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Interaction of laser-generated surface acoustic pulses with fine particles: Surface cleaning and adhesion studies

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The mechanical forces associated with the surface acceleration in high-amplitude surface acoustic waves (SAWs) detach the particles from the surface. The removal of micron sized particles with a nanosecond SAW pulse excited by a focused laser beam in a silicon wafer was quantitatively investigated. Both vertical and horizontal particle displacements have been observed. It is shown that for nanosecond SAW pulses the limit of the surface acceleration of about 10^{10} m/s^2 is set by the fracture of the material and corresponds to the removal of particles larger than about 0.05 μm. In addition, the nonlinear transformation of the excited SAW pulses results in an increase of the surface acceleration and contributes to the cleaning process extending it to even smaller particle dimensions. The technique is applicable in vacuum and improves the energetic effectiveness of the cleaning due to the removal of particles not only in the irradiated region, but also in the wider area covered by the SAW pulse propagation. It can be also used for the determination of the Hamaker constant of the adhesion force. [S0021-8979(98)02317-2]

I. INTRODUCTION

There are several fields in modern semiconductor and integrated circuit technology for which the development of semiconductor processing free of fine particles becomes increasingly important.[1,2] One of the fields of application is in microcircuit technology, where patterns with submicron dimensions are produced, which need to be free from particulates. Another field is in mask production in x-ray lithography. At the submicron level new methods for detaching submicron sized particles have to be used, since the traditional surface cleaning techniques are no longer effective. A better understanding of the attachment of fine particles to surfaces and the development of more efficient cleaning methods requires also a detailed study of the adhesive forces.

In the present work a novel cleaning technique with laser-generated surface acoustic waves (SAWs) and the mechanism of particle detachment by SAWs are studied. In particular, the influence of the ambient conditions on the detachment of particles is investigated and the interaction of linear and nonlinear SAW pulses with the particles are considered.

A. Traditional and laser techniques for surface cleaning and adhesion measurements

The smaller the particles, the harder they are removed from the surface. This is due to the fact that the ratio of surface adhesion forces and forces proportional to the particle cross section, such as those created by gas or liquid flows, or those proportional to the particle volume, i.e., the force of gravity, increases with a decrease of the particle dimensions. Adhesion forces are usually measured by some method involving the detachment of particles. Therefore, the same methods can also be used for the purpose of cleaning. It is pointed out that the traditional methods[2,3] based on centrifuge, vibration, and hydrodynamic flow are not able to produce accelerations higher than about 10^7 m/s^2. This is at least an order of magnitude less than what is required for the detachment of submicron particles.

In recent years several laser cleaning techniques[4–12] have been developed. Some of them[4,5,7–12] are wet techniques and are based on the deposition of a thin liquid film on the surface, with the subsequent explosive evaporation of the adsorbed film by laser heating. Such rapid evaporation produces forces, which are larger than the adhesion force, and propel the particles off the substrate. Other techniques use absorption of laser radiation by the particles themselves, or in the substrate and therefore do not need immersion of the surface into a liquid. Therefore, these methods are referred to as dry techniques.[7] It is pointed out that almost all of the mentioned methods are ''local,'' since they work only in the region of the interaction of laser radiation with the surface. The exception is the technique of Ref. 6 which employs for cleaning sound waves excited in a thick liquid layer. A shock wave created by the laser-induced explosive evaporation of a thin liquid layer was observed in Ref. 10, however the influence of the shock wave on the size of the cleaned area was not studied.

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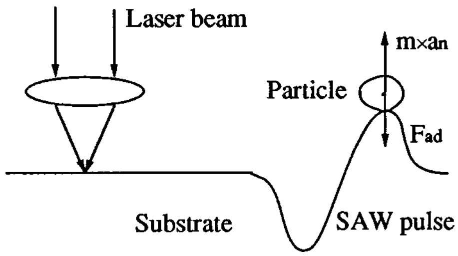

FIG. 1. Schematic diagram of surface cleaning with a laser generated SAW pulse.

B. Cleaning of surfaces with laser-generated SAWs

The high accelerations produced in the region of the interaction of laser radiation with matter can be transferred to a much wider surface area via SAWs propagating outward from the region of laser action. The process of cleaning based on this principle[13,14] is depicted in Fig. 1. The laser pulse should be short and sharply focused onto the surface[15] to produce SAWs of the Rayleigh type with high amplitudes. Extremely high surface accelerations can be realized with this laser technique and allow the advancement of surface cleaning and adhesion measurements far into the domain of submicron particle dimensions. This technique is essentially dry and applicable also under vacuum conditions where most of the other methods cannot be used.

