First publ. in: Applied Physics A 69 (1999), pp. 335-337

Surface acceleration during dry laser cleaning of silicon

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Received: 21 July 1999/Accepted: 11 September 1999/Published online: 22 December 1999

Abstract. We report on measurements of the surface acceleration for the application of dry laser cleaning. For that purpose, industrial silicon samples were irradiated by a frequency-doubled Q-switched Nd:YAG laser. The surface displacement was measured by a heterodyne interferometer and recorded by a digital storage oscilloscope. Several hundreds of shots were averaged to give smooth displacement curves which could be derived numerically. The experiments show that the highest accelerations, which are thought to be responsible for the cleaning, occur on the time scale of the laser pulse. Simple theoretical models are in good agreement with the experimental data. The maximal displacement depends only on the deposited energy, while the maximal acceleration shows also a strong dependence from the temporal pulse shape. This knowledge allows one to optimize the pulse shape for the cleaning process.

PACS: 81.65.C; 79.60.Bm

In order to remove particles with diameters below 1 μm from substrates, a cleaning force exceeding the strong van der Waals adhesion must be applied to the particle. Because the van der Waals force grows rapidly with decreasing particle diameter as compared to the forces used in conventional cleaning techniques (e.g., ultrasonic cleaning), these methods are not capable of removing particles below several hundreds of nanometers. A technique called dry laser cleaning has been proposed to remove such small particles from substrates [1–4]: A short laser pulse irradiates the substrate, which expands during the pulse and accelerates the particles. The particles are ejected because of their inertia at the high negative acceleration (the rapid stop of the thermal expansion) at the end of the laser pulse.

Dry laser cleaning has been proposed for cleaning surfaces like hard disk heads and silicon wafers in microelectronics, in which such small particles can lead to defects on disk heads and yield loss in chip production [5].

We report on the surface acceleration of commercial silicon wafers in dry laser cleaning conditions with a frequency-doubled Nd:YAG laser.

1 Experimental setup

The experimental setup is depicted in Fig. 1: The beam of a Q-switched Nd:YAG laser is frequency-doubled ($\lambda = 532$ nm) and guided to the silicon substrate by several prisms. The laser energy can be attenuated in a controlled way by $2n$ glass plates ($n = 1 \ldots 5$); if necessary, a lens can be used to increase the energy density at the surface. We used commercial silicon wafers (Wacker siltronic, thickness 0.75 mm) as substrates.

The surface displacement of the silicon substrate was measured by a heterodyne interferometer (B.M. industries, SH-130, bandwidth 200 kHz–45 MHz) and recorded on a digital storage oscilloscope (LeCroy 9450A, 400 MHz). A fast photodiode (FND100, rise time 1 ns) was used to register the temporal shape of the incident laser pulse. The pulse duration could be changed by variation of the flash lamp energy of the Nd:YAG laser between approximately 10 ns and 20 ns

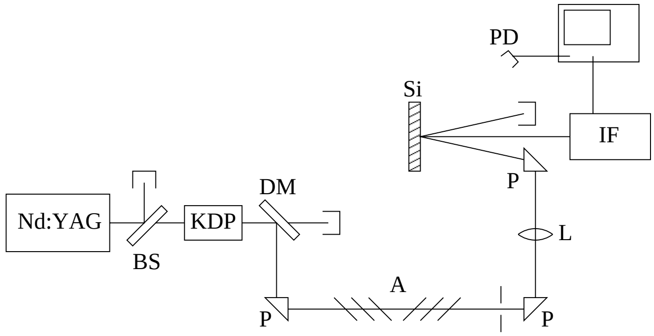

Fig. 1. Experimental setup. BS: beam splitter; KDP: frequency doubler; DM: dielectric mirror; P: prism; L: lens; PD: photodiode; IF: interferometer; A: attenuator; Si: silicon sample

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COLA'99 – 5th International Conference on Laser Ablation, July 19–23, 1999 in Göttingen, Germany

(FWHM). Energy density was calculated from the spot size and the pulse energy.

In order to reduce noise, we averaged the displacement signals over 600 shots. The surface acceleration was calculated by the numerical derivation of the surface displacement.

