Why does a plasma treatment prior to the wafer direct bonding increase the bonding energy of silicon wafer pairs in the low-temperatur range ?

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In the last few years, the technological impact of the wafer direct bonding in the bulk micromechanical device industry has increased remarkably. Especially, the low-temperature wafer bonding moved into spotlight, since most applications include temperature-sensitive materials which limits the annealing after bonding at temperatures below about 400°C [1]. Unfortunately, the required bonding energy for postpreparation and utilisation of the devices cannot often be attained by annealing the usually hydrophilic bonded silicon wafer pairs at 400°C within some hours.

It is well known that applying an oxygen-containing plasma treatment prior to wafer bonding is a suitable approach to increase the bonding energy of the wafer pairs [2]. A considerable number of investigations on this topic have been published presenting more or less different results in terms of temperature-dependent energy enhancement which indicates that the responsible effects are not yet clear [3-4].

The objective of this study is to present a common model which can be used to describe the observed behavior of the bonding energy of plasma treated and bonded silicon wafer pairs in the low-temperature range. Therefore we have applied various O_2, N_2 and CO_2 plasmas to activate the CZ-grown silicon surface after a usual RCA-cleaning. Later on we characterized the treated surfaces via microscopical, ellipsometrical, infrared-spectroscopical and chemical methods. In the same way a certain number of wafers were hydrophilically bonded in a micro-cleanroom setup after a final DI-water rinse in order to investigate the buried interfacial oxide-layer by microscopy and infrared-spectroscopy. The bonding energy was measured by the crack opening method in air using a very thin blade. Figure 1 presents the measured bonding energy of the wafer pairs as a function of the annealing temperature.

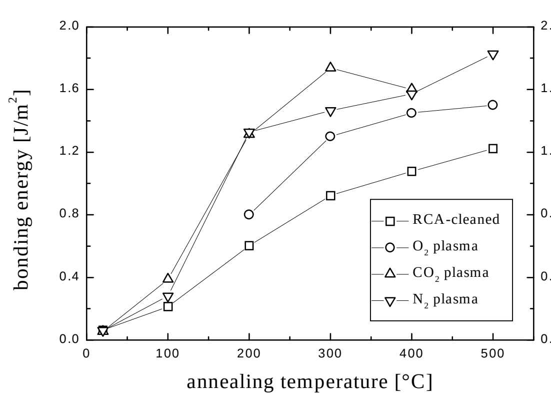

Fig. 1: Bonding energy of different plasma-treated and bonded silicon wafer pairs vs. the annealing temperature. The data are compared to RCA-cleaned wafer pairs (annealing time always 2 h).

The various results of our study let us assume that the observed increase of bonding energy results of a mixture of different effects, which can be described by the following peculiarities:

- the microroughness of the silicon surface (topological structures)
- the thickness and structure of the interface-oxide (porosity), and
- the type and order of the chemical interface-species (water, silanol-groups, peroxides and hydroper-oxides)

Thereby, the level of bonding energy strongly depends on the grade of each single effect being a complex function of the parameters of the plasma treatment.

Due to the extended duration of the plasma treatment the microroughness is increasing slightly. Using the sizes and distances of the surface structures, obtained by atomic force microscopy, a simplified calculation of the “real” surface can show that the plasma treated silicon surface is up to about 2.5 times larger than of an RCA-cleaned silicon surface. This also enlarges the possible number of surface-bonded silanol-groups which are assumed to be the essential surface species of hydrophilic silicon wafers to form strong siloxan-bonds. Indeed, the comparison of the absorption intensities of the multiple internal transmission infrared spectra attributed to the interfacial silanol-groups of RCA-cleaned and plasma treated wafer pairs could reveal an increase of these species in the bonding interface of the plasma treated wafer pairs.

Furthermore, the results of ellipsiometric measurements, transmission electron microscopy and infrared spectroscopy refer to an increasing porosity of the surface oxide after a plasma treatment. This would enhance the diffusion of the interfacial water molecules far from the interface which is assumed to be most important to generate chemical bonds via the interface.

In addition, peroxids and hydroperoxids are probably also present at plasma treated surfaces. Such species are known for their thermal instable peroxid-bonds (O–O). Once cracked at very low temperatures – even at room temperature – they also can form strong inter-surface bonds and by this way increase the bonding energy in the range up to about 200°C.

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