Since surface acoustic waves are concentrated within a surface layer having a thickness of the order of the acoustic wavelength, their amplitude decreases relatively slowly, namely as the square root of the distance in the case of a point source. Even this decrease can be avoided when creating a line-shaped source providing SAWs without divergence in the near field. This photoacoustic technique is also useful for the in-detail investigation of the adhesion forces, since it is quite easy to control the parameters of the laser-generated SAW pulse by varying the size of the focal spot or by changing the incident laser power.

C. Detachment of fine particles from the surface

The principle interaction that is encountered in the adhesion of fine micron-sized particles to solids is a molecular interaction that is determined by the Van der Waals forces. At a spherical-planar contact boundary[2,3,16] we have

$$F_{ad}=A_{132}d/12z_0^2, \tag{1}$$

where A_{132} is the Hamaker constant dependent on the particle material "1," the solid surface properties "2," and the ambient medium "3." The latter is assumed in our consideration to be air or vacuum; d is the particle diameter, and z_0 is the separation distance between the particle and the surface.

The inertial force due to the normal component of the surface acceleration is $F_n=ma_n$, where m is the mass of the particle. For detachment of a particle from the surface it should be larger than the adhesion force (Fig. 1). Thus, the necessary acceleration is

$$a_n>A_{132}/(2\pi\rho d^2z_0^2), \tag{2}$$

where ρ is the density of the particle material. For short pulsed accelerations another condition also becomes important: the particle should obtain a kinetic energy sufficient to overcome the surface potential well created by the attractive molecular forces. This condition can approximately be presented in the form[14]

$$m\nu_n^2/2>F_{ad}z_0, \tag{3}$$

where ν_n is the normal component of the surface velocity.

The surface potential has a minimum at about 4–10 Å from the surface.[2] Therefore, in the estimates we assume that the distance z_0 is 4 Å. The Hamaker constant has the value of order of 1 eV.[2,3] From Eq. (2) it follows that in order to remove a 1 μm particle it is necessary to reach the normal acceleration of 4.5×10^6 g, where g is the acceleration of gravity. For a 0.1 μm particle the necessary acceleration for removal is two orders of magnitude higher.

The force required for dragging the particle tangentially is

$$F=ma_t>\mu F_{ad}, \tag{4}$$

where a_t is the tangential acceleration and μ is the friction coefficient. The value of μ for static friction lies in the range from 0.5 to 2.0 for different clean materials, for instance, for glass on glass $\mu=0.9-1.0$, and for glass on metal we have $\mu=0.5-0.7$.[17]

It should be noted that adhesion forces of particles depend, aside from the dimensions and the material, also on the particle shape and local properties of the surface (roughness, hardness, etc.) which determine an overall statistical character of these forces. Moreover, the deformations of the interacting surface forces change the contact area produced which complicates the description of the adhesion forces.[18–20] These deformations, which depend on the mechanisms and the magnitude of the surface interactions as well as on the elastic and electronic properties of contacting materials, should be taken into account for the accurate determination of the adhesion characteristics and evaluation of surface forces. In particular, the friction coefficient for microscopic particles can deviate substantially from its macroscopic value due to the surface deformation in the contact area. In the following analysis we present estimates based on a simplified approach of Eq. (1), which is a reasonable approximation for the hard surfaces of the Al_2O_3 particles and the Si substrate considered.

D. Influence of the ambient conditions on the removal of particles

In humid air condensation can occur in the gap between the contacting surfaces. This provides an additional contribution to the adhesion force. For a 1 μm particle this contribution can exceed[2,3] the molecular component of Eq. (1) by a factor of up to 10.

Another contribution of the adhesive force arises as a result of the electric charge of a particle caused by the contact potential or charge buildup. Such an electrostatic force can be comparable[2,3] to the molecular Van der Waals force of Eq. (1).

The viscosity of air slows down the particles propelled off the surface. An estimate based on Stokes' formula shows that a 1 μm particle with the initial velocity of 1 m/s will move away from the surface only a distance of about 12 μm at atmospheric pressure. The stationary velocity of such a particle falling under the action of gravity is about 120 μm/s. Therefore, even when the surface is positioned vertically, the particle will with a high probability return to the surface due to the long-range molecular attractive forces.