2 Theoretical description

Let R denote the reflectivity of the surface, $f(t)$ and F the normalized intensity and the energy density of the laser pulse, α the linear thermal expansion coefficient, and C_P and ϱ the specific heat and density of the material. At the time t, the energy per area $(1-R)F\int_{-\infty}^{t} f(t')\mathrm{d}t'$ has been deposited in the substrate. This leads to a temperature rise and a thermal expansion $d(t)$, which can be written as

$$d(t) = \frac{\alpha}{\varrho C_p}(1-R)F\int_{-\infty}^{t} f(t')\mathrm{d}t' \quad (1)$$

if $\alpha/(\varrho C_p)$ is not temperature-dependent (which, in first approximation, is justified for silicon). Here, one neglects effects of stress generated by the constrained lateral expansion of the surface and any other thermoelastic effects.

More rigid calculations have been performed by [6] and [7]; both lead, for the early time scale, to the displacement

$$d(t) = 2(1+\nu)\frac{\alpha}{\varrho C_p}(1-R)F\int_{-\infty}^{t} f(t')\mathrm{d}t' \quad (2)$$

with ν the Poisson ratio. More complex thermoelastic models, such as [8] or [9], allow only numerical treatment and will not be considered here.

Assuming $f(t)$ to be Gaussian with FWHM τ, the maximal acceleration $a_{\max}$ of the surface becomes

$$a_{\max} \approx \pm\begin{pmatrix}4.10\\1.71\end{pmatrix}\times 10^6\,\mathrm{g}\frac{\mathrm{ns}^2}{\mathrm{mJ/cm}^2}\frac{F}{\tau^2} \quad (3)$$

with the upper value for the thermoelastic calculation (2) and the lower value for the simple model (1). Both models show a linear dependence of the maximal achievable negative surface acceleration $a_{\max}$ from the incident energy density F and a quadratic dependence of the FWHM τ on a Gaussian pulse.

To check the influence of the temperature dependence of the material properties, we did some numerical calculations: We integrated the one-dimensional heat diffusion equation with fully temperature-dependent material properties and light absorption to obtain the temperature distribution in the substrate. These data allowed us to derive the surface displacement and acceleration. The numeric values are in good agreement with the simple model (1).

3 Results

Figure 2 shows a typical result of the experiment: The silicon expands during the laser pulse and reaches a plateau $d_{\max}$. A three-point numerical derivation gives the acceleration also shown in Fig. 2. Ejection of particles is expected to take place during the high negative acceleration ($a_{\max}$), when they leave the surface as a result of their inertia.

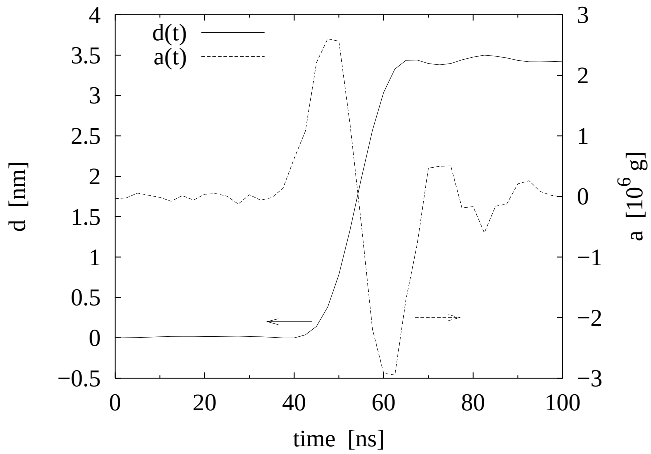

Fig. 2. A typical result for the displacement $d(t)$ and the acceleration $a(t)$. The offset in time is introduced by the interferometer electronics. The interesting part for dry laser cleaning is the region between 50 ns and 60 ns with the maximal negative acceleration of $a_{\max} \approx -3\times 10^6$ g and $d_{\max} \approx 3.5$ nm

On a longer time scale (not shown here), the surface displacement is governed by elastic waves and effects of plate bending. Although these effects give rise to great displacements, their contribution to the surface acceleration is negligible.

3.1 Dependence from pulse energy

Figure 3 shows the maximum displacement $d_{\max}$ (the value of the plateau) as a function of the incident flux. The expected linear dependence (cf. (1) and (2)) is clearly visible.

The maximum negative surface acceleration $a_{\max}$ is a linear function of $d_{\max}$, as can be seen in Fig. 4, and hence is also proportional to the incident laser flux. The ratio $-a_{\max}/d_{\max}$ is therefore independent from the incident energy density and can be used as a measure of the influence of the temporal pulse shape.

