Acoustic laser cleaning of silicon surfaces

Universität Konstanz, Universitätssstr. 10, 78457 Konstanz, Germany

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ABSTRACT We investigate the detachment of small particles from silicon surfaces by means of acoustic waves generated by laser-induced plasma formation at the back side of the sample. It is demonstrated that sufficiently high acoustic intensities can be reached to detach particles in the submicron regime. In order to study this “acoustic laser cleaning” in more detail, we have developed an interference technique which allows one to determine the elongation and acceleration of the surface with high temporal resolution, the basis for an analysis of the nanomechanical detachment process, which takes place on a temporal scale of nanoseconds. We find that the velocity of the detaching particles is significantly higher than the maximum velocity of the substrate surface. This indicates that not only inertial forces, but also elastic deformations of the particles, resulting from the acoustic pulse, play an important role for the cleaning process.

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1 Introduction

Adhesion phenomena are omnipresent in everyday life, but in spite of their importance, the underlying mechanisms are not yet fully understood, due to the complexity of the surfaces in contact, their structure and their interactions. This not only holds for the adhesion of biological objects like cells [1] or even animals like spiders and geckoes [2], where progress in the microscopic understanding has been achieved only recently, but is also true for, at first sight, much simpler examples like dust particles on flat surfaces. The adhesion of unwanted small particles poses serious problems in micro- and nanotechnology and is one of the main sources of malfunction, e.g., of semiconductor chips. For this reason understanding the mechanisms of adhesion is also crucial for the development of new cleaning schemes for particle removal from surfaces.

One of these schemes, being developed complementary to conventional ultrasonic techniques, is laser cleaning [3]. The basic concept in its simplest form, the so-called dry laser cleaning (DLC), is to heat the sample by a short laser pulse, which gives rise to a rapid expansion of the substrate. According to this concept inertial forces acting on the particles during the deceleration phase of the substrate surface can become sufficiently large to overcome the adhesion forces, and the particles will detach [4]. Vice versa, one might consider this technique not only for cleaning, but also as a means for a determination of adhesion forces, provided the time-dependent position of the substrate surface is known with sufficient accuracy. This dynamic approach appears as an alternative to the quasi-static measurement of adhesion forces acting on small particles by means of atomic force microscopy [5].

A direct application of this dynamic concept for determining adhesion forces is hampered, however, by the fact that in the standard DLC process further mechanisms come into play. In addition to the thermal expansion, local ablation of the substrate due to enhancement of the incident laser intensity by the optical near field of the particles occurs [6]. In this work we present a method in which these complications are avoided by irradiating not the front, but the back side of the sample. An acoustic pulse is generated, which propagates through the sample, leading to a momentary elongation of the surface without the simultaneous presence of an optical field in the vicinity of the particle. We describe below how the displacement can be measured with an accuracy of 0.1 nm and a temporal resolution of 0.2 ns and demonstrate that the inertial forces reached in this way are sufficient for an acoustic removal of test particles from silicon wafer surfaces by means of “acoustic laser cleaning”.

2 Experimental setup

The pulsed laser source used in our experiments for the generation of the acoustic pulses was a frequency-doubled Nd:YAG laser with a pulse length of 10 ns at 532 nm and a Gaussian profile. The laser was focused to a 0.54 mm FWHM spot at the back side of the samples, 3.05 mm thick boron doped Si slabs with (111) orientation. The front side of the samples was either carefully cleaned for the measurements of the surface displacement (Figs. 2–4) or covered with test particles for the investigation of the acoustic cleaning efficiency (Figs. 5 and 6). As test particles we used colloidal polystyrene spheres with a diameter of 840 nm, which were distributed uniformly across the substrate by means of a spin coating pro-
In order to detect the time-resolved displacement of the reflecting sample surface, we used a modified Michelson interferometer, as described in [8, 9] (Fig. 1). In our set-up the interferometer is stabilized by a piezoelectrically driven mirror in the reference arm. The adjustment is obtained by a common scanning tunneling microscope control unit. This leads to a stabilization of the interferometer up to 1 kHz, suitable for eliminating temperature fluctuations and slow vibrations, whereas faster mismatches between the two arms will not be corrected. Thus the optical output of the interferometer, registered with a fast photodiode (Det2 in Fig. 1), allows one to measure surface displacements with frequencies higher than 1 kHz. Full width at half maximum of our detector (Hamamatsu GA4176) is 200 ps as tested with a fs light pulse. The light source of the interferometer is an Ar-ion laser at a wavelength \(\lambda_{\text{int}} = 488\) nm, single longitudinal mode and an output of 1.5 W cw. In contrast to a common interferometer set-up, we use a polarizing beam splitter cube in order to minimize reflections on the beam splitter surfaces, to control different reflectivities of the mirror materials and to avoid the reflection of the inverse interference pattern into the laser. To get the reflected light from both arms into the detection arm the quarter-wave plate rotates the polarization of the waves by \(90^\circ\) after two passes. Both reflected and orthogonally polarized beams of the two arms are brought to interference by a second beam splitter cube, as the cube transmits only those parts of the beams with the same polarization. From the measured intensity \(I\) in the center of the interference pattern the displacement \(\Delta d\) of the surface is obtained, using

\[
I = I_{\text{max}} \frac{4R_0}{4R_0 + R_{\text{Ref}} + \sqrt{R_{\text{Ref}}R_{\text{Si}}}} \cos \left( \frac{4\pi \Delta d}{\lambda} \right),
\]

where \(I_{\text{max}}\) is the maximum intensity, and \(R_{\text{Ref}}\) and \(R_{\text{Si}}\) are the reflectivities of the reference mirror and the silicon sample. The displacement resolution achieved with the interferometer is 0.1 nm for single shot experiments and

cess [7]. Whether or not these particles were removed from the sample surface by the acoustic pulse was determined by light scattering. For this purpose we used a He-Ne probe laser (632.8 nm) to illuminate the particles residing on the surface and a photomultiplier to register the scattered light. Any detachment of particles results in a decrease in scattering intensity. In addition, the samples were inspected afterwards ex situ with a dark field microscope, where particle detachment showed up as a dark spot (Fig. 5).