Vacuum conditions change the secondary sedimentation of particles drastically. Even at the low vacuum of 0.1 Torr a particle of the same size as above will be stopped due to remaining air viscosity at a distance of 4 cm and its stationary velocity due to gravity will be about 40 m/s. For a vertical orientation of the surface after detachment the particle will most likely fall off without returning back to the surface.

II. LASER GENERATION OF HIGH AMPLITUDE SAW PULSES

Laser methods allow the excitation of SAW pulses with extremely high amplitudes. A short duration laser pulse is focused on the surface of the sample, producing a point or a line source with a characteristic duration of the excited SAW pulse determined by the duration of the laser pulse and the SAW traversal time through the area of the laser spot. Different processes may be responsible for the SAWs excitation:[15,21] thermoelastic stresses, surface vaporization, and optical breakdown, the latter two also causing surface ablation. In the case of semiconductors the optical breakdown is usually more efficient than the thermoelastic interaction since the thermal expansion coefficient in these materials is rather small.[17] The SAW pulse amplitude may be increased substantially by depositing on the solid surface a layer of a strongly absorbing liquid.[22] Very high amplitude SAW pulses were recently generated with this method.[23,24] In this case the SAW pulse in the solid sample is excited by a strong pressure pulse produced in the liquid layer. Pulsed pressures with an amplitude of up to 1 GPa were produced with a picosecond erbium laser.[25] If a strong optical absorption takes place in the substrate, a transparent layer deposited onto the surface constrains the ejection of vapor and facilitates the increase of pressure in the interaction region.

Thus, the generation of SAWs by the ablation mechanism or when acting with laser radiation through a liquid layer can be modeled by a pressure pulse $p(\mathbf{r},t)$ acting on the free surface of a solid. Assuming a Gaussian distribution $p(\mathbf{r},t)=p_0\exp[-(x^2+y^2)/a^2)-t^2/\tau_0^2]$ the normal velocity component $\nu(\mathbf{r},t)$ in the excited SAW pulse can be described in a linear approximation by the expression:[22,26]

$$\nu(\mathbf{r},t)=\frac{c_R}{4}\left(\frac{a^2}{2rb}\right)^m\frac{ac_R\tau_0}{b^2}\frac{p_0}{\rho c_t^2}\,\Gamma\gamma\Phi_m[(c_Rt-r)/b],$$

$$\Phi_m(\xi)=\int_0^\infty k^{1+m}\exp(-k^2/4)\cos(k\xi+\pi m/2)\,dk, \qquad (5)$$

$$b=(a^2+c_R^2\tau_0^2)^{1/2}.$$

Here a is the Gaussian parameter of the laser intensity distribution, b is the characteristic wavelength of the SAW pulse, $m=0$ for a line-shaped source (near acoustic field), and $m=1/2$ for a pointlike source. In Eq. (5) dimensionless combinations of the elastic constants were introduced[26]

$$\gamma=[(1-c_R^2/c_l^2)/(1-c_R^2/c_t^2)]^{1/4},$$

$$\Gamma=\{(c_t^2-c_R^2/2)[(c_t^2-c_R^2)^{-1}+(c_l^2-c_R^2)^{-1}]-2\}^{-1}, \qquad (6)$$

where $c_{t,l,R}$ are the propagation velocities of the transverse, longitudinal, and Rayleigh waves. For different solids the product $\Gamma\times\gamma$ ranges from 0.1 to 1.

The relative magnitude of the SAWs is conveniently described by the dimensionless acoustic Mach number $M=\nu/c_R$, where ν is the amplitude of the surface velocity and c_R is the propagation velocity of the Rayleigh surface wave. We find from Eq. (1) that a pressure pulse with $p_0=10^8$ Pa is enough to generate in silicon as SAW pulse with $M=10^{-4}$ assuming the acoustic wavelength of $b=100$ μm, $\tau_0=20$ ns, that are typical for laser excitation. Similar conditions have been realized experimentally[22] when a SAW pulse with $M=2\times10^{-4}$ was registered at a distance of 1 cm from the source. In this experiment the excitation was produced by a 10 mJ, 10 ns yttrium aluminum garnet (YAG):Nd^{3+} laser pulse in silicon. Even higher Mach numbers about 0.003 were reached with an intermediate liquid layer on the surface.[23,24] In such SAW pulses nonlinear distortions can develop already over a distance of about 1 cm.

