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Effect of wavelength and incident angle in the laser removal of particles from silicon wafers

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Abstract:

As semiconductor and microelectronic devices are becoming increasingly smaller, surface contamination of these devices is becoming an increasing problem for manufacturers due to the adverse effects that micron and sub micron particles have on the device performance. As a result of this there proves to be a continual need to develop effective techniques for the removal of small particles in the semiconductor industry.

Recently, a non-contact dry laser cleaning technique, using a short-pulse (in the order of ns) laser irradiation on the surface, has been demonstrated as a potential solution for the removal of particles from critical surfaces.

In this paper the removal of small copper particles with a diameter of 1 μm from silicon wafers has been carried out over a range of different wavelengths, since wavelength is one of the most crucial parameters for successful laser cleaning. Moreover it has been found that a dramatic improvement of cleaning efficiency in terms of number of particles removed is produced when using the laser at glancing angle of incidence as compared with normal incidence. The process mechanism is discussed by considering the adhesion and the laser-induced cleaning forces for different incident angles.

Introduction

Microelectronic devices in the semiconductor industry are becoming increasingly smaller and hence the tolerence for contaminants that adhere to such devices is becoming more critical. This type of contamination is becoming an increasing problem for manufacturers due to the adverse effects that these micron and submicron particles have on the device performance[1]. In some cases they act as a potential source of circuit failure, threatening production yield. For example,

particles in the size of about 0.1 μm to several microns which can be deposited on surfaces from air, liquids and humans in the processing environment are considered to have killer defects for the generation of dynamic random access memory (DRAM) and microprocessors[2,14,15]. In order to ensure device quality and performance and reduce scrap rates removal of such contaminants is vital. Conventional cleaning techniques such as wiping and scrubbing are often limited due to possible substrate damage caused by the mechanical action on the surface. Ultrasonic (or megasonic) and chemical flux as more effective cleaning techniques can also pose environmental problems due to disposal of the large quantities of water that are used. In addition the discarding of chemicals after use has the added disadvantage of hazard to human health, and hence large financial penalties can be encountered in avoiding this problem.

Recently lasers have been considered as a promising new technique, which may overcome the disadvantages induced by conventional cleaning techniques. This approach utilises the versatile, controllable, selective and environmentally friendly nature of the laser system to optimum effect[3, 4,16]. It is seen to be non - obtrusive in the production process since no vacuum or special protective atmospheres are required and the beam of the laser can be highly localised allowing specific areas of contamination to be targeted. These unique characteristics of laser cleaning have been demonstrating an effective removal of particles from various surfaces in industry[5-8]. However utilization of a laser for such cleaning purposes has its own disadvantages. The beam itself is highly localized as stated and so targeted areas are controlled by the spot size of the beam, which in most cases is very small, (usually a few mm^2). Therefore it would take considerable time to clean large areas using this technique, making the process relatively slow. Moreover one has to be careful in avoiding damage to the underlying substrate when removing contaminants as this could render the device useless. This is caused by overexposure of the high density laser beam. As a result there is a need to find a cleaning technique that will not only improve the cleaning efficiency of semiconductor devices, but also not affect the manufacturing yield by inducing damage to critical surfaces during the cleaning process.

In this paper, an alternative laser cleaning method known as “angular laser cleaning” has been used for the removal of small copper particles (≈ 1 μm) from silicon wafers. This particular technique irradiates the silicon wafer surface at a glancing angle in contrast with typical laser cleaning in which the laser beam is directed at a normal angle of incidence to the target material.

Removal of copper particles from silicon wafers was carried out using a Q-switched Nd:YAG laser having three different wavelengths of 1064 nm (near infrared), 532 nm (visible) and 266 nm (ultraviolet) produced by frequency harmonic generation. Quantitative analysis was carried out in order to determine the cleaning efficiencies in conjunction with beam incidence at the three wavelengths and also to compare the process characteristics of angular laser cleaning with conventional normal incidence laser cleaning.

Cleaning mechanisms are also discussed by considering laser-induced cleaning forces and radiation pressure exerted at the particle/substrate interface.

Experimental

One of the most important issues in the cleaning of copper particles from semiconductors is preventing them from getting into the front-end processing where they could possibly destroy the integrity of the gate oxide and hence create leakage currents[1,13]. Surface defects such as

roughening with the presence of copper contaminants, can be also introduced, moreover copper can flake off the back of a wafer in solution leading to back-to-front-end contamination.

In this work, the laser removal of around 1μm sized copper particles on silicon wafer substrates was carried out. The wafers were coated with copper particles using a spinning slurry deposition technique.

