Atmospheric-pressure plasma activation of silicon for MEMS packaging

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Abstract: Surface treatment by dielectric barrier discharges (DBDs) at atmospheric pressure has been used for the pretreatment of silicon wafers for low temperature direct bonding. The paper presents different plasma techniques based on DBDs and describes the influence of basic plasma parameters. Furthermore results of an innovative method for fracture surface energies measurement performed in-situ during annealing will be discussed.

Keywords: packaging, local plasma treatment, plasma printing, in-situ surface energy.

1. Introduction

Wafer-level packaging with silicon wafers is state of the art in the production of microelectromechanical systems (MEMS). The encapsulation for MEMS devices like pressure, acceleration or IR sensors make high demands on hermeticity and mechanical stability.

Especially direct bonding is appropriate, since no intermediate layer is needed. In order to achieve high bond strengths, void free interfaces, and high yields, the required annealing temperatures generally exceed 900 °C. For temperature sensitive materials and bonds between materials with different thermal expansion coefficients, there is a strong demand for low-temperature bonding processes.

Different atmospheric pressure plasma techniques based on DBDs were reviewed and discussed in the following.

2. Used plasma techniques

Dynamic DBD

In the *Dynamic DBD* the discharge is ignited between a grounded electrode (substrate table) and two high voltage ceramic electrodes (**Fig. 1**).

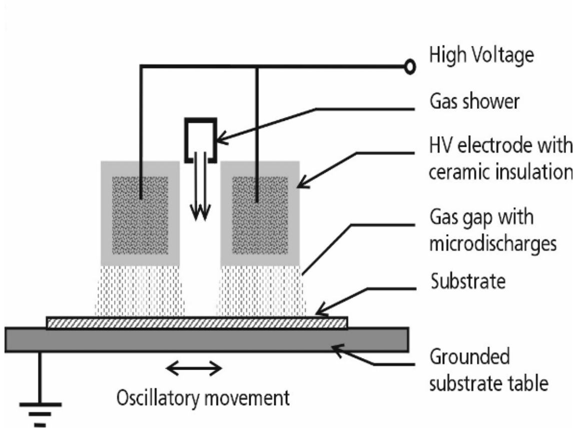

Fig.1 Principal of *Dynamic DBD* treatment.

Treatments with different process gases can be realized by controlling the atmosphere in the discharge area by a gas shower.

The process takes only seconds of time and is highly flexible with respect to the wafer size. Thus, wafers of different sizes can be processed on the same equipment without any changes of the installation. In addition, the system can be easily integrated into a wafer bonding cluster. The development of the activation process was a joint project between the SUSS Micro Tec, Fraunhofer IST and MPI of Microstructure Physics [1].

SUSS MicroTec AG has introduced this method as “nano PREP”, a surface activation and wafer-to-wafer bonding method that enables semiconductor materials, such as silicon on insulator (SOI) and strained silicon using direct wafer bonding, to be created (**Fig. 2**).

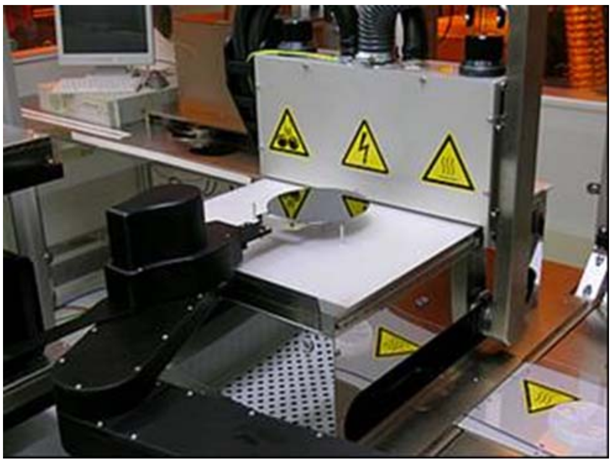

Fig.2 nano PREP integrated in a wafer bonding cluster by SUSS MicroTec.

