate has been produced by solid-state diffusion bonding and preferential electrochemistry thinning technology. The SiO_2 thickness can range from native oxide to serveral micron. After high temperature (850-1250°C) solid-state diffusion process, the fracture strength of the SOI substrate is increased to 150-185 kg/cm^2 and the perfect bonding throughout the interface between bare silicon wafer and oxided silicon wafer has been made. The SEM and Van Der Pauw measurement results prove that the material properties of the produced SOI substrate are comparable favourably to those of the original bulk silicon wafer.

1. INTRODUCTION

Semiconductor on insulator is a very attractive substrate for achieving intergrated circuits with greater complexity, higher speed, improved reliability, higher operating voltage and operating temperature. Silicon wafer direct bonding (SDB) technology is one of the promising methods for producing good quality SOI substrate through simpler processes[1-2]. However, in published reports on SDB research work, the study of the bonding mechanism is far from perfect, the insufficient bonding area and limited bonding materials make the SDB technology not yet available to the advanced VLSI fields. This paper describes the bonding process and mechanism of the solid-state diffusion bonding method. Moreover, the electrical and material properties of the produced silicon on silicon dioxide substrate have been investigated extensively.

2. Si ON SiO_2 PROCESS

a. Grow a lightly doped n^- type epitaxial layer (several micron thickness) on a heavily doped p^+ type substrate (A) and grow a thermal oxidation layer on the n^- epitaxial layer.

b. Bare silicon wafer surface (B) and silicon dioxide surface (A) are slightly etched or plasma activated to form vast dangling bonds on the surfaces.

c. They are put in Molecular type Surface Activated Solvent (MSAS in short) to absorb large amount of OH groups on the surfaces.

d. They are washed in deionised water and brought into contact face to face (bare silicon surface (B) to silicon dioxide surface (A) in relatively low temperature (150-450°C) for about 1hr with slightly pressure (0.2kg/cm^2 or so) for initial bonding.

e. The pairs with no pressure are treated in the vaccum furnace at high temperature (850-1250°C) for 1hr to

form large bonding area by solid-state diffusion bonding.

f. p^+ type heavily doped part of silicon wafer (A) is removed by lapping and preferential electrochemistry thinning process (using KOH solvent) so that a n^- type SOI active layer (several micron) on a thermal oxidation layer and a holding wafer (B) is automatically retained.

3. RESILTS AND DISCUSSIONS

From experiment results on the relation between fracture strength and thermal treatment temperature (see Fig. 1), we find that the bonding process consists of two main steps. The first step is low temperature initial bonding process in which the polymerization reaction of silanol bonds (Si-OH groups on the bare silicon or silicon dioxide surfaces formed by the hydrophilic treatment) occurs as follows:

$$Si\text{-}OH+OH\text{-}Si = H_2O+Si\text{-}O\text{-}Si \qquad (1)$$

Water molecules release through the silicon and silicon dioxide bonding interface or diffuse into the bulk silicon resulting reoxidizing of the silicon surface. The experiments show that OH amount on the bare silicon and silicon dioxide surfaces, the treatment time and temperature are important factors to the first bonding step. The experiments also indicate the reaction (1) takes place at temperature grater than 150°C, and the fracture strength as well as bonding area grows as the surface OH amount and the thermal treatment temperature increase. At around 450°C the reaction stops so that the fracture strength saturates. The second step is a high temperature process (850 to 1250°C) in which the atoms get thermal energy so that two kinds of diffusion processes act as the primary means of grain boundary rearrangement, void elimination. The first one is mutual diffusion process of atoms on the mating surfaces (bare silicon wafer (A) and oxided silicon wafer (B)). The second one is diffusion process into bulk silicon or silicon dioxide of oxygen atoms in Si-O-Si structure (reaction (1)) at the bare silicon and silicon dioxide interface. With higher temperature and longer time, atom diffusion process and pore elimination are enhanced and the mating surface contact area grows to a large fraction of bonding area which makes the fracture strength increase greatly. In the high temperature bonding process, bonding temperature is the most influential parameter since it determines the atom diffusion rate which governs void elimination and silicon atom rearrangment in the interface. The experiments also show that the temperature for the solid-state diffusion bonding process (T) lies in the following values:

$$T = (0.56\text{-}0.85)\ Tm \qquad (2)$$

where Tm is the melting temperature of the silicon material.

