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Shock Pressure Measurements for the Removal of Particles of Sub-micron Dimensions from Silicon Wafers

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Abstract:

Laser Shock Cleaning (LSC) is a new mechanism of laser cleaning recently proposed and investigated at University of Liverpool. By aligning the incoming laser beam to be horizontal to the surface to be cleaned but close to it and selecting operating parameters that lead to a breakdown of the air above the object to be cleaned, a laser induced shock wave is produced that is very much more effective than conventional normal incidence cleaning in removing surface pollutants. However, because the laser does not come into contact with the substrate, this method significantly minimises the potential for substrate damage.

Experimental work has been carried out to investigate the use of LSC in the removal of micron and sub-micron size particles from silicon wafers, a significant problem in the fabrication of microprocessors and associated components.

In this paper, typical shock pressures induced at the particle/substrate interface have been measured using calibrated piezo-ceramic sensors and the values compared with typical adhesion forces to predict success in the removal of particles of sub-micron dimensions effectively.

The process mechanism is discussed by considering adhesion forces at the particle/substrate interface and the pressure generated as gap distance from the surface is increased.

Introduction

One of the most important factors affecting production yields, device performance, and device reliability in the semiconductor industry is contamination. Approximately 80% of wafer loss in production is caused by contamination problems.[1] In particular, semiconductor manufacturers focus on air-borne contaminants.

Air-borne contaminants fall into three main categories: particles, metallic ions, and gases. Particles include dust, smoke, skin, and human hair which can settle onto the metal lines and substrates of electronic devices, potentially breaking circuits or otherwise interfering with the functioning of specific circuit components. Even a particle up to ten times smaller than the minimum feature size on a chip can pose a significant risk.[2] Therefore, as circuit component geometries become smaller, the number and kinds of particles that can cause harm increase. Metallic ions are atoms of metals that have either gained or lost extra electrons to become electrically charged. They are very mobile in silicon and other semiconducting material and can serve as a dopant, altering electrical characteristics of the device in unintended ways. Gases, including oxygen and water vapour, also serve as contaminants because they can react to materials already deposited on the wafers, producing new compounds, corrosion and rust, and other effects that damage the functionality of the device.

Of these three types of contaminants, particulate contamination is the most insidious. Normal air contains a large number of particles that remain air-borne for long periods of time and then randomly settle on exposed surfaces. Small particles are more difficult to remove due to their higher adhesion force on the surface.[1] Conventional cleaning techniques such as ultrasonic, high pressure gas jet and chemical flux are known to be ineffective in removing the micron or sub-micron particles; they introduce the possibility of mechanical pressure-induced damage in the surface profile as well as posing environmental problems due to the use of chemicals.[1]

Recently, laser cleaning techniques have been demonstrated to offer a new approach for the effective removal of small particles by an environmentally-friendly route, since it is a dry process.[3-9] However cleaning efficiency is normally strongly dependent on laser wavelength and physical properties of the particles since removal involves laser absorption on the particle surface producing different cleaning forces. Thus the removal of all particles having different optical and thermal properties using a certain wavelength is difficult due to the different interactions between laser and particles.

In this paper, the removal of small particles (size approximately one micron) on a silicon surface by airborne plasma shock waves induced by air breakdowns due to intense laser pulses is reported. This method has the unique characteristic of being independent of the properties of the particles since it does not include direct laser-particle interaction, hence this method may remove all kinds of particles even those having a very strong adhesion force on the surface. The basic principle of this method is described. Typical shock pressures induced at the particle/substrate interface have been measured using calibrated piezo-ceramic sensors and the values compared with typical adhesion forces to predict success in the removal of different particles of sub-micron dimensions effectively.

Experimental Procedure

A recent new mechanism of laser cleaning has been proposed by Liverpool University, "*Shock Cleaning*".[10,11]This particular technique uses a plasma shock wave, produced by a breakdown of air due to an intense laser pulse to remove the contaminants from a substrate. The beam is directed parallel to the surface in order to avoid direct laser interaction with the target material and is focused a few mms above the area to be cleaned. The power density of the beam at the focal point is around 10^{12} W/cm^2. The gaseous constituents begin to break down and ionize as a result a shock wave is produced which has an audible snapping sound. In air, the typical peak pressure of the shock front for a spherically expanding plasma is estimated to be the order of hundreds of MPa, however the precise value depends on the laser power density and the distance from the shock wave. The risk of damage to the underlying substrate is eliminated, as the incident beam does not come directly in contact with the work piece. Precise control of the gap distance between the surface to be cleaned and the laser focus is critical in terms of successful cleaning as this distance alters the pressure of the shock wave striking the surface.