Whole wafer DBD treatment

The *whole wafer DBD* plasma system consists of a grounded chuck, serving as the wafer carrier, and an indium tin oxide layer on the glass electrode as transparent high voltage electrode, covering the whole wafer (**Fig. 3**). The electrode can be aligned to the substrate in different distances with an accuracy of 10 µm. For the alignment a wedge error correction is integrated. The gap between the substrate surface and the electrode can be flushed with a process gas. The discharge is powered by a 7010-type corona generator (*Softal electronic GmbH, Germany*).

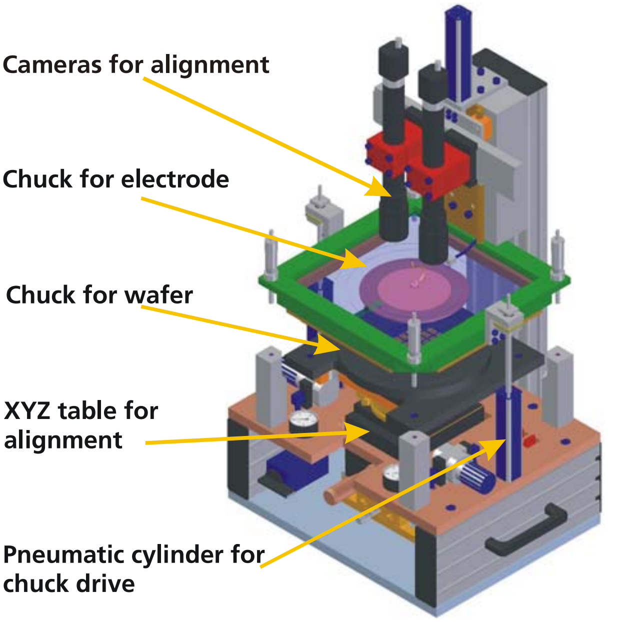

Fig. 3 Transportable experimental setup for *whole wafer DBD*.

With this "open" setup, the intrusion of ambient air into the process gas atmosphere cannot completely be excluded, but typically the amount of oxygen introduced from the surrounding is less then 1 %. In **Fig. 4** the discharge on a 4" silicon wafer with a discharge gap distance of 500 µm in nitrogen is shown [2].

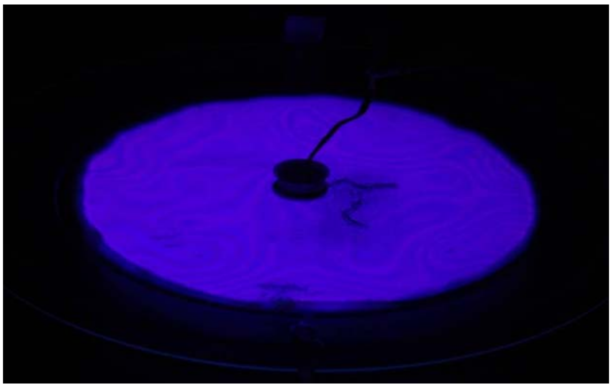

Fig. 4 Plasma activation of 4" silicon wafer in nitrogen.

Furthermore atmospheric pressure plasmas offer the unique opportunity to realize patterned surface modifications in a very easy way by localizing the discharge at specific substrate regions. Therefore the same equipment can be used in two different ways for the following methods.

The *plasma printing* and the *local plasma treatment* method are of considerable interest for the treatment of wafers on which surface modifications have to be limited to certain areas, e.g. for the production of MEMS containing elements such as membranes and valves. All of them suffer from the so called sticking effect, which comes from the unwanted adhesion of surfaces with high surface energy. One way to prevent sticking is an area-selective plasma treatment which can be applied not only to increase but also to decrease the free surface energy and thus bonding abilities.

The principle of the whole wafer DBD in Fig. 5 a is shown to compare with the area-selective treatments. The electrode and the substrate of the whole wafer DBD form a uniform gap for plasma generating.