III. DETACHMENT OF PARTICLES INDUCED BY SAW PULSES

A particular feature of cleaning with SAW pulses is its ''nonlocal'' character. Indeed the cleaning effect produced by a high amplitude SAW pulse will take place not only in the region of the laser irradiation, but in the much larger area covered by the propagation of this pulse. We will use the following approach to consider in more detail the interaction of the SAW pulse with a particle in the linear and nonlinear SAW regimes. Assuming that the acoustic nonlinearity induces small changes in the generation process of the SAW pulse parameters of the order of the Mach number, one can see that even at Mach numbers of about $M=10^{-2}$ the linear description of the generation process is a good approximation. Then the excitation and propagation processes can be considered sequentially: initially the excited SAW pulse can be calculated according to Eq. (4) and then the velocity of the excited SAW pulse can be used as the initial profile in the nonlinear evolution equation.

A. Linear approximation for SAW pulses

In Figs. 2(a)–2(d) the time dependences of the velocity and acceleration for a one-dimensional SAW pulse, $m=0$, are presented. In the linear approximation of Eq. (5) the profiles do not depend on the distance. They were used as the initial profiles in the calculations of the SAW pulse nonlinear evolution in the next section. Such initial profiles are labeled by the distance $x=0$ mm. The dependences were calculated for $p_0=2.4$ GPa, $b=30$ μm, $\tau_0=10$ ns, and typical values $c_R=3.40\times10^3$ m/s, $(c_t/c_R)=1.10$, $(c_l/c_R)=1.59$.

As an example we considered the conditions for the detachment of a 0.4 μm particle. The detachment of a particle

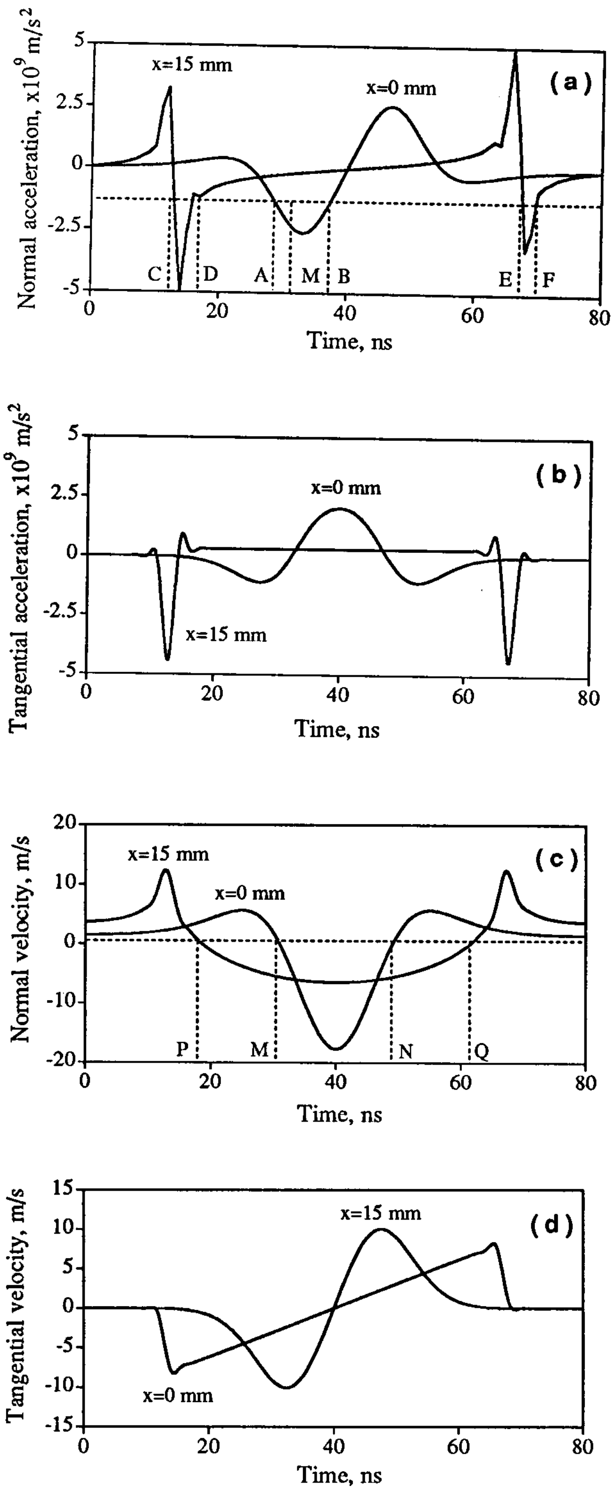

FIG. 2. Surface acceleration and velocity in SAW pulses vs time: (a) normal acceleration, (b) tangencial acceleration, (c) normal velocity, and (d) tangencial velocity. The waveforms at $x=0$ mm are calculated using Eqs. (5) and (6), the waveforms at $x=15$ mm are calculated with the nonlinear evolution Eq. (7) and presented with the time shift equal to the propagation time of a linear SAW.