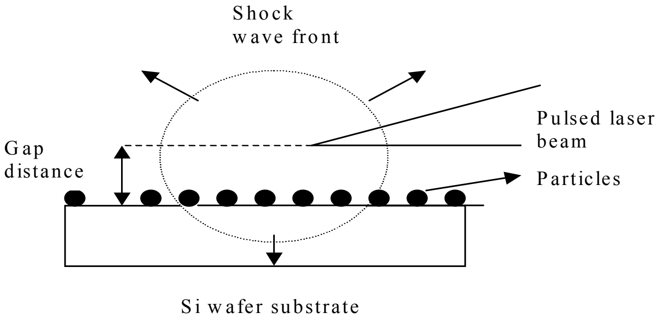

Fig 1. Experimental set-up of laser shock cleaning

In this paper shock pressures induced at the particle/substrate interface were measured using calibrated piezo-sensors and the values compared with typical adhesion forces of various particles including W, Au , Cu and polymer to predict removal success.

From research conducted in the past at Liverpool University it became apparent that micron-sized tungsten (W) particles prove to be one of the most difficult particles to remove from a surface by direct pulsed laser radiation, including an energetic UV source, due to its strong adhesion force. Furthermore, the thermo-elastic force per unit area, F, caused by the rapid thermal expansion of the particle resulting from the laser absorption is low for W since the thermal expansion coefficient ($\gamma = 4.5\times10^{-6}$ K^{-1}) is small and poor thermal properties such as conductivity (1.74 W cm^{-1} K^{-1}) and diffusivity (0.653 cm^2 s^{-1}) leads to a relatively small temperature rise (ΔT) at the particle-substrate interface. The thermo-elastic force has been considered in this paper to be the pre-dominant cleaning force for the particle removal from a surface using laser irradiation. If the thermo-elastic force exceeds the adhesion force, the particle may be detached from the surface.

The experiments were conducted using a Q-switched Nd:YAG laser at the fundamental wavelength of 1064 nm and a pulse length of 10 nsec. A piezo-sensor was fixed onto the reverse side of the wafer using a thin film of grease The beam was directed parallel to the surface of the otherside of the silicon wafer in order to avoid the direct laser interaction with the wafer and focused above it in order to carry out cleaning.

The distance between the laser beam and the wafer was altered and the corresponding voltage readings were noted and converted into pressure values. These values were then compared with typical adhesion forces of various particulates on silicon wafer surfaces in order to predict removal success.

Calibration of the sensors was conducted utilizing a modally tuned hammer and a cathode ray oscilloscope (C.R.O). Both the sensor and the modal hammer were connected to the C.R.O. Using varying degrees of force the hammer was used to strike the centre of the sensor in a pendulum motion and as a result two signals were generated on the C.R.O. One signal relates to the output from the sensor alone and the second signal relates to the output when the hammer strikes the sensor. A variety of tip hardness and mass extenders can be used with the hammer in order to tailor the required frequency range.

Each tip used with the hammer is itself calibrated, therefore it is possible to determine the sensor calibration by taking a large number of voltage readings from the C.R.O over a range of forces.