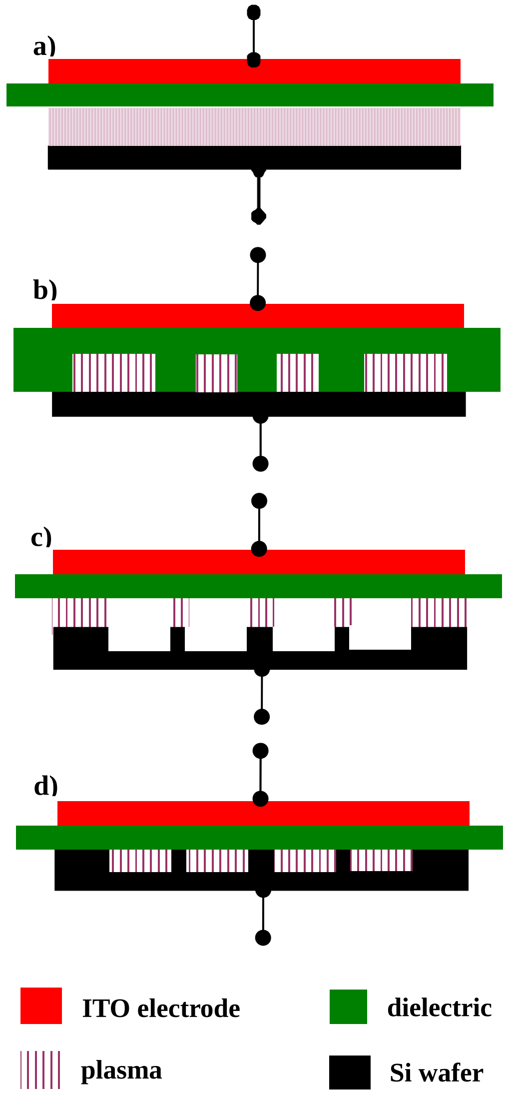

Fig. 5 Different methods for plasma treatment by DBDs: a) Whole wafer DBD; b) Plasma printing; c) and d) Local plasma treatment.

Unpatterned wafers can be treated area-selectively by the *plasma printing* method (**Fig. 5 b**): An electrode with a structured dielectric mask is aligned on the wafer. By applying a voltage to the electrode, discharges are obtained in the cavities formed by the dielectric mask and the grounded wafer.

The structured mask can be realized by well-known lithographic processes. In this way a layout can easily be transferred to the wafer. For demonstration of the plasma effect, an HF-dipped hydrophobic silicon wafer was treated with nitrogen plasma. **Fig. 6** shows the plasma in the cavities between the hydrophobic wafer surface and the transparent mask. In the plasma-treated areas, the wafer turns hydrophilic as shown in a wetting experiment with water.

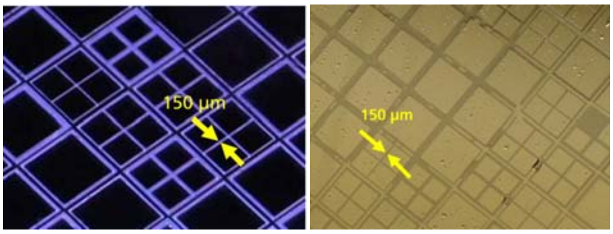

Fig. 6 Plasma printing of 4" silicon wafer in nitrogen (left). Plasma treated areas turn hydrophilic (right).

The *local plasma treatment* method is used for MEMS wafers having etched structures. An insulated high-voltage electrode is aligned in a small distance above the grounded wafer. By controlling the distance between the structures on the wafer and the electrode or the voltage on the electrode, a plasma discharge can be ignited on selected areas of the wafer (**Fig. 5 c and d**).