from a surface occurs, when the acceleration is directed into the surface, which provides a detaching inertial force counteracting the adhesion force. In Fig. 2(a) this condition together with that of Eq. (2) is fulfilled in the time interval AB. For the particle to be removed from the surface the normal velocity of the particle after detachment should be directed away from the surface and the condition of Eq. (3) should be satisfied. This imposes some requirements for the values of the normal velocity component which are fulfilled in the corresponding intervals in Fig. 2(c) to the left from point *M* and to the right from point *N*. Thus, the detachment of the particle occurs only in a rather narrow time interval AM shown in Fig. 2(a).

B. Nonlinear SAW pulses

The shape of high amplitude SAW pulses is changing in the course of the propagation due to the acoustic nonlinearity. Therefore, the acceleration and velocity are also changing. To describe nonlinear SAW pulses an evolution equation was derived.[27] Taking into account the possible divergence of the SAW pulse and its attenuation, which becomes especially important with the nonlinear steepening of the wave fronts, the evolution equation for the tangential component of the surface velocity ν at the distance $x \geqslant b$ can be presented in the form

$$c_R^2 \frac{\partial \nu}{\partial x} = \epsilon_1 \nu \frac{\partial \nu}{\partial \tau} + \frac{\epsilon_2}{2} \frac{\partial}{\partial \tau} \{\nu^2 + (H[\nu])^2\} + \epsilon_3 \left\{ \nu \frac{\partial \nu}{\partial \tau} + H\left[\nu H\left[\frac{\partial \nu}{\partial \tau} \right]\right]\right\} + \beta \frac{\partial^2 \nu}{\partial \tau^2} - m c_R^2 \frac{\nu}{x}. \tag{7}$$

Here $\tau = t - x/c_R$ is the retarded time, the nonlinear parameters $\epsilon_{1,2,3}$ depend on the shear and bulk moduli as well as the third-order nonlinear constants of the solid. This equation describes the changes in the wave profile (left hand side) induced by different effects presented by different terms in the right hand side: dependence of the propagation velocity on the amplitude (the terms proportional to ϵ_1), nonlocal nonlinear interactions in the SAW (the terms proportional to ϵ_2 and ϵ_3), absorption proportional to the attenuation parameter β, and divergence of the SAW [the quantities *b*, *m* has the same meaning as in Eq. (5)].

The normal component of the surface velocity can be calculated using the relationship

$$\nu_n = -\frac{1}{\gamma} H[\nu], \quad H[\nu] = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{\nu(t')dt'}{t'-t}, \tag{8}$$

where the constant γ is defined in Eq. (6), and *H* denotes the Hilbert-transform operator. The most characteristic nonlinear distortions in the wave profile (increase of the steepness of the fronts and accelerations during the propagation) are connected with the nonlinear parameter ϵ_1. Our estimates and experimental results[23,24] show that the value $\epsilon_1 = -1$ is of the right order of magnitude for such materials as fused silica and silicon. On the other hand, the acoustic parameters $\epsilon_{2,3}$ are not yet measured accurately. Therefore, in the calculations the nonlinear constants $\epsilon_{2,3}$ were assumed to be zero and the value $\epsilon_1 = -1$ was used. The temporal profiles of the normal acceleration and velocity in the SAW pulse at a distance of 15 mm from the line-shaped source ($m=0$) are shown in Fig. 2. The amplitude of the acceleration after the pulse which experiences a nonlinear transformation is much higher than that of the initial pulse. This means that even smaller particles can be detached from the surface by the SAW pulse with the nonlinear distortions in the profile. The condition (3) becomes more restrictive for short pulses. Nevertheless, the intervals CD and EF, where the condition (2) is fulfilled, are in this case within the corresponding interval to the left of point P and to the right of point Q, where the condition (3) holds.

It should be taken into account that the physical absorption coefficient in Eq. (7) is about two orders of magnitude less for real single crystals than the value $\beta=2.5\times10^{-8}$ cm which was assumed in the calculation. This higher artificial attenuation was introduced to stabilize the calculation procedure. With the real physical absorption the corresponding duration of the shock front is reduced by a factor of about 100 as compared to Fig. 2(d). Therefore, shock fronts as short as about 10 ps can be formed by nonlinear SAW pulses in single crystals. Although the amplitude of the acceleration can amount in this case to values up to 10^{12} m/s^2, the lower limit for the size of removable particles of about 0.01 μm is imposed by Eq. (3), since fracture of the material limits the velocity values which can be reached.

