Perfecting Chucks: Clamping Force and Flatness

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Introduction: What is a chuck? Why is it important?

In general a chuck is used to support a substrate. Its purpose is to fix the substrate, to straighten it, to keep it at a certain temperature and to release it quickly without damaging the substrate or causing contamination. It is a versatile tool, the semiconductor industry uses it to process Silicon wafers in lithographic processes [1, 2], inspection steps, etching processes, handling wafers and for bonding of wafers. Furthermore chucks are used in other areas such as display manufacturing, where the chucked substrates are usually different types of glasses. All these different applications with very different environmental conditions lead to a broad range of specifications for the chuck [3].

In this paper we'd like to focus on two key factors which are important for most applications: the clamping force and the burl pattern which in combination strongly influence the flatness. Why are these features important?

Firstly, the chuck has to hold the substrate securely. Often the acceleration in the machines or a certain pressure of heat conductive gasses, e.g. Helium, require a minimum clamping force which an electrostatic chuck (ESC/e-chuck) or vacuum chuck has to maintain. The substrate material is often Silicon, coated Silicon wafers, glass or even more exotic materials like sapphire – all together materials with very different material parameters, e.g. volume resistivity, dielectric constant etc. Furthermore the chucking has to be highly reproducible with high accuracy, sometimes this is called "overlay", sometimes "run-out". Considering the multitude of different influences, it is necessary to determine clamping forces by measurement. Thus, we developed a measurement method and tested the influence of the electrode pattern on the clamping force for different substrate materials.

Secondly, the chuck has to release the substrate quickly. No sticking of the substrate is allowed, yet often occurs, resulting in a displacement of the wafer or even the breakage of substrates in the process chamber. For this purpose, a typical high quality chuck features protrusions, which limit the contact area between chuck and wafer. The wafer is fixed on a plane defined by the protrusions, also called pins, burls or mesas. The contact area is typically reduced down to 5%-0.1%. These burls not only limit the amount of sticking of the wafer to the chuck, they also help to keep the backside contamination of the substrate low. Fewer particles are generated in the first place and existing particles, e.g. from the resist, are more likely to drop between the burls rather than sitting on the top of them.

And here's the catch: the combined clamping force and burl pattern can lead to a deformation of the substrate between the burls [4, 5]. This deformation or sag between the pins causes focus and overlay errors in lithographic and optical inspection applications. In bonding applications the out-of-plane distortion between burls can lead to bond defects and positioning inaccuracies. Therefore the burl pattern has to be designed carefully.

Measurement Set up

a) Measurement of the clamping force

For the qualification of chucks made by Berliner Glas we use a customized Zygo interferometric set-up to measure the flatness of vacuum and electrostatic chucks with an accuracy of 1-2nm. For the characterization of electrostatic chucks a vacuum chamber with a window is installed underneath the measurement optics allowing us to collect interferometric data under vacuum (Figure 1).

Figure 1: Zygo measurement set up with vacuum chamber and measurement data showing interferometric rings as a black and white pattern.

For the measurement of clamping force the deformation between the burls is analyzed. For this purpose, substrates from glass and Silicon with a burl pattern were used. The burl pattern of 7 by 7 pins was formed on a glass sheet with the thickness of 0.7mm and a side length of 152mm x 152mm and on a Silicon wafer with a thickness of 0.775mm and a side length of 152mm x 152mm. The burl height is in the order of 10µm. The burl pitch was 20mm. The pitch was chosen because deformation between the pins should be clearly measureable. Firstly, we generated a calibration curve by using increasing vacuum pressures and chucking the substrate against a defined and flat Zerodur test surface (Figure 2). The deformation was well detectable and in the range of a few micrometers. Then the deformation was plotted as a function of vacuum pressure. This calibration curve was used later to translate the interferometric data of an ESC.