A Q-switched Nd:YAG laser (a Paragon 2XL laser) was used as the cleaning source, which is capable of operating at wavelengths of 1064 nm, 532 nm, and 266 nm. The visible and UV frequencies were achieved by frequency doubling and quadrupling of the fundamental wavelength of 1064 nm after passing through a KTP ($KTiOPO_4$) crystal. The laser has a pulse length of 10 ns. The maximum pulse energies obtainable were 500 mJ, 250 mJ, and 50 mJ for 1064 nm, 532 nm and 266 nm respectively. These three wavelengths were used to remove the copper particles from the silicon wafer over a range of glancing angles. An illustration of the angular laser cleaning technique used in this investigation is schematically shown in Fig. 1. The beam is directed to the surface at two different angles; one is normal incidence to the surface ($\theta = 90^o$) as for conventional laser cleaning and the other is almost parallel to the surface with a glancing angle ($\theta = 10^o$). A particle counter software package was used to determine the number of particles present on the surface. The cleaning efficiency was achieved by determining the number of particles before and after the laser treatment.

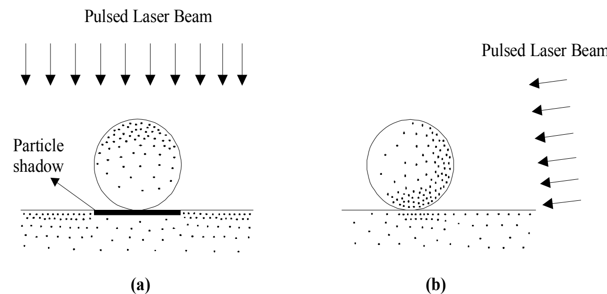

Fig. 1. Schematic illustration of the laser absorption on the surfaces of the particle and the substrate for different laser incident angles: (a) normal incidence angle and (b) glancing angle. The density of “dots” indicates the amount of heating due to the laser absorption on the surfaces.

Results

The effect of angle of laser incidence on the contaminated silicon wafer surface is shown in Fig. 2. The cleaned surface was achieved after the irradiation of 10 laser pulses with a pulse energy of 0.24 J and using a wavelength of 532 nm. It is shown that both processes can remove the copper particles from the surface. Interestingly, the laser-cleaned area at the glancing angle of 10° is around ten times larger than that at the perpendicular angle of 90°. This implies that the cleaning efficiency in terms of area is much larger at the glancing angle. This new technique enables

larger contaminated areas to be cleaned at a greater rate compared with that of conventional perpendicular cleaning. Moreover the fluence used to achieve complete removal of the copper particles is also smaller by an order of magnitude compared with the fluence required at the perpendicular incidence. Thus laser cleaning at a glancing angle of incidence is much more efficient in terms of energy and can remove the particles from the surface more easily and effectively without causing any substrate damage, as cleaning is carried out well below the damage threshold of the underlying substrate.

Fig. 3 shows the laser cleaning efficiency as a function of the laser fluence at the normal incident angle of 90° to the surface for the three different wavelengths. The cleaning efficiency is defined as the ratio of the number of copper particles removed from the surface after irradiation to the total number of particles before cleaning, and measured by the particle counter. It is shown overall that the cleaning efficiency increases with increasing laser fluence at all wavelengths. Very little improvement in the cleaning efficiency was observed with an increase in laser fluence at 1064 nm, below the damage threshold fluence, which were determined prior to any cleaning experiments. These thresholds were approximately; 0.62 J/cm^2 for 1064 nm, 0.68 J/cm^2 for 532 nm, 1.2 J/cm^2 for 266 nm.

Fig. 4 shows the laser cleaning efficiency as a function of incident angle using a wavelength of 1064 nm. It is shown that as the glancing angle is reduced from 90^0 to 5^0 the cleaning efficiency increases dramatically.

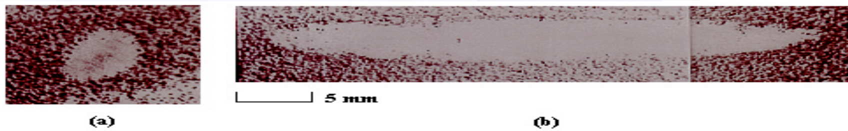

Fig 2. Effect of angle of laser incidence on a contaminated surface: (a) at the normal incidence angle of 90° and (b) at the glancing angle of 10°.