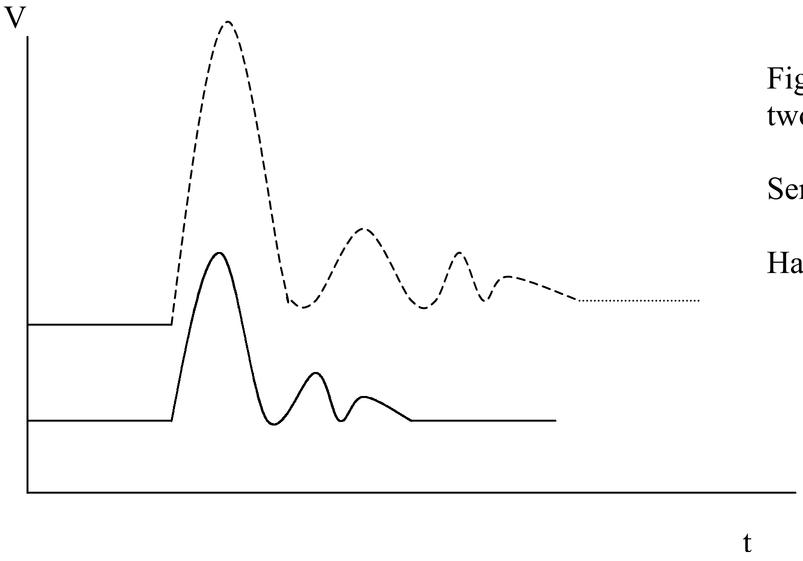

Fig 2: A schematic of how the two signals may appear on a CRO

Sensor signal --------

Hammer +sensor signal ———

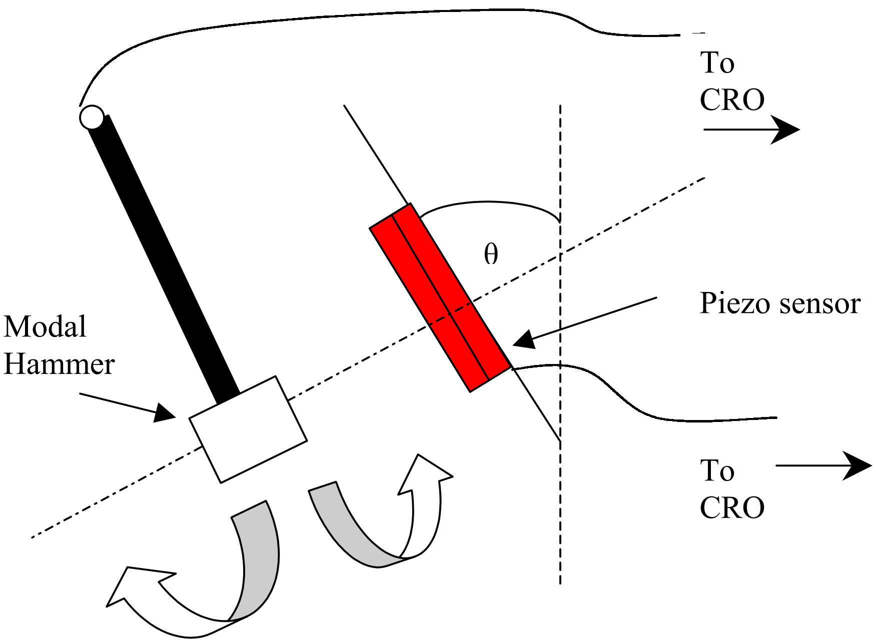

Fig 3: Schematic diagram showing how the piezo- sensors were calibrated using varying degrees of force based on a pendulum set-up.

Results:

Adhesion forces of micron particles on silicon wafers

The principal forces responsible for particle adhesion on a solid surface are Van der Waals' force, the capillary force and the electrostatic force.[12,13] The predominant adhesion force for particles less than 50µm in diameter on a dry surface is due to Van der Waals' force.[12,14] The adhesion force, F, for a spherical particle on a flat substrate surface with a certain deformation at the particle-substrate interface is given by[13]

$$F = \frac{h\, r}{8\pi\, Z^2} + \frac{h\, r_c^2}{8\pi\, Z^3} \tag{1}$$

where h is the material-dependent Lifshitz-Van der Waals constant, r is the particle radius, r_c is the radius of the contact surface area and Z is the atomic separation between the substrate surface and the bottom surface of the particle respectively. The Lifshitz-Van der Waals constant, h, is related to the Hamaker constant, A, by the equation $h = 4\pi A/3$.[14,15] . The Hamaker coefficient of a particle on a silicon substrate is based on the formula; $A_{p\text{-}Si} = (A_p\, A_{Si})^{1/2}$. The Lifshitz-Van der Waals constant ranges from 0.6 eV for polymers to 9eV for certain metals.

