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Fabrication and Characterization of High Temperature Electrostatic Chucks

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It was suggested that tape casting method can be used to fabricate high-temperature electrostatic chucks (HTESC) based on a metal substrate coated with a glass-ceramic insulating layer. The adhesion of the coating was excellent such that it was able to withstand temperature cycling to over 300°C without spalling. The electrostatic clamping pressure reached a very high value of about 9 torr at 600 V and generally followed the theoretical voltage-squared curve. Based on these results, we believe that we successfully developed a viable technique for manufacturing low-cost HTESC.

Key words : High temperature electrostatic chuck, Electrostatic clamping pressure, Tape casting

I. Introduction

In the semiconductor manufacturing, close control and repeatability of the process conditions are necessary to ensure the quality and reliability of the fabricated devices. Wafers are usually held in place mechanically by clamping around the wafer periphery to secure them on the susceptor.[1-4] Nonreactive gas is then passed in the wafer/susceptor interface to provide efficient cooling. The mechanical clamp allows a gas pressure higher than that in the reactor to be maintained in the interface. However, this clamping method produces an uneven force distribution that causes the wafer to bow.

Electrostatic chucks (ESC) represent an improvement over mechanical clamping devices. Electrostatic clamping is based on the electrostatic attraction that is generated between objects under an applied electric potential.[1,5] The elimination of mechanical parts (e.g., clamping ring) minimizes particle contamination and increases the available wafer area. The electrostatic force is distributed uniformly over the entire chuck area and is sufficiently high to prevent bowing of the wafer. Enhanced contact with the chuck surface also provides a more uniform heat transfer over the entire wafer area.

Variations in the design and type of materials are found in the literature and patents but ESCs can be classified into three basic configurations, namely: the monopolar, bipolar, and Johnsen-Rahbek (J-R).[1,5] The monopolar configuration is the simplest and is the design of our interest here. It is based on a parallel plate capacitor with the wafer acting as the second electrode. The plasma serves as a conductor to complete the electrical circuit. Theoretically, this configuration also generates the largest clamping force among the three types. Because of the simple form, monopolar chucks are easier to manufacture than the other configurations.

Low-temperature ESCs (LTESC) based on polymeric insulating layers are commercially available. They are relatively easy and inexpensive to produce. In contrast, the wide adoption of electrostatic clamping at higher temperatures is hampered by the difficulties involved in manufacturing durable and reliable chucks that can withstand the harsher service environments found in high-temperature processes. Most of the research efforts were focused on ceramic coatings notably alumina and silica. These materials have the physical properties that are desirable for high-temperature applications. However, they are difficult and expensive to fabricate, requiring very high firing temperatures. The glass-ceramic based ESC is intended to eliminate, if not minimize, such problems while providing a much cheaper alternative to ceramic-based devices. While the work done is based on a monopolar configuration, this does not preclude the application of the materials system and fabrication technique to other configurations.

This research was undertaken to demonstrate the feasibility of using glass-ceramic coatings on metal substrates for the fabrication of high-temperature ESC (HTESC) which can be used up to 500°C. They have lower firing temperatures compared to the currently favored materials such as alumina and silica. The fabrication method is based on the tape casting process that is widely used in the manufacture of microelectronics packaging substrates and multilayer ceramic capacitors.[6,7]

The key to the success of this process is in finding the right combination of dielectric material and metal substrate. Important properties of the glass-ceramic that must be considered are the coefficient of thermal expansion (CTE), sintering temperature, electrical resistivity, dielectric constant, and adhesion and wetting characteristics among others. Since the electrostatic force is caused by the charge accumulated in the insulating layer and the accumulation speed depends on the electrical resistivity of the insulating layer, it is necessary to keep the resistance low enough for charge accumulation. Contrary to this, insulating layer with a electrical resistivity too low to prevent leakage current is not desired since the large current may damage devices on the wafer. Optimum resistivity is considered to be 10^{10}~10^{13} ohm-cm.[8] If the chuck is to be used at high temperature, it is necessary to settle for a composition that retains those optimum resistivity at or near the operating temperature. This alone narrows down the choice to compositions that are alkali-free. In addition, the dielectric constant should not be too high although electrostatic clamping pressure is proportional to that value. For a insulating layer with too high dielectric constant, dechucking time is unacceptably long. A suggested value of dielectric constant of the insulating layer is in the range of 3 and 10. A glass composition that meets most of the requirements is a magnesium-aluminosilicate glass that crystallizes into cordierite. By adding a buffer layer, it can be cofired with molybdenum to produce a very strong and adherent coating on the substrate.