Fig.2 gives out the relation between bonding area (by means of infrared thermalgraphic image) and treatment time during the high temperature solid-state diffusion bonding process. The longer the treatment time, the lower the solid state diffusion bonding temperature is required.

In one of the experiments on Si and SiO_2 bonding process, we choose 300°C/1hr and 1100°C/2hr respectively as the low and the high thermal bond-

ing conditions. The corresponding fracture strength is 56 kg/cm^2 and 185 kg/cm^2 respectively. SIMS measurements prove that plasma activation of the bare silicon surface and thin SiO_2 layer in NH_3 or O_2 is very helpful for absorption of OH amount on both bare silicon and thin SiO_2 layer (see Fig.3A&B). The use of MSAS, can greatly increase OH amount on bare silicon and silicon dioxide surfaces so that the bonding strength and the bonding area of the first step low temperature initial bonding grows efficiently. SIMS measurement results indicate that OH amount on the original silicon surface is one order of magnitude lower than that of the wafer treated with MSAS (see Fig.3A&C).

The low temperature initial bonding process is very important to the high temperature solid state diffusion bonding process. Without the first one, solid-state diffusion bonding does not happen even with high temperature for long time. The bonding strength is not great enough after initial bonding process so that high temperature solid-state diffusion bonding process must be used to get high fracture strength, sufficient bonding area and perfect bonding interface. Fig.4 shows SEM microphotograph of the produced silicon on silicon dioxide substrate after low temperature initial bonding and high temperature solid-state diffusion bonding process.

Microstructure and electrical properties of the produced SOI substrate using this SSDB technology have been experimentally investigated. Since no pressure is needed during the high temperature SSDB process, no additional defects have been developed in produced SOI layer. The bonded SOI layers are stable at high temperature process. The measurement results show that hole and electron mobilities and fracture strength of the resultant SOI substrate are almost identical to those of the original bulk silicon (see table 1).

Table 1

	Un	Up
SOI	1096 cm^2/vs	409 cm^2/vs
Bulk Si	1160 cm^2/vs	420 cm^2/vs

	fracture strength
SOI	185 kg/cm^2
Bulk Si	185 kg/cm^2

4. CONCLUSION

By SSDB process, the Si on SiO_2 material with high fracture strength and sufficent bonding area is successfully made. The material properties and electrical characteristics of the Si on SiO_2 substrate are as good as those of the original bulk silicon material. In addition to Si and SiO_2 material, the experiments prove the process can also be applied to other semiconductor and insulator materials such as quartz and Si_3N_4.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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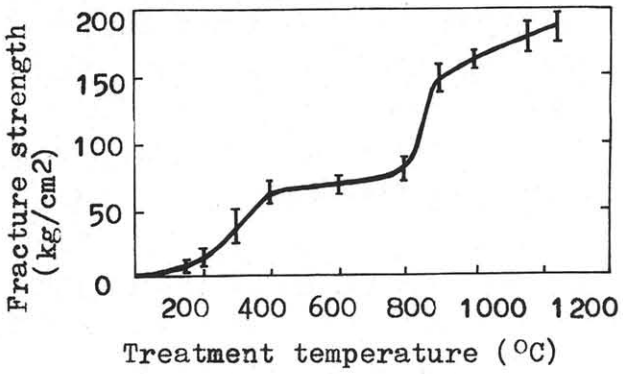


Fig.1 The relation between fracture strength and treatment temperature.

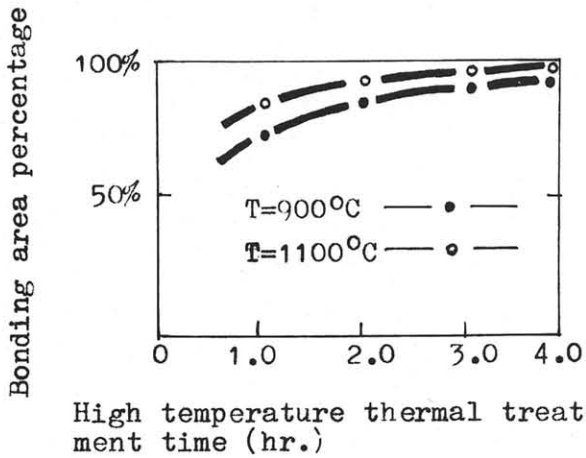


Fig.2 The relation between bonding area and high temperature thermal treatment time.