It is also pointed out that the movement of the particle normal to the surface cannot be affected by the tangential force, but the tangential drag may be facilitated or suppressed by the vertical acceleration, since the friction is mostly determined by the resultant force of the adhesion and inertia. Therefore, a horizontal displacement of the particle becomes possible, even when the detachment does not occur.

IV. OBSERVATIONS OF SURFACE CLEANING

In our experiments SAW pulses were excited by a Molectron UV-24 Nitrogen Laser with a pulse duration of 10 ns, a pulse energy of 9 mJ, a repetition rate of up to 50 Hz, and a wavelength of 337 nm. The laser beam with 6 mm$\times$32 mm dimensions was focused with a $f=10$ cm quartz lens on a sample at a conjugate ratio of 40:1. In this way a source with 150 μm$\times$800 μm dimensions was formed on the sample surface. The light intensity was enough to give rise to an intensive SAW Rayleigh pulse with a characteristic wavelength of 100 μm.

The SAW were excited in a (100) single crystal commercial silicon wafer having a diameter of 76 mm and a thickness of 380 μm. This wafer was dusted uniformly with a mixture of 1–10 μm size Al_2O_3 particles. The sample was placed vertically to reduce the secondary sedimentation of the detached particles by the gravitational force.

The pressure created on the surface was monitored by a thin film acoustic transducer[28] which had a 80 MHz bandwidth. The transducer measured the acoustic pulses at the side of the sample opposite to the surface of the interaction using also a layer of matching liquid.

Figure 3 shows surfaces of silicon wafers which were dusted with fine particles and then exposed to 50 pulses of the nitrogen laser. Figure 3(a) corresponds to the case when the experiment was made in ambient air. The photographs were made with scattered light, therefore the cleaned area

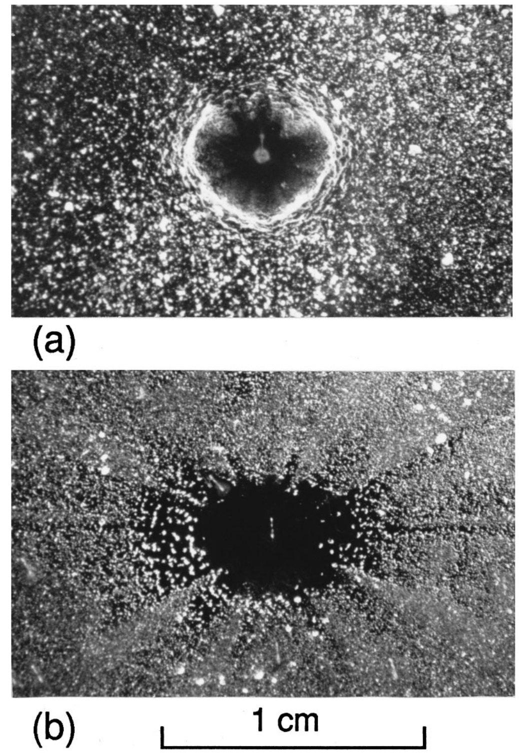

FIG. 3. Photographs of a silicon surface with dust particles after exposure to 50 laser pulses: (a) in ambient air, (b) in vacuum.

appears dark. The increased density of particles near the lower edge of the cleaned area is due to a secondary sedimentation. A larger density of particles is observed around the cleaned area due to their tangential displacement. The optical breakdown near the surface produces a shock wave in the air which also contributed to the removal of particles. Figure 3(b) corresponds to observation in vacuum with a pressure of about 0.1 Torr. In this case the cleaning of the surface is even more pronounced although the sound wave in the rarefied gas has practically no influence on the detachment of particles. The dark rays noticeable in the photograph correspond to phonon focusing directions[29] in which the SAW amplitude decreases with distance much slower than in other directions. As is seen in Fig. 3(b) the diameter of the cleaned area is in this case about 5 mm, whereas the diameter of the laser spot is less than 1 mm, which explicitly demonstrates the nonlocal property of the cleaning process.

At atmospheric pressure but with the application of a gas flow over the surface the number of particles settling back to the surface was substantially reduced. In this case the cleaned area approached that shown in Fig. 3(b) and dark rays in the phonon focusing directions also appeared more distinct.