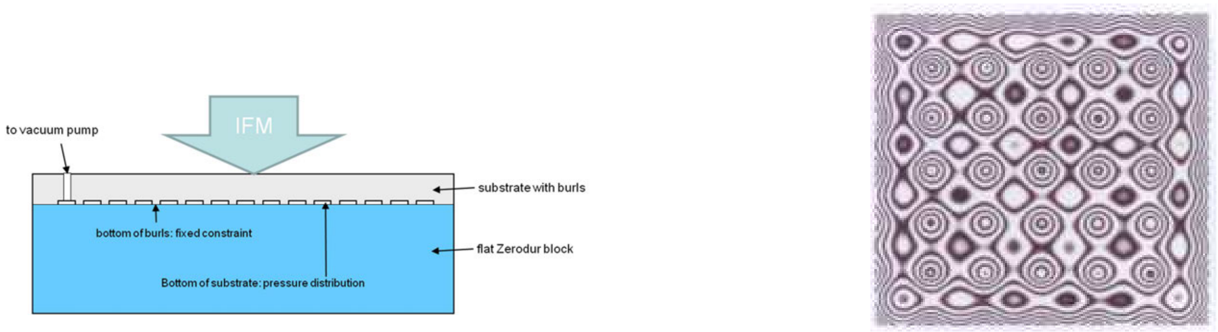

Figure 2, left: set up for calibration of the clamping force, later the Zerodur block was exchanged for an ESC.

Figure 2, right: interferometric data of one of the substrates.

After the calibration, the glass substrate (soda-lime glass) and the Silicon substrate were put on a Coulombic ESC with two rectangular and two interdigitated electrode patterns. For both substrates and both electrode pattern the clamping pressure was recorded as a function of the clamping voltage, which ranged between ±1kV to ±3kV.

b) Designing the burl pattern

For the simulation of the burl pattern we use the linear elastic model, well known in structural mechanics. The strain conditions at a point will be described with the deformation components—(u, v, w) in 3D—and their derivatives. The shear strain can be expressed in a tensor form, ε_{xy}, ε_{yz}, ε_{xz}, or in an engineering form, γ_{xy}, γ_{yz}, γ_{xz}. Following the small-displacement assumption, the normal strain components and the shear strain components are given from the deformation as follows [6, 7, 8]:

$$\varepsilon_x = \frac{\partial u}{\partial x} \qquad \varepsilon_{xy} = \frac{\gamma_{xy}}{2} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$

$$\varepsilon_y = \frac{\partial v}{\partial y} \qquad \varepsilon_{yz} = \frac{\gamma_{yz}}{2} = \frac{1}{2}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)$$

$$\varepsilon_z = \frac{\partial w}{\partial z} \qquad \varepsilon_{xz} = \frac{\gamma_{xz}}{2} = \frac{1}{2}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)$$

The symmetric strain tensor ε consists of both normal and shear strain components:

$$\varepsilon = \begin{bmatrix} \varepsilon_x & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{xy} & \varepsilon_y & \varepsilon_{yz} \\ \varepsilon_{xz} & \varepsilon_{yz} & \varepsilon_z \end{bmatrix}$$

The stress in a material is described by the symmetric stress tensor

$$\sigma = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} \qquad \tau_{xy} = \tau_{yx} \qquad \tau_{xz} = \tau_{zx} \qquad \tau_{yz} = \tau_{zy}$$

consisting of three normal stresses (σ_x, σ_y, σ_z) and six, or if symmetry is used, three shear stresses (τ_{xy}, τ_{yz}, τ_{xz}). The stress-strain relationship for linear conditions reads: σ = D ε, where D is the 6×6 elasticity matrix, and the stress and strain components are described in vector form with the six stress and strain components in column vectors defined as

$$\sigma = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \end{bmatrix} \qquad \varepsilon = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{bmatrix}$$

The equilibrium equations expressed in the stresses for 3D are

$$-\nabla \cdot \sigma = \mathbf{F}$$

where F denotes the volume forces.