Z is approximately equal to $4\overset{\circ}{A}$.[12] The adhesion force per unit area between the various particles under investigation and the silicon substrate surface was calculated according to Eq. (1) and the above constants as a function of the particle diameter. The results are shown in Figs. 4,5,6 and 7, where the radius of contact surface area, r_c, is considered to be 3 % and 10 % of the particle radius (r). It is seen that the adhesion force increases significantly with decrease of particle diameter. Therefore smaller particles are expected to be much more difficult to remove from the surface compared with larger ones. It is also seen that the adhesion force increases with increasing contact surface area between the particle and the substrate.

Fig 9 shows a typical trace observed on the C.R.O when the shock wave is generated on the surface of the wafer. From these traces the voltages are converted into pressures, from which one can predict whether or not the particles will be removed (i.e if the pressure generated is greater than the adhesion force then removal will be successful).

Fig 10 shows the experimental shock pressures as a function of gap distance. If we consider the measured values of pressure generated on the surface and compare them to the typical adhesion forces calculated, we can see that the adhesion force is much smaller than the typical pressure from the shock wave arising from airborne plasma, therefore removal of particles will take place. This pressure is governed by the gap distance between the focus of the laser beam and the target material and the laser power density. If the conventional laser cleaning technique is used (i.e. direct interaction between the laser beam and the target material) then one has to be careful to avoid substrate damage and hence usually relatively low laser powers are used. However when using the shock technique because the beam is guided parallel to the surface higher powers can be utilized without the risk of damage to the underlying substrate. For very small particles of W on silicon with a diameter of 0.1 μm and a large contact area of 10 %, the adhesion force per unit area is around 5.0 MPa, which is lower than the measured shock pressure within a short distance of the shock origin. The shock wave generated is enough to sever the bond between the particle and the substrate surface and the detached particles are accelerated to very high velocities due to their small mass and are carried away in the expansion following the shock wave. Fig 8 shows a typical wafer surface, which has been irradiated using the shock cleaning technique.

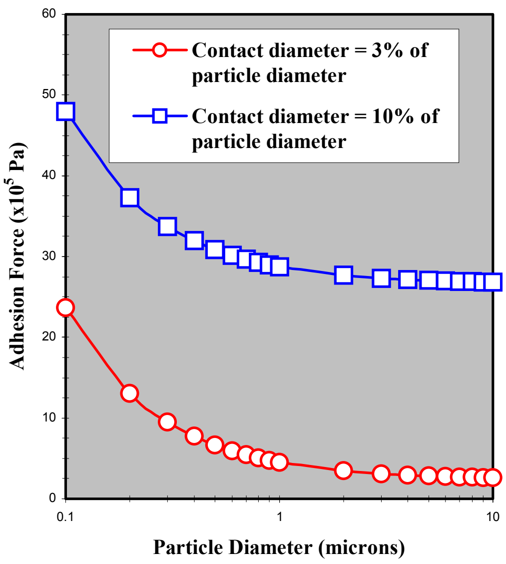

Fig 4: Adhesion force (per unit area) between a tungsten particle and a silicon wafer substrate as a function of particle diameter for two different contact surface areas.

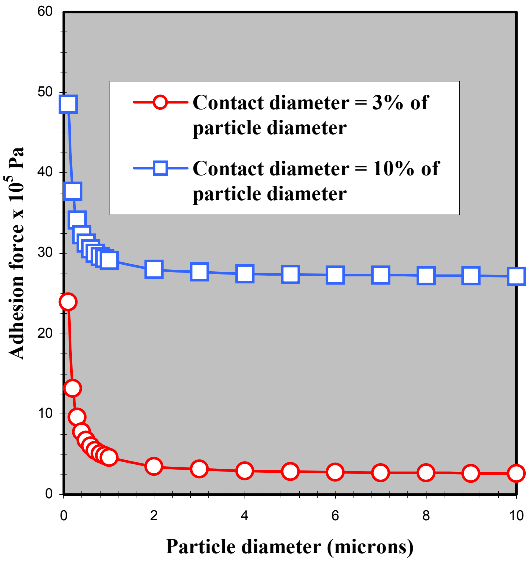

Fig 5: Adhesion force (per unit area) between a copper particle and a silicon wafer substrate as a function of particle diameter for two different contact surface areas