For experiments a conductive wafer was grounded by the chuck and a transparent ITO electrode was sputtered on a glass substrate with dielectric constant ε_r and thickness t_b, the gap t_g between substrate and dielectric was precisely adjusted. The voltage V_0 applied to the electrodes leads to the voltage V_g across the gap. V_g is given by:

$$V_g = V_0 \cdot \left(\frac{t_b}{\varepsilon_r \cdot t_g} + 1 \right)^{-1} \qquad \text{Eq. (1)}$$

Together with Paschen's law for the ignition voltage V_i of the discharge:

$$V_i = (Bp) \cdot t_g \cdot \left(\ln \frac{(Ap) \cdot t_g}{\ln(1 + 1/\gamma)} \right)^{-1} \qquad \text{Eq. (2)}$$

an equation for the required ignition voltage $V_{0,i}$ as a function of t_g can be derived.

Fig. 7 shows this dependence for a borosilicate glass ($\varepsilon_r = 4.6$) of thickness $t_b = 2$ mm and nitrogen gas in the gap ($A \cdot p = 977$ mm^{-1}, $B \cdot p = 25.5$ kV/mm [3]). For the expression $\ln(1+1/\gamma)$, which is strongly dependent on the electrode material, a typical value of 10 was assumed [3]. The graph in **Fig. 7** shows, that for an applied voltage, e.g. $V_0 = 6$ kV, the discharge will only be ignited for gap widths between 100 and 470 µm.

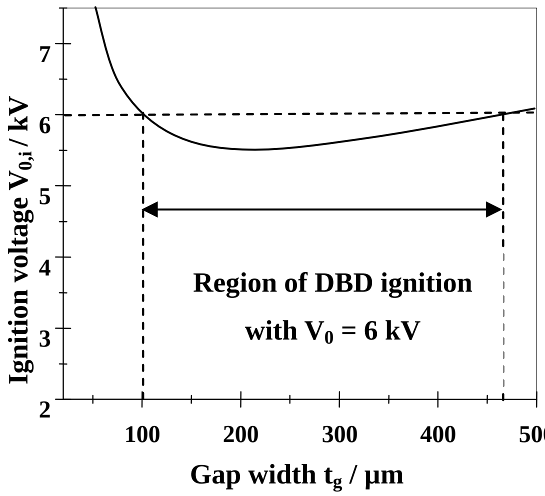

Fig. 7 Dependence of the voltage required to ignite a nitrogen DBD in the arrangement shown in Figure 5 c) and d); see text for parameters used.

The dependence of the gap distance t_g on the plasma formation of an etched silicon wafer was investigated for nitrogen process gas and is shown in **Fig. 8**. A distance of 50 µm or less limits the plasma to the etched cavities. If the gap is increased to 100 µm, the discharge covers both, the cavities and the elevated structures of the wafer. Above 150 µm the plasma concentrates on the edges of the bond areas. This can be prevented by increasing the gap distance up to 300 µm.

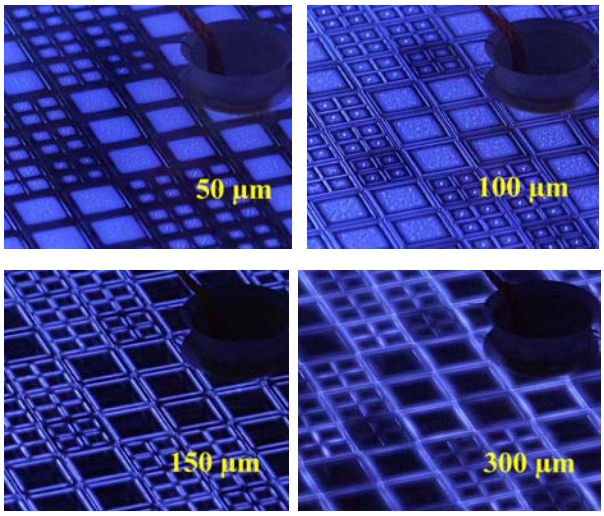

Fig. 8 Plasma formation on a etched 4" silicon wafer in nitrogen process gas atmosphere.