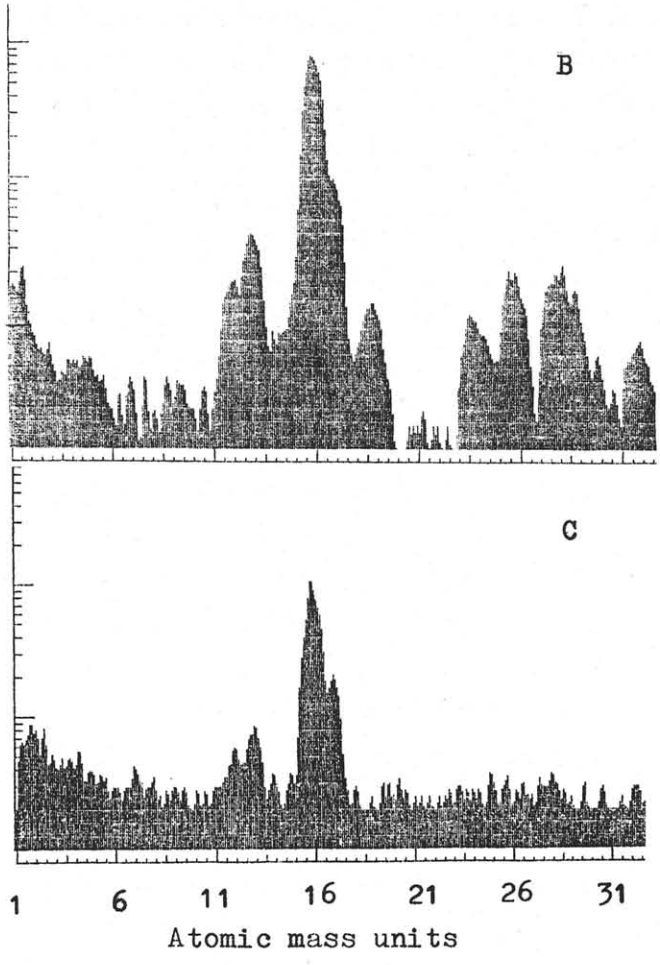
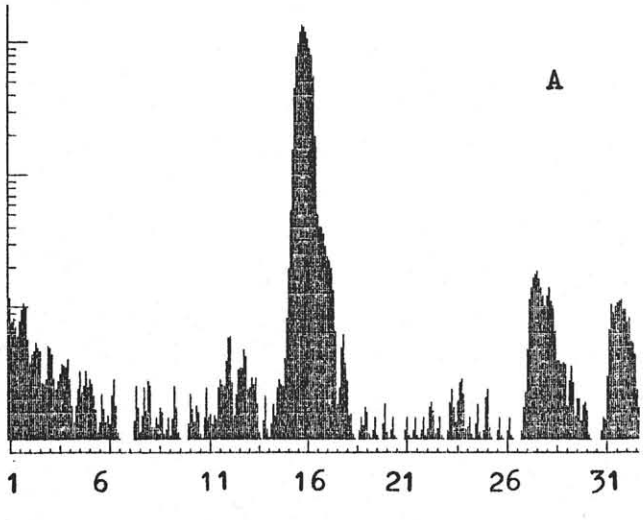


Fig.3 SIMS measurement of OH amount on silicon surfaces.
A: Original bare silicon wafer surface.
B: Silicon wafer surface after NH_3 plasma activation treatment.
C: Silicon wafer surface after MSAS treatment.



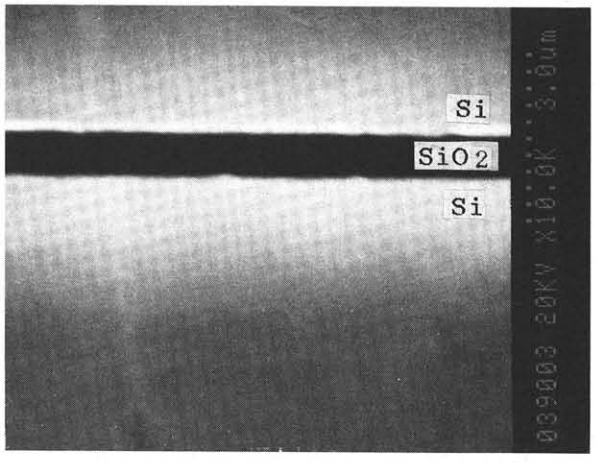


Fig.4 SEM microphotograph of the produced silicon on silicon dioxide substrate.