II. Experimental Procedure

The insulating layer of the HTESC consisted of a magnesium-aluminosilicate crystallizable glass obtained from Sem-Com Co. (P.O. Box 8428, Toledo, OH 43623). It has an average particle size of 10 μm, a density of 2.66 g/cm^3, and a thermal expansion coefficient (CTE) of 4.6×10^{-6}/°C and 4.1×10^{-6}/°C in the glass and crystalline state, respectively. The substrate is made of pure molybdenum with a buffer layer of sputtered chromium. Its CTE is slightly higher than that of the insulating layer putting the glass-ceramic under compressive stresses in service temperature range. It is, however, easily oxidized above 500°C such that firing has to be done in a slightly reducing atmosphere.

A two-stage milling procedure was adopted in the preparation of the glass slurry.[7] The glass powder was mixed with fish oil, ethanol, and toluene and milled in a ceramic jar for 24 h. The polyvinyl butyral (PVB) binder and plasticizer were then added and the mixture was milled for another 24 h. The slurry was then deaired in vacuum for about half an hour. The deaired slurry was cast on the substrate using a doctor blade to form a dried green layer about 100 μm thick. The films were allowed to dry in air for 24 h. Machined molybdenum having a diameter of 2.5 inches was used as the substrate. The chromium buffer layer was coated by sputtering to the thickness of about 13 μm before being coated with the glass slurry. The insulator-coated substrates were fired in a atmosphere of 10% H_2 and 90% He at 950°C for 3 h after binder burnout at 450°C. The chucks were subsequently polished with 1 μm diamond paste to improve the flatness of the chuck and eliminate much of the surface roughness.

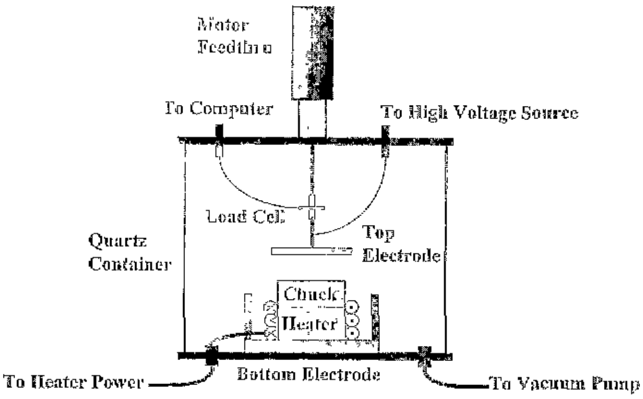

Fig. 1. Schematic diagram of the apparatus for clamping pressure measurement

Microstructures were examined in a scanning electron microscope (SEM, JSM-5800LV). Electrical resistivities of the insulting layer were measured at temperatures between 200°C and 500°C using a pA meter (HP 4140B). Dielectric constants of the insulating layer were measured at temperatures between 25°C and 400°C and at frequencies of 540 Hz and 1 kHz by HP 4284A LCR meter.

Clamping force measurements were performed using a custom-built vacuum chamber enclosing a disk heater and a load cell attached to a motor-driven micrometer screw as shown in Fig. 1. The HTESC is mounted directly on the disk heater with a hollow screw. A thermocouple is inserted into the metal substrate through the screw hole such that the tip is as close as possible to the insulating layer. The metal substrate serves as the bottom electrode and a rigid alumina plate electroless-plated with a thin layer of copper acts as the top electrode. A machinable ceramic rod attached to the load cell is linked to the top electrode through rotatable joint to enable the electrode to be seated properly on the chuck surface. The voltage is applied to the top electrode as shown schematically. Data acquisition was done automatically by a personal computer equipped with a data acquisition card. In a typical run, the electrode is lowered onto the chuck and charged at a set voltage for 5 or 10 min. After charging, the electrode is slowly lifted until it is detached from the HTESC. The clamping pressure is defined to be the maximum pressure just before the electrode breaks free from the electrostatic force developed in the HTESC.