To test the thereby designed burl pattern a chuck was equipped with a burl pattern. With the Zygo measurement set up the flatness of a chucked wafer was determined. The clamping pressure was 200mbar to 500mbar. The local flatness was analyzed with in-house software (ISA-MFK).

Results

The interferometric pattern of a chucked test substrate can be transformed into a 3-d plot of a deformation landscape as shown in Figure 3.

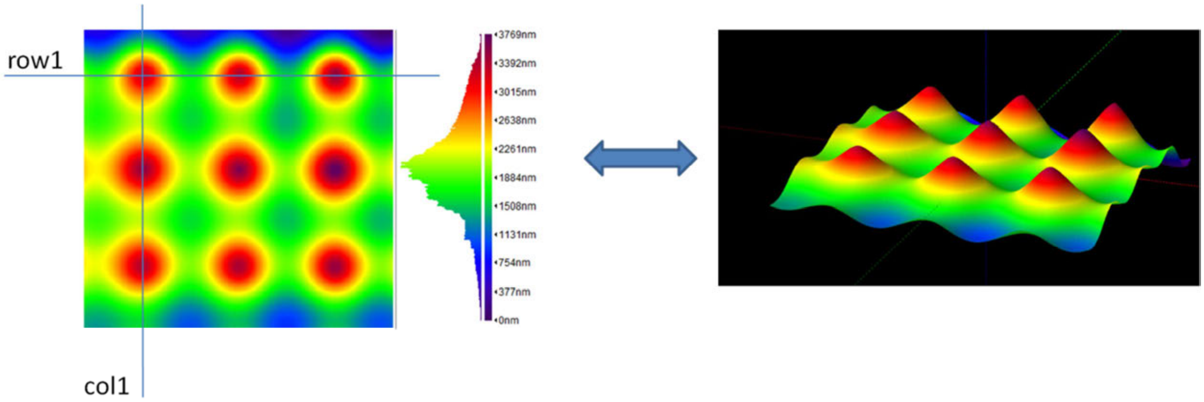

Figure 3: measurement data for 100mbar differential pressure as a color-coded height map (left) and the same information translated into a 3-d plot (right).

Shown is a color-coded map of the heights, where protruding features are coded red, whereas blue features mark indented structures. This can also be transformed into a 3-d plot, clearly showing the deformed test substrate between the burls. The pressure distribution is assumed to be homogeneous. For the average deformation of the substrate a cross-section of each row and column was analyzed. This procedure was performed with vacuum pressures from 100 – 500mbar. The vacuum pressure between chuck and substrate was correlated with the deformation between the burls. Calibration curves for glass and Silicon substrates were generated.

Secondly, a bipolar electrostatic clamp was charged with ±1000V to ±3000V. The deformation between the burls was measured again with the interferometer also resulting in a similar color-coded height map as in Figure 3. The calibration curve was used to translate the results from electrostatic chucking to a distinct clamping pressure expressed in mbar.

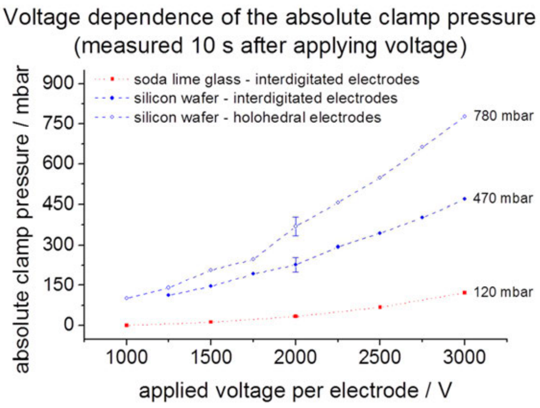

Figure 4: the clamping pressure as a function of the clamping voltage.

