Ultra precision waviness and figure error correction of silicon crystals by local plasma jet machining

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Abstract

Local plasma assisted etching of crystalline silicon with a fine focused plasma jet provides a method for high accuracy computer controlled surface waviness and figure error correction as well as free form processing and manufacturing. We investigated a radio-frequency powered atmospheric pressure $He/N_2/CF_4$ plasma jet for the local etching of silicon with a typical tool function width of about 0.5 to 1.8 mm. The relationship between etching rate and plasma jet parameters is discussed in detail regarding gas composition, working distance, scan velocity and RF power. Surface roughness after etching was characterized using atomic force microscope and white light interferometer.

1. Introduction

Atmospheric plasma jet machining with reactive gas components has a great technological potential for the ultra-precision modification and correction of optical surfaces [1,2]. The pure chemical material removal and the possibility of using fine focussed plasma jets with a tool half width smaller than one millimeter for effective machining with high lateral resolution are the great advantages of this method.

For the plasma assisted etching of crystalline silicon we used a radio frequency (RF) powered plasma source at 13.56 MHz with He as plasma gas, tetrafluoromethane (CF_4) as reactive gas component and nitrogen as shield gas to minimize the influence of the surrounding atmosphere. The plasmajet source consists of a metallic conductor with an inner tube. The tube has an inner diameter of 1 mm which forms the outlet for the helium/CF_4 plasma jet. Figure 1 shows the plasma jet in free burning and contact mode on a silicon wafer. In contact mode the plasma jet forms a disc at the silicon wafer surface which determines the active etching region.

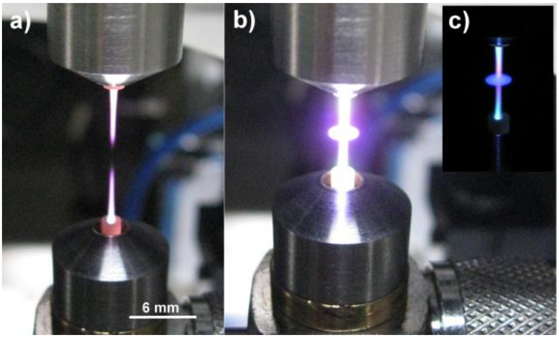

Figure 1: Fine focussed, RF powered plasma jet: a) free burning, b) in contact with silicon wafer, c) plasma jet and plasma disc on the silicon wafer surface.

2. Plasma jet process – etching rate dependencies

The material removal of silicon is based on the reaction of the silicon atoms and free fluorine radicals in the plasma jet active region. The fine focussed plasma jet forms a nearly Gaussian shaped tool function with a full with half maximum (FWHM) of 0.5 to 1.8 mm. Figure 2 shows the volume etching rate in dependence on the plasma parameters: RF power *P*, working distance between silicon surface and ceramic tube *Z*, CF_4 gas flow and scan velocity *v* over the silicon wafer. For all experiments the He plasma and the N_2 peripheral gas flow was held constant to 1000 sccm and 1500 sccm, respectively. To avoid material re-deposition on silicon wafer, the samples were heated up to 150 °C. Otherwise C-and F-containing reaction products can affect the etching process by masking the surface. The parameter dependencies were investigated using a raster path scanning with a line feed distance of 100 µm. A maximum volume etching rate of 0.054 mm^3/min was obtained using RF power of 80 W, CF_4 gas flow of 0.7 sccm, scan velocity of 1 mm/s and a surface distance of 3.5 mm. Under these condition the etching process has an etching efficiency of 10%. The FWHM of the plasma tool function has a nearly linear dependence on the surface distance and RF power supply. With a FWHM of 1.8 mm at a surface distance of 3.5 mm at 80 W and 0.8 mm at 5 mm surface distance or 65 W RF power a plasma jet machining of different kinds of free forms and errors is possible. The effect of the scan velocity on the volume etching rate is almost negligible. That indicates that the surface temperature (and therefore the etching rate) is not influenced by the plasma jet heat flux to the surface. Measurements using a thermal imaging camera showed a surface temperature increase of 20 – 30 K during the plasma etching process.