III. Results and Discussion

Fig. 2 is SEM micrograph of the cross section of ESC. The thicknesses of the insulating layer and chromium buffer layer were about 75 μm and 13 μm, respectively. No delaminations were observed at the interfaces, indicating that the adhesion of Cr_2O_3, which is a oxidized phase of chromium, is excellent to both molybdenum and insulating layer. Good adhesion of the insulating layer

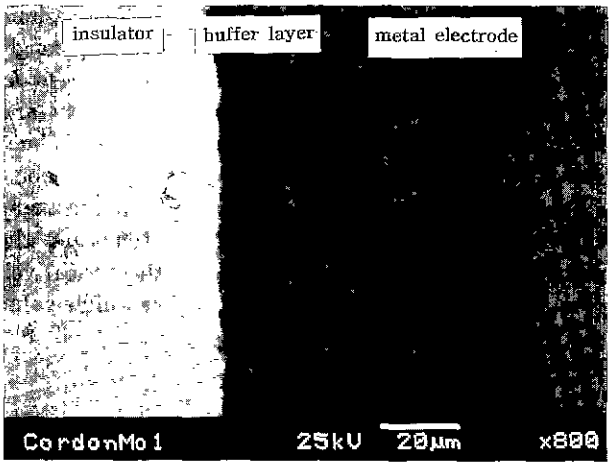

Fig. 2. SEM micrographs at insulator/electrode interfaces after 3-h sintering at 950°C.

on the metal substrate is essential to the reliability and life of the HTESC and it is for this reason that the molybdenum substrate was pre-coated with the chromium buffer layer. There were several cracks observed in the chromium buffer layer. These cracks might possibly be generated by the tensile stress in the layer which is caused by the CTE mismatch between Cr_2O_3 and molybdenum and/ *or between* Cr_2O_3 *and insulating layer; i.e.* Cr_2O_3 *has a CTE* of about 10 ppm which is about twice that of molybdenum and insulating layer. However, these kinds of cracks were not observed in the insulating layer and molybdenum even after temperature cycling to over 300°C. A careful examination of the microstructure also indicated that there were significant crystallization progressed in the insulating layer.

Fig. 3 is a plot of the electrical resistivity of the insulating layer measured at temperatures between 200°C and 500°C. The electrical resistivities were in the range of 10^{10} and 10^{13} ohm-cm indicating that the insulating layer has the optimum resistivity properties for HTESC application.

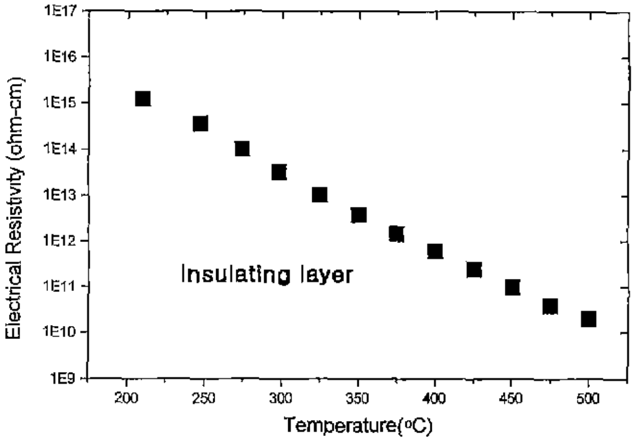

Fig. 3. Electrical resistivity of the insulating layer on molybdenum.

Plotted in Fig. 4 are the relative dielectric constants versus temperature measured at the frequencies of 540 Hz and 1 kHz. The measured dielectric constants were slightly higher at the frequency of 540 Hz than those at 1 kHz. The relative dielectric constants were in the range of 5 and 7 satisfying the requirement described previously.

The insulating layer was polished using 1 μm-diamond paste. The clamping pressure measurements were conducted at 300°C after 0, 24, 48, and 72-h polishing. A *charging time of 5 min at voltages between 100 V and* 600 V was set before reading were obtained. The results are shown in Fig. 5. The curves show a dramatic increase in the clamping pressure during the first 48 h of polishing with only a minor improvement after 72 h. At 600 V, the clamping pressure increased by at least three times. To analyze the results, we took a clamping pressure equation for the monopolar configuration. The clamping pressure (clamping force per unit area of contact assuming perfect contact), P, is governed by[1,5]