With standard silicon wafers clamping pressures up to 780mbar can be reached (Figure 4). It can also clearly be seen that the clamping pressure depends on the substrate material, the clamping voltage and the shape of the clamping electrode. Glasses in general are harder to clamp due to their high resistivity, but using a specially designed electrode pattern, soda lime glass can be attached to the chuck with a clamping pressure of 120mbar (Figure 4), which is more than the typical backside gas pressure (used for improved thermal conductance) of 20mbar – 50mbar.

The pressure range 200mbar to 800mbar is a very typical range for clamping pressures, since it ensures secure clamping of the wafer in a broad range of applications. For this range of pressures we designed the proper burl pattern. The goal for the chuck design is a burl pattern which has a low surface coverage of less than 3% and at the same time generating a minimum deformation between the pins.

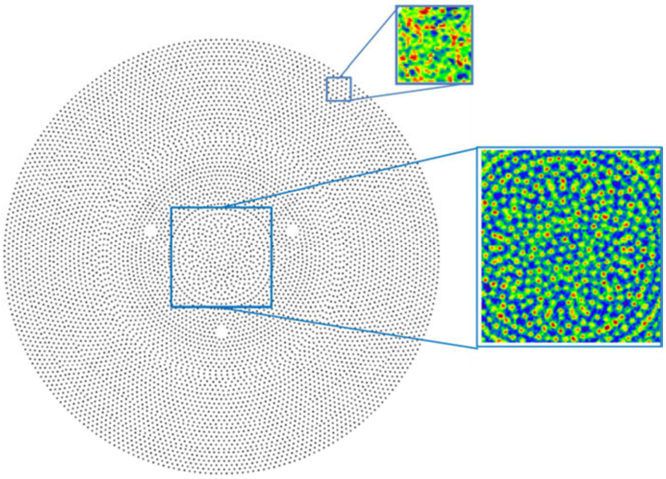

Figure 5: 300mm burl pattern, simulated and transferred to a wafer chuck. The center burls are visible for higher vacuum pressure the outer five rows of burls not.

Figure 5 shows a complete view of the 300mm burl pattern as well as two details from the measurement at 500mbar vacuum pressure. The measurement was performed at different vacuum pressures: 200mbar, 500mbar and 800mbar differential to atmosphere. The center burls can be clearly distinguished at vacuum pressures from 500mbar to 800mbar, whereas burls at the rim of the chuck can't be distinguished from each other at any pressure. Table 1 summarizes the results:

differential pressure to atmosphere [mbar]	deformation [nm]	simulation [nm]
200	< 1nm (below accuracy)	-
500	2.42 ± 0.74	2.9
800	2.82 ± 0.89	4.7

Table 1: deformations from the measurement and the simulation.

It can be seen that the measured out-of-plane-distortions are even smaller than those the simulation suggests. The deviation is in the range of a few nm and this is a range where effects like noise in the interferometric measurement, manufacturing tolerances from structuring and polishing of the burls and local variation of the Young's modulus in the reference wafer come into play. The simulation also shows quite a high sensitivity to different burls shapes, resulting in higher deformations for round edges (Gaussian profile), and also a higher deformation of the burl itself. In Table 1 the edge was assumed to be sharp and almost rectangular (continuous function).

Future work will have to determine the true edge radius of the pins on the wafer chuck and should also clarify the influence of the pins' shape, probably leading to even lower deformations due to specially designed edge curvatures.

Conclusion

In summary, Berliner Glas is able to control two important aspects of a vacuum or electrostatic chuck. We provide chucks with a high clamping pressure, which we can measure, and we are also able to design and manufacture chucks with an optimized burl pattern which keeps the in-plane- and out-of-plane distortion of the wafer low. For different wafer materials we determined the clamping pressure as a function of the clamping voltage. For given clamping pressures in the range 200mbar – 800mbar we designed a burl pattern. We measured the deformation between the burls, which ranged between <1nm and 2.9nm. Interestingly, we also observed a dependency of the wafer deformation between pins from the micro-shape of the burls. This will be subject to further studies. Also we are working on improving the clamping force measurement towards the behavior of the clamping force for temperatures up to 500℃.

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