Plasma-enhanced semiconductor wafer bonding: 
Mechanism and applications

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Semiconductor wafer bonding generally refers to a process where two mirror-polished wafers adhere to each other at room temperature without the application of any macroscopic gluing layer or outside force. The process is realized also under atmospheric conditions making the analysis of the physical and chemical processes at the interface difficult. It is generally assumed that adhesion forces (van der Waals forces, electrostatic Coulomb forces, capillary forces or hydrogen bridge bonds) are the primary bonding forces. The measured interface energy is low and is about 0.1 J/m² for bonded hydrophilic wafers. An increase of the interface energy by a factor of 10 or more is obtained by a subsequent annealing at elevated temperatures (T ≥ 1000°C) which transforms e.g. hydrogen bridge bonds across the interface via the reaction

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\text{Si-OH} \cdots \text{HO-Si} \rightarrow \text{Si-O-Si} + \text{H}_2\text{O}
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into Si-O bonds (bonded hydrophilic wafers) or via the reaction

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\text{Si-H} \cdots \text{H-Si} \rightarrow \text{Si-Si} + \text{H}_2
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into Si-Si bonds (bonded hydrophobic wafers). The resulting water molecules react with silicon to form hydrogen and silicon dioxide. There are, however, numerous future applications in the fields of micro- or nano-systems requiring maximum annealing temperatures below 400°C. This means that surface conditions must be realized during this low-temperature annealing resulting in interface forces comparable to those generated at high temperatures. For hydrophilic surfaces the interface energy is equivalent to the number of silanol groups (Si-OH) at the initial surface. Therefore, an activation of the surfaces by an increasing density of silanol groups would also increase the interface energy. This can be obtained by plasmametns of the surfaces before bonding as has been suggested and partly realized already a decade ago [1]. We performed a systematic investigation of the effect of different plasma activation treatments.

Different plasma treatments were used to modify silicon surfaces and to analyze their effect on the wafer bonding behavior. The treatments included chlorine- and fluorine-containing plasmas as well as oxygen- and nitrogen plasmas [2]. Analysis of the surfaces by atomic force microscopy (AFM), spectroscopic ellipsometry, infrared spectroscopy (ATR), and contact angle measurements.

![Surface Tension of a plasma activated silicon surface. Data from contact angle measurements.](image)
Selected Results

Fig. 3: Infrared microscope image of a bonded wafer pair containing arrays of cavities.

Fig. 2: Interface energy of bonded silicon wafer pairs annealed for 2 hours. Different plasma treatments were applied before bonding.

proven strong modifications depending on the plasma applied. A fluorine-containing plasma, for instance, results in a hydrophobization, while adding oxygen into the plasma causes an increasing hydrophilicity. The most hydrophilic surfaces are obtained by treatments in an oxygen plasma. The plasma causes the formation of a thin oxide layer on the silicon surface. AFM measurements proved an increasing microroughness of the layer with increasing time of the treatment. This results in an increasing active surface area. Furthermore, the surface tension increases also (Fig. 1) which is mainly caused by an increasing polar component of the surface tension [3]. Both, the larger surface area and the higher polarity are associated with an increasing number of silanol groups on the plasma-treated surface. Their existence was proved by infrared attenuated total reflection spectroscopy (IR-ATR).

The bonding of silicon surfaces activated in an oxygen plasma results in an increase of the bonding energy by a factor of about 2 already at room temperature. An additional annealing, however, increases the interface energy rapidly to more than 1.5 J/m² after an annealing at 300°C for 2 hours (Fig. 2).

Such interface energies allow further processing for microsystem applications (Fig. 3). Analogous results are found for treatments in a nitrogen or carbon dioxide plasma (Fig. 2). Treatments in oxygen-containing plasmas do not only generate more silanol groups but also a nanoporous subsurface structure of the oxide. These nanopores allow easy incorporation of H₂O and H₂ into the oxide and an easier formation of Si-O-Si bonds by the suppression of a possible back reaction.

References