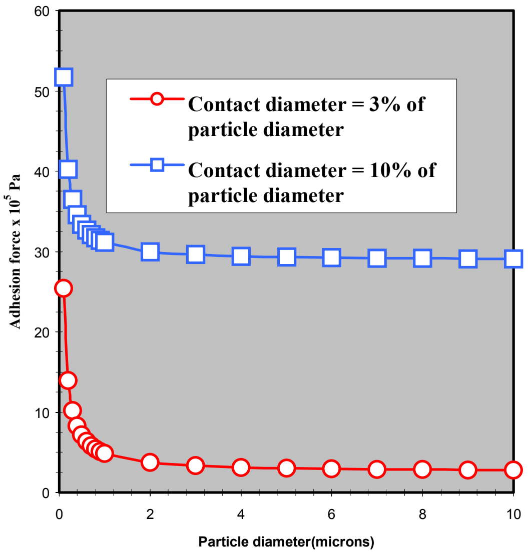

Fig 6: Adhesion force (per unit area) between a tungsten particle and a silicon wafer substrate as a function of particle diameter for two different

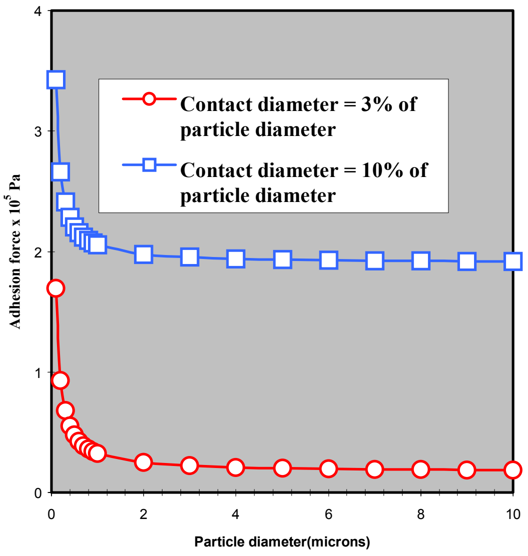

Fig 7: Adhesion force (per unit area) between a tungsten particle and a silicon wafer substrate as a function of particle diameter for

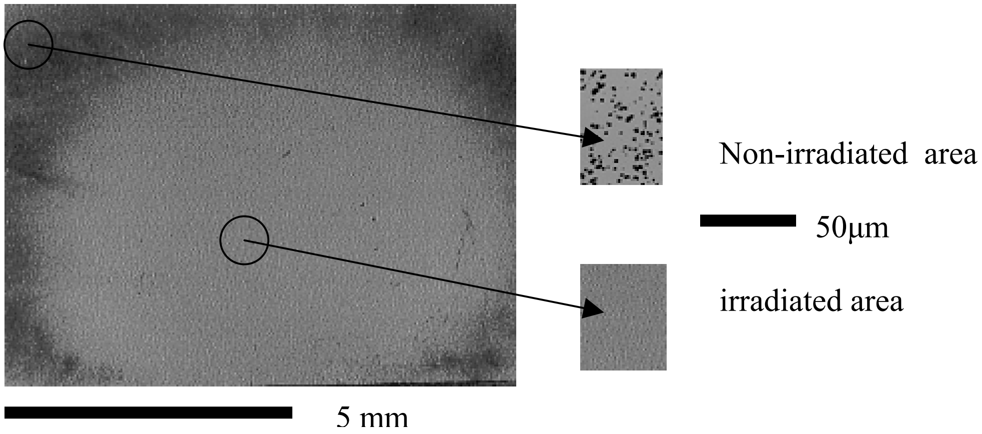

Fig 8: Optical micrograph of silicon wafer after irradiated using shock technique