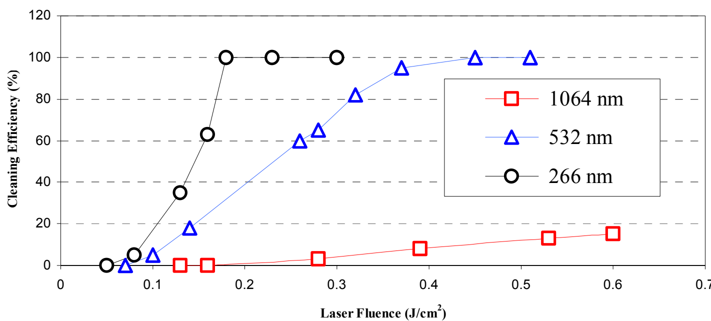

Fig. 3 The laser cleaning efficiency as a function of the laser fluence at the perpendicular angle of 90° to the surface for the three different wavelengths.

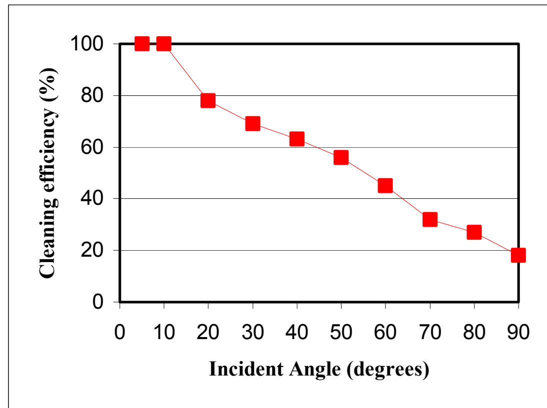

Fig 4. The cleaning efficiency of copper particles with varying angles of incidence at 1064 nm from silicon wafer at a fluence of 0.6 J/cm^2

Process mechanism

Theoretical Analysis for copper on silicon wafer using 1064 nm, 532 nm and 266 nm

The predominant adhesion force of small particles (microns) on a dry surface is due to Van der Waals force. The adhesion force, F_a, for a spherical particle on a flat substrate surface with a certain deformation at the particle-substrate interface is given by ;

$$F_a = \frac{h\,r}{8\,\pi\,Z^2} + \frac{h\,r_c^2}{8\,\pi\,Z^3} \qquad (1)$$

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 $h = 4\pi A/3$. Since the Hamaker coefficients of a copper particle on a copper substrate and a silicon particle on a silicon substrate are $A_{Cu} = 40\times10^{-20}$ J and $A_{Si} = 25.6\times10^{-20}$ J respectively, the Hamaker coefficient of copper particle on the silicon substrate $A_{Cu\text{-}Si}$ is approximately 32.0×10^{-20} J based on the formula $A_{Cu\text{-}Si} = (A_{Cu}\,A_{Si})^{1/2}$. The Lifshitz-Van der Waals constant, h, for a copper particle on a silicon substrate then 13.4×10^{-19} J. For Van der Waals bonded crystals, Z is approximately equal to 4 Å (= 10^{-10} m) . If it is assumed that the diameter of the copper particle is 1 µm and the diameter of the contact area between a copper particle and a copper substrate is 2 % of the particle diameter, then r, r_c are 5×10^{-7} m and 0.1×10^{-7} m respectively. From Eq. (1) and the above constants, the adhesion force between the copper particle and the silicon substrate surface is approximately 1.6×10^{-7} N for a point contact (without any deformation of the particle on the surface) and 2.4×10^{-7} N with the contact area (or deformation) of 2 %. These correspond to the forces per unit area of 2.0×10^5 Pa and 3.0×10^5 Pa respectively.

The predominant cleaning force for the removal of small particles from a substrate surface is due to thermo-elastic force[9,10]. This force is caused by the rapid thermal expansion of the particle and the substrate resulting from the absorption of the laser radiation on the surface. If a laser

pulse with a pulse length of t_p is absorbed on the particle and the substrate, then a temperature rise (ΔT) at the interface between the particle and the substrate surface is induced. The incident angle of the laser beam makes a geometrically difference in the laser absorption on the surfaces of the particle and the substrate and thus produces a different temperature rise at the interface. This is schematically illustrated in Fig. 1 for the perpendicular angle (a) and the glancing angle (b). It is clearly seen that at a glancing angle direct absorption at the interface between particles and substrate is possible. This absorption can be enhanced by multiple reflections and the increased absorption for polarisation in the plane of laser incidence[4]. However at the perpendicular angle, the temperature rise at the interface is restricted by the absorption on the top surface of the particle and the particle induced shadow on the substrate, as shown in Fig. 1 (a).