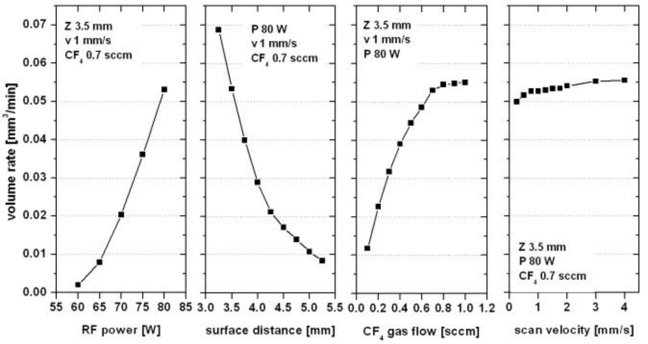

Figure 2: Volume etching rate dependence on RF power, surface distance, CF_4 gas flow and scan velocity.

Surface roughness after etching was characterized using atomic force microscope and white light interferometer. Due to the pure chemical removal of the material the plasma jet machining works sub-surface damage free. That means no mechanical force takes effects on the sample surface. On polished and cleaned silicon wafers the micro roughness after a 10 µm deep plasma etching was characterized using MicroXAM white light interferometric surface profiler with 50x objective. The root mean square roughness R_q retained the initial value of 0.35 nm. Atomic force microscopy measurements of 10x10 µm^2 indicated a homogeneous covering of the silicon surface with nanometer sized particles/structures changing the R_q initial value of 0.2 nm to 2.44 nm. On the other hand the plasma jet process has a polishing effect on rough surfaces. A stepwise removal of silicon material on ground/etched wafer backsides decreased the initial R_q value of 0.73 µm down to 0.2 µm.

2.1 Plasma jet machining

Local plasma assisted etching provides a method for high accuracy computer controlled surface waviness and figure error correction as well as free form processing and manufacturing using the dwell time technique [3]. Figure 3 shows a plasma jet machining summary using a reduced RF power of 65 W with a tool function of 0.8 mm and an etching rate of 0.0069 mm^3/min.

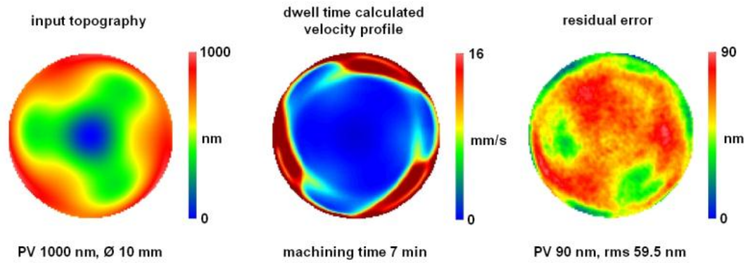

Figure 3: Plasma jet machining of a Zernikes-generated surface profile (left), dwell time calculated velocity profile and residual error after plasma jet machining.

The input topography was generated using a mathematical surface description of Zernike polynomials (Z3: 0.5, Z8: -0.15, Z10 -0.25, Z18 -0.5, Z24 -0.25) with a peak to valley PV value of 1 µm. After a plasma machining process of 7 min the generated surface profile was measured by interferometer. A final residual error of 90 nm PV indicates a slight over-etching at the edges.

3. Conclusion

In this paper we presented detailed investigations of local plasma assisted etching of crystalline silicon with a fine focused plasma jet for ultra-precision waviness and figure error correction. Since there are almost no geometric restrictions for the contactless plasma jet tool machining there exist nearly no limitations for surface design and correction.

References:

[1] T. Arnold, G. Böhm, R. Fechner, J. Meister, A. Nickel, F. Frost, T. Hänsel, A. Schindler, Nucl. Instrum. Meth. A, 616 (2010), 147.

[2] T. Arnold, G. Böhm, I. Eichentopf, M. Janietz, J. Meister, A. Schindler, Vakuum in Forschung und Praxis, 22 (2010) 10.

[3] T. Hänsel, F. Frost, A. Nickel, A. Schindler: Vakuum in Forschung und Praxis 19 (2007) 24-30.