3. In-situ surface energy measurement

In order to obtain information about the temporal development of bond strength during annealing of a wafer pair, dynamic surface energy measurement was used, similar to the method described earlier by Zhang and Raskin [4]. However, we used it in-situ by measuring the crack length in a furnace using a custom-made setup, consisting of fixtures for the wafer pair and the blade and a motor to drive the blade through the bonded interface. Pictures of the crack were taken by IR transmission photography using a Sensicam pco (PCO AG, Germany). The measurement was controlled by a computer program, which initiated the crack propagation by driving the motor and triggered the camera to take a picture 30 s after stopping the motor. This procedure was repeated in fixed time intervals. Fracture surface energies were calculated as shown in **Eq. 3**, E being the uniaxial Young's modulus of silicon (130 GPa), t the wafer thickness (in our experiments 525 µm), b the blade thickness (40 µm), and L the crack length.

$$\gamma = 3\,E\,t^3\,b^2 / (32\,L^4) \qquad \text{Eq. (3)}$$

For the calculation of surface energies at elevated temperature, room temperature values have been adopted for E and t, because the slight decrease of E with increasing temperature is partly compensated by the thermal expansion of the wafer and the blade thickness, resp. However, humidity has a pronounced influence on the measurements, due to the temperature dependence of relative humidity (r. h.) at constant absolute humidity: The ambient air in the lab, where the furnace is used, has a temperature of 20 °C and a relative humidity of 50 %. Inside the heated furnace, working like a convection oven, a r. h. of only 19 % was measured already at 40 °C, in reasonable agreement with expectation. Therefore all values in the following figures were normalized at room temperature surface energies. More details about the normalization can be found in [5] and in further publications.

The experiments were done with single-side polished [100] 4" Si wafers. Before plasma treatment, the wafers were cleaned using the standard RCA procedure.

The characteristic of surface energy increase during annealing was investigated for wafer pairs treated with O_2, synthetic air, and N_2 as process gases, resp., and compared with an untreated RCA cleaned reference wafer pair. The results are shown in **Fig. 9**.

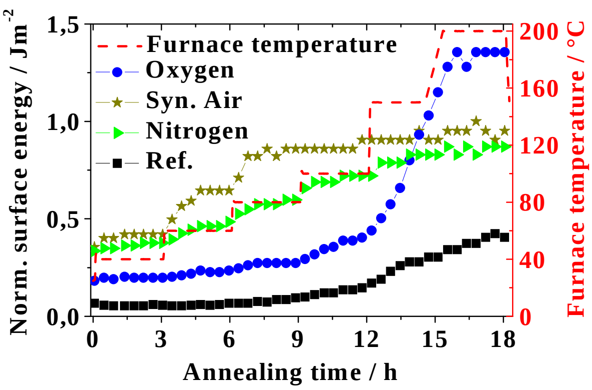

Fig. 9 Normalized surface energy during annealing for differently treated wafer pairs.

For all plasma treated wafer pairs the surface energy is higher than for the reference. Especially for the wafer pairs treated in synthetic air and nitrogen plasma, the surface energy increases almost linearly up to 100 °C with the highest surface energy measured for synthetic air. Up to 100 °C almost no increase of surface energy is observed for the oxygen plasma treated wafer, but above 100 °C, its surface energy rises strongly, eventually reaching the highest final value at 200 °C. In agreement with formerly published results [6], higher surface energies are obtained below 100 °C from synthetic air and above 100 °C from oxygen plasma treatment.

3. Conclusion

Atmospheric pressure plasma treatment based on dielectric barrier discharge is an industry-proven activation method for low-temperature wafer bonding. Furthermore atmospheric pressure plasma treatment can be used for a patterned surface treatment. These methods provide new opportunities for silicon multistack systems.

Experiments using atmospheric-pressure plasma ativation have shown, that the annealing temperature can be reduced down to 100 °C while still achieving bond energies two or three times higher than with RCA-cleaned reference wafer pairs.

In order to characterize the bond strength development during annealing, we realized a setup which allows measuring the bond energy in-situ in a furnace.

4. Acknowledgments

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