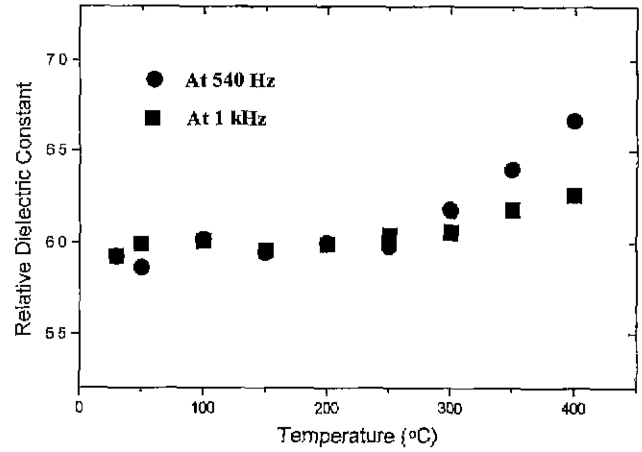

Fig. 4. Relative dielectric constant of the insulating layer on molybdenum at different frequencies.

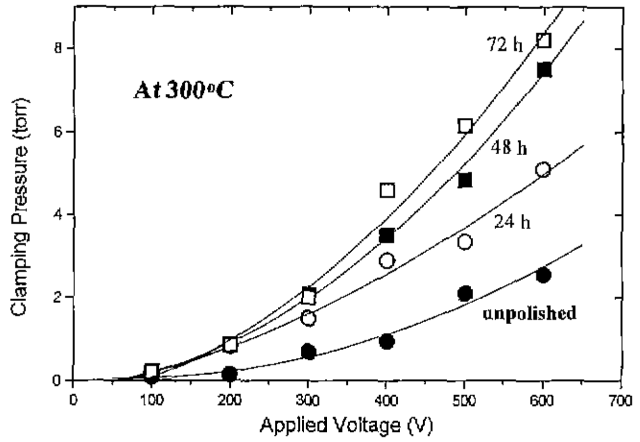

Fig. 5. Clamping pressure of HTESC at various polishing times.

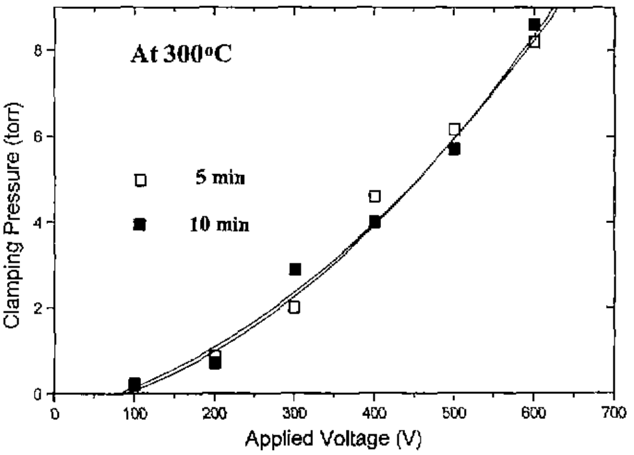

Fig. 6. Clamping pressure of HTESC at different charging times.

$$P = 1/2\varepsilon_0 \varepsilon_r (V/t)^2 \quad (1)$$

where ε_0 is the vacuum dielectric constant, ε_r is the relative dielectric constant of the insulating layer, V is the voltage applied to the electrode, and t is the insulator thickness. According to Eq. (1), the increase in the clamping pressure with polishing time is due to the increase of the actual contact area between the wafer and chuck considering the fact that ε_0 and ε_r are independent of the polishing. The superimposed solid lines in Fig. 5 represent non-linear least square fits to V^2. Statistical fitting performed on the earlier result showed a very close dependence to the square of the voltage as predicted by Eq. (1).

Plotted in Fig. 6 are the clamping pressure versus applied voltage curves measured at 300°C after charging for 5 min and 10 min. The clamping pressure reached a very high value of about 9 torr at 600 V. The solid lines in Fig. 6 are also non-linear least square fits to V^2. The two curves, essentially coinciding with each other, indicate that at 5 min the accumulated charges are saturated.

IV. Conclusions

High-temperature electrostatic chucks (HTESC) were successfully produced by tape casting glass slurry on the chromium coated molybdenum substrates followed by sintering at a temperature under 1000°C. The magnesium-aluminosilicate glass-ceramic layer (*insulator*) was strongly bonded to the molybdenum substrate (*the bottom electrode*) through chromium oxide (*buffer layer*). Resistivity and dielectric constant measurements indicate that this chuck is suitable for high temperature chucking applications. The electrostatic clamping pressure was measured using a custom-built setup. Measurement showed that the clamping pressure generally followed the theoretical voltage-square relationship and reached a very high value of about 9 torr at 600 V.

Acknowledgment

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