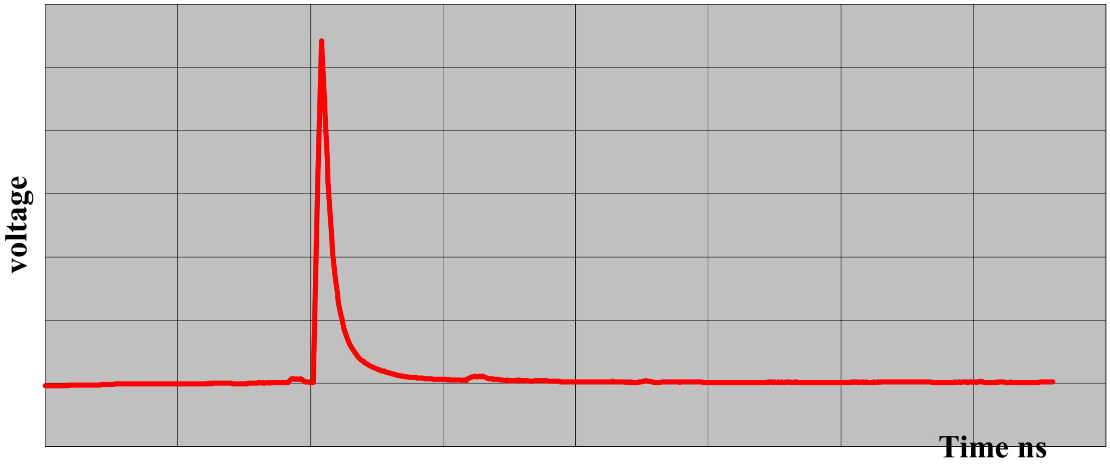

Fig 9: A typical trace observed on the CRO generated by a shock wave on the surface of the wafer

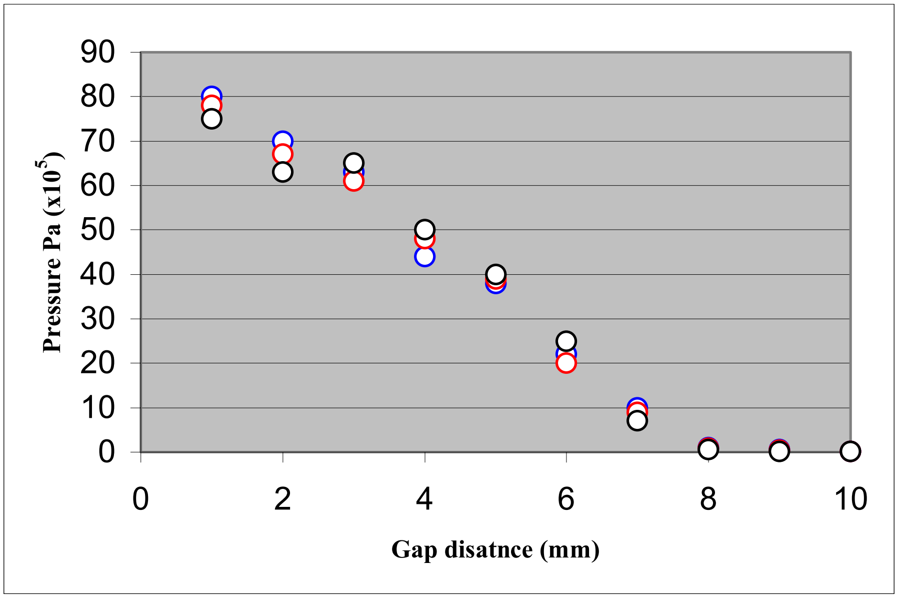

Fig 10: Experimental measured shock pressures on the reverse of silicon wafers using piezo sensors as a function of gap distance

Conclusions:

A new approach to laser cleaning has been demonstrated in which the removal of various particulates on silicon surfaces has been carried out using air borne plasma shock waves. Using calibrated sensors typical pressures generated on the surface from such waves has been measured. These measurements allow for predictions in removal success of a range of contaminants. If the thermo-elastic forces generated on the surface are larger than the adhesion forces of the particles then cleaning will be successful. The cleaning success is dependent however on the gap distance between the laser focus and the substrate (cleaning efficiency dramatically increases with decreasing gap distance) and also the laser power density as this dictates the pressure generated on the surface.

An advantage of this technique is that the fundamental wavelength can be utilized with success whereas it has been noted in the past that UV wavelengths perform better in removing particles from surfaces in comparison.

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