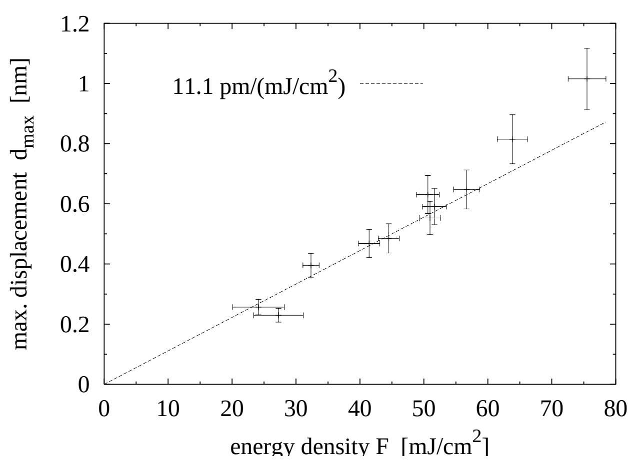

Fig. 3. Maximum displacement $d_{\max}$ as a function of incident laser energy density F

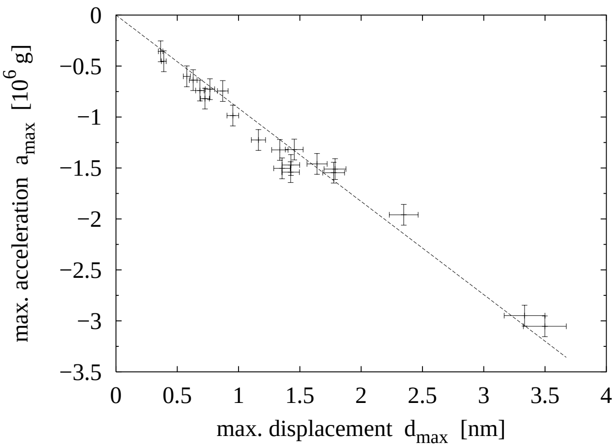

Fig. 4. Maximum acceleration a_{max} as a function of maximal surface displacement d_{max}

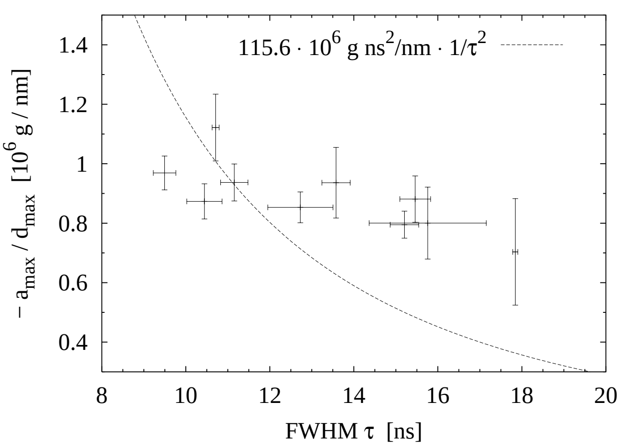

Fig. 5. Dependence of $-a_{max}/d_{max}$ on the pulse width τ. The *dashed line* is a best $1/\tau^2$ fit to the data

3.2 Dependence on pulse width

The ratio $-a_{max}/d_{max}$ (see Fig. 5) increases for shorter pulse widths but not as strongly as is expected for a Gaussian temporal pulse profile. There may be two causes for this behavior: The pulse shape is not an ideal Gaussian (rise time $<$ fall time) and the bandwidth limit of the interferometer is reached for the shorter pulse widths.

Combining the results from Fig. 3 and those of the $1/\tau^2$ fit from Fig. 5, one obtains

$$a_{max} \approx -1.3 \times 10^6\,\mathrm{g}\,\frac{\mathrm{ns}^2}{\mathrm{mJ/cm}^2}\,\frac{F}{\tau^2} \tag{4}$$

which is in fairly good agreement with the value of the simple model in (3).

4 Conclusion

We determined the maximal achievable surface acceleration during dry laser cleaning of silicon wafers. A simple model for the thermal expansion gives correct values for the displacement and good estimates for the acceleration. While the displacement is dominated only by pulse energy, the acceleration shows a clear dependence from the temporal pulse shape: Shorter pulses yield higher accelerations, therefore cleaning experiments with shorter pulses would be obvious.

Acknowledgements. This work was performed at the university of Burgundy (Dijon/France) as part of the TMR project ERB FMRX-CT98-0188 “Modelling and Diagnostics of Pulsed Laser-Solid Interactions. Applications to Laser Cleaning”.

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