In another series of experiments the SAW pulses were excited with the beam of a YAG:Nd^{3+} laser which was focused to a line with the dimensions 10 μm$\times$3 mm. The parameters of the laser pulse were: $\lambda=1.06$ μm, pulse duration 10 ns, and pulse energy 10 mJ. This source produced SAW pulses with quasiplane fronts which propagated perpendicular to the source line. The pulses detected with the probe beam deflection setup at a distance of 10 mm from the exci-

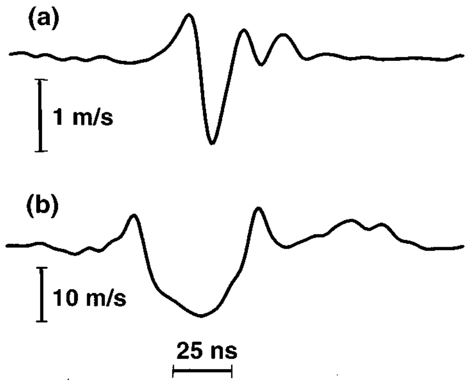

FIG. 4. Measured waveforms for the normal surface velocity component in SAW pulses: (a) excitation in a Si wafer with optical breakdown, quasilinear regime; (b) excitation in fused silica through a strongly absorbing liquid layer, nonlinear regime.

tation spot are shown in Fig. 4. The oscillogram of Fig. 4(a) corresponds to the SAW pulse produced due to the optical breakdown on the surface of a silicon wafer. The high-amplitude SAW pulse presented in Fig. 4(b) was generated in fused silica through a liquid layer of about 100 μm thick using the method described in more detail in Ref. 24 and registered at the distance of 15 mm from the excitation region. The shape of this SAW pulse exhibits characteristic nonlinear distortions: two maximums appear as relatively sharp peaks with an increased duration of the valley in between [compare to the calculated waveform at $x=15$ mm in Fig. 2(c)].

The SAW pulses produced in the ablation regime [Fig. 4(a)] interacted with the particles uniformly distributed on the surface of a silicon wafer. The distributions of the particles before and after the surface was exposed to 50 laser pulses and are shown in Fig. 5. The measurements of particle distributions were made by an automated optical surface analyzer with a resolution of 1 μm which limited the minimal diameter of the detected particles. Figures. 5(a) and 5(b) correspond to the experiments performed in the air at atmospheric pressure and to vacuum at a pressure of about 0.1 Torr. It can be seen that in vacuum the cleaning process is more efficient.

V. DISCUSSION

The presented results demonstrate that the technique of cleaning with laser-generated SAW pulses is rather efficient under vacuum conditions, where most of the other methods are not applicable. The employment of covering layers (which can be liquid or solid) provide a possibility to increase the SAW pulse amplitude to values where nonlinear elastic properties of solid materials become important. For efficient generation of a SAW pulse the thickness of the layer should be about the penetration depth of the laser radiation. In the case of an aqueous solution layer with the thickness $h=10$ μm an estimate of the pressure produced on the surface with the laser fluence $F=30$ J/cm^2 corresponding to our experiments with YAG:Nd laser gives $p=GF/h=3$ GPa, where $G=0.1$ cm^3/(g K) is the Grueneisen parameter for water. According to Eq. (5) such high-amplitude transient pressure pulses, which were indeed observed in similar laser experiments,[30] produce SAW pulses with the acoustic Mach number about $M=0.003$ in agreement with the experimental results of Fig. 4(b).

From the oscillograms of Fig. 4 the accelerations reached in our experiments can be estimated. The maximum value of the normal acceleration for the pulse in the Fig. 4(a) is $a_n=1.9\times10^8$ m/s^2, and the maximum value for the pulse in Fig. 4(b) is $a_n=3\times10^9$ m/s^2. The limit for the surface accelerations which can be reached is set by inelastic deformations and fracture of the material at Mach numbers of about $M\approx10^{-2}$. The minimal duration of the SAW pulse is limited by the strong attenuation of SAWs with frequencies $\geqslant$1 GHz at distances $\geqslant$1 cm. Thus, for SAW pulses with a nanosecond duration the limit for the surface acceleration of about 10^{10} m/s^2 is set by fracture. Such accelerations and pulse durations according to Eqs. (2) and (3) allow to effectively remove the particles with a diameter $\geqslant$0.05 μm.