If it is assumed that the particle is plate-like and most of the laser radiation is effectively absorbed at the interface at the glancing angle as shown in Fig. 1 (b), the temperature rise at the interface can be simply estimated by a one-dimensional heat equation and be compared for the two different incident angles. . Surface reflectivities for copper are 0.33 for 266 nm, 0.62 for 532 nm and 0.97 for 1064 nm and absorption coefficients are 7.9×10^5 (cm^{-1}) for 266 nm, 6.1×10^5 for 532 nm, 8.1×10^5 for 1064 nm respectively[11]. The pulse length (t_p) of laser used in this work was 10 nsec and the particle size was assumed to be 1 μm. It is assumed that the particle size was 1μm and the laser absorptivity increased to 0.9 at glancing angles of incidence. Consequently, At the depth of 1 μm (≅ at the particle-substrate interface), the temperature rises are approximately 10 °C for 1064 nm, 50 °C for 532 nm and 80 °C for 266 nm respectively. for a laser fluence of 0.1 J/cm^2 while the rise for the glancing angle cases was 253 °C for 1064 nm, 323 °C for 532 nm and 373 °C for 266 nm. This is a significant difference.

The normal expansion of the surface (Δl) due to the temperature rise (ΔT) is given by[9]

$$\Delta l = \alpha \, \delta \, \Delta T \qquad (2)$$

where α is the thermal expansion coefficient and δ is thermal diffusion length during the laser pulse. Inserting both the estimated temperature rises and the following typical numerical values for copper: $\alpha = 17.0\times10^{-6}$ K^{-1}, $\delta = 2.1\times10^{-4}$ cm [15], the expansion amplitudes (Δl) are estimated from Eq. (2) as 3.6×10^{-8} cm (1064 nm) , 1.8×10^{-7} cm (532 nm) and 2.9×10^{-7} cm (266 nm) for the perpendicular cases and as 9.2×10^{-7} cm (1064 nm) , 1.2×10^{-6} cm (532 nm) and 1.4×10^{-6} cm (266 nm) for the glancing angle cases. If the expansion is achieved during the pulse duration of 10 nsec, the acceleration at the interface, a, resulting from the thermal expansion is approximately given by

$$a = \frac{\Delta l}{t_p^{\,2}} \qquad (3)$$

From the Eq. (3) the accelerations at the interface are 3.6×10^8 cm/s^2 (1064 nm), 1.8×10^9 cm/s^2(532 nm), and 2.9×10^9 cm/s^2 (266 nm) for the perpendicular cases and 9.2×10^9 cm/s^2 (1064 nm), 1.2×10^{10} cm/s^2(532 nm), and 1.4×10^{10} cm/s^2 (266 nm) for the glancing angle cases. Consequently, the thermo-elastic force, F, exerted at the interface is given by

$$F = m \, a \qquad (4)$$

where m is the mass of the copper particle[12], which can be calculated by $\rho \times V$: ρ (density) = 8.96 g/cm^3, V (particle volume) = 5.24×10^{-10} cm^3. The resulting thermo-elastic forces at the particle-substrate interface for perpendicular cases are 1.7 dyne (1064 nm), 8.4 dyne (532 nm) and 14 dyne(266 nm).The resulting forces for the angular cases are; 43 dyne(1064 nm), 56 dyne (532 nm), and 65 dyne (266 nm).

From these approximately calculated values both of adhesion force and cleaning force, it is seen that the thermo-elastic forces at the glancing angles of laser incidence with a fluence of 0.1 J/cm^2 are much larger than the adhesion force between the copper particle and the substrate whereas the force at the perpendicular angle is smaller than the adhesion force at a wavelength of 1064 nm. This implies that the cleaning force at 0.1 J/cm^2 and the glancing angle is high enough to break the adhesion bond thus detaching the particles from the surface; while the cleaning force at 0.1 J/cm^2 and using 1064 nm and a perpendicular angle is not high enough to break the bond and will need much higher laser fluence to exceed the adhesion force.

Conclusions:

A dramatic improvement of laser cleaning efficiency in the removal of small particles from the solid surface has been demonstrated using an angular laser cleaning technique in which a laser beam irradiates a surface at a glancing angle of incidence. It was found that the cleaned area at the glancing angle is about 10 times larger than the typical laser-cleaned area using a perpendicular angle. This offers an advantage of speed of laser cleaning for glancing angles of incidence. The process mechanism has been discussed by considering the cleaning force (induced by rapid thermal expansion at the particle-substrate interface) and the adhesion force between the particle and the substrate surface for the two cases. From this theory an explanation for the improved cleaning capability at glancing angles could be described.

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