The calculations for high-amplitude SAW pulses for the formation of a shock front show an increase of the front steepness and the amplitude of the normal acceleration. In the experiments the registered resolution of the SAW pulse fronts was limited by the 300 MHz frequency range of the detection setup. In the calculations the introduction of an artificial viscosity also increased the width of the wavefront. The estimates for single crystals such as crystalline silicon with physical values of attenuation yield the width of the shock wavefront to be in the picosecond range with the corresponding increase of the acceleration magnitude up to about 10^{12} m/s^2. To determine the ultimate limits for the realizable accelerations it is necessary to obtain data on the visco-elastic dynamic properties of the material at very high stresses close to the threshold of elastic deformations and fracture. At present these data are not available and laser excitation of SAW pulses provides a method for such studies.

So far we have used an isotropic model for describing the generation of SAW pulses and their nonlinear evolution. However, for anisotropic materials such as crystalline silicon this procedure is not strictly applicable and gives only ''on the order of magnitude'' description. To take into account simultaneously materials anisotropy and nonlinear effects a further generalization of the theory is necessary.[31,32]

An important characteristic of the cleaning process is the specific surface energy necessary for the removal of particles of definite dimensions. For cleaning with SAW pulses this

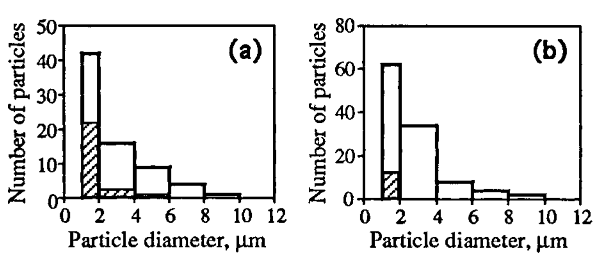

FIG. 5. Distribution of particles by size on a silicon surface on an area 0.018 mm^2 before (light boxes) and after (shaded boxes) 50 laser shots: (a) in ambient air, (b) in vacuum.

value is about two orders of magnitude less, than for ''local'' cleaning methods[4,5,7,11,12] and consists only about 10^{-3} J/sm^2, since the particles are removed not only in the interaction region, but also in the wider area covered by SAW pulse propagation.

It should be noted that to implement the proposed technique of surface cleaning it is necessary to avoid the damaging of the substrate area intended for microcircuit manufacturing processes. This can be done by different approaches: (1) the laser impact and the excitation of the SAW pulses can be performed outside the useful area of the semiconductor chip in such a way that intensive SAW pulses propagate across the wafer; (2) by an optimization of SAW pulse generation it is possible also to excite high amplitude SAW pulses in the nondestructive thermoelastic regime.[15,21]

In addition to the cleaning of surfaces, the optoacoustic method described allows the study of the adhesion forces. The value of the Hamaker constant corresponds in our case to the interaction of Al_2O_3 with silicon in vacuum. According to previous studies[2] for Si–Si interaction in vacuum $A_{132}=1.6$ eV and for the Al_2O_3–Al_2O_3 interaction in vacuum $A_{132}=1.1$ eV. Based on the results of Fig. 5(a) and using Eq. (1) the estimate $A_{132}=2$ eV was obtained which corresponds to Al_2O_3–Si interaction.

Still another application of the particle detachment by SAW is for the purpose of the injection of small particles which may be necessary in different studies, such as for measuring charges and masses of the particles or their chemical composition.

VI. SUMMARY

In conclusion, we have studied the detachment and removal of fine particles from the surface by an intensive laser-generated SAW pulse. It was demonstrated that micron and submicron particles can be shaken off from the surface by such a pulse, thus providing an efficient method of surface cleaning. By going to the ablation regime SAW pulses with accelerations of about 1.9×10^8 m/s^2 were produced on a silicon surface. Using excitation of SAW pulses through a covering layer, when the acoustic nonlinearity during the propagation of the SAW pulse becomes important, surface accelerations of about 3×10^9 m/s^2 were experimentally realized. It was shown that particles with diameters as small as 0.05 μm can be removed when accelerations of about 10^{10} m/s are reached. The detachment of the particles was analyzed for both linear and nonlinear SAW pulses. The proposed method has some advantages in comparison with previously used methods of laser-assisted cleaning. It is applicable under vacuum conditions and works not only in the region of the laser impact on the surface, but also in a larger area around this region where the propagating SAWs have sufficiently high amplitudes. As a consequence, the specific surface energy of about 10^{-3} J/cm^2 necessary for cleaning in the proposed nonlocal method is about two orders of magnitude less than for the local laser cleaning techniques.

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