Challenges of Finer Particle Detection on Unpatterned Silicon Wafers

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Abstract. As the size of yield-limiting particles has significantly decreased with the decrease in the feature size of leading-edge ULSI devices, a clear need has arisen for a system capable of detecting particles of far below 50 nm in diameter on the surface of silicon wafers. If we employ a shorter wavelength (266 nm or below) laser for the laser-scanning wafer inspection system, its sensitivity level can be raised to the range of 20 to 30 nm in diameter on smooth surfaces. However, so far, silicon surface morphology, such as crystal originated pits (COPs), micro-scratches, microroughness, as well as residual chemical contamination on the surface of a mirror-finished wafer, prevents the detector sensitivity from being raised to such a high level. Therefore, before further raising the particle detection sensitivity of the system, we must establish technologies for obtaining a super-smooth silicon surface by employing scratch-free precision surface polishing, COP-free crystal growing/annealing, and microroughness/particle-free wafer cleaning.

INTRODUCTION

As device architectures continue to shrink and die sizes grow, particulate contamination as well as chemical contamination [1, 2] has an ever-increasing impact on device yields. Of the many potential contamination sources, particle generation within process equipment is by far the most frequent cause of yield loss in the manufacture of modern ULSI devices [3, 4].

Mechanical operations such as wafer handling and transport, pumping and venting, shaft rotating, and valve operations, all produce detrimental particles, as do the wafer-processing operations such as plasma-enhanced chemical vapor deposition, plasma etching, and metal sputtering. Both chemical and physical reactions within the vacuum chamber of such equipment produce, by their nature, detrimental particles. Indeed, every wafer-processing step is a potential source of contaminants and extreme care must be taken at all times to prevent the introduction of process/equipment-generated particles.

Therefore, to reduce the defects and attain acceptable levels of yield and reliability in leading-edge devices — or to improve them to more profitable levels — more stringent control of particles on wafers is required throughout the wafer processing operations [3,4].

Fundamental to the reduction of process/equipment-generated contamination is the monitoring of wafer-surface particle levels [4-7]. Automated laser-scanning particle detection systems have been used in semiconductor manufacturing lines to determine the quantity, size, and location of the particles on unpatterned silicon wafers. Some systems that employ light scattering and/or pattern comparison have recently been available that can detect particles on a patterned product wafer as well, but the systems' usefulness is limited by their lower detection limit [4-6].

The particle detection program in a production line comprises, in general, both a surface inspection of unpatterned monitor wafers to check process/equipment cleanliness and a surface inspection of patterned product wafers to monitor on-going total process cleanliness [3,4]. As the size of potentially yield-limiting particles has decreased along with the decrease in the feature size of leading-edge ULSI devices, a clear need has arisen for systems capable of detecting finer particles.

In fact, the acceleration of the International Technology Roadmap for Semiconductor (ITRS) will continue for 15 years into the future in terms of the "technology node", which is associated with both the DRAM half pitch and the MPU/ASIC half pitch, as shown in Fig. 1 [8]. In accordance with this trend, the ITRS requirements for the particle sizes have been and will be tightened towards the year 2016, as also shown in Fig. 1.

We have been preparing for the production of 65-nm technology-node CMOS devices, and have already...
started developing 45-nm devices in order to meet the strong demand from our video-game and broadband-networking digital consumer electronics business. The minimum detection size of the commercially-available unpatterned-wafer particle detection systems remains, however, almost at the same level of the critical feature sizes of these leading-edge devices. Figure 2 shows typical defect-map displays of a monitor wafer generated by major commercially-available models of unpatterned-wafer inspection systems, which have their own different optical configurations to make the collection angle of the scattered light as large as possible [4,6,9]. For the monitor wafer, polystyrene latex (PSL) spheres with diameters of 48, 50, and 60 nm were deliberately placed on limited areas of the wafer surface to check the sensitivity of each instrument. The histogram shown in the figure displays two clear peaks of 50-nm and 60-nm particle distributions. Therefore, the minimum detection size of these systems is defined under the optimized conditions, to be the 50-60 nm level in PSL equivalent optical diameter. This paper focuses on the particle detection on unpatterned silicon-wafer surfaces and describes several challenges faced in providing finer particle detection to meet the ITRS requirements or even surpass them. An emphasis is placed on the importance of the control of silicon surface morphology, such as crystal originated pits, micro-scratches, and microroughness, which prevent the detection sensitivity from being raised to higher levels.

**HOW TO INCREASE PARTICLE-DETECTION SENSITIVITY**

The scattered light intensity for a small spherical particle illuminated by an incident beam is given by the

![FIGURE 1. Trends in the technology node and the critical particle size requirements in the ITRS Roadmap 2001.](image)

**FIGURE 2.** Defect-map displays of commercially-available particle detection systems for 48, 50, and 60 nm PSL spheres intentionally placed on limited areas of the surface of a monitor wafer.
FIGURE 3. Various methodologies for increasing the particle detection sensitivity for the wafer-surface inspection system.

following Rayleigh’s equation [10],

\[ \frac{I_s}{I_i} = \frac{8\pi r^6}{\lambda^4 R^2} \frac{n^2 - 1}{n^2 + 2} \left(1 + \cos^2 \theta\right) \tag{1} \]

where \( I_s \) and \( I_i \) are the scattered and incident light intensities, respectively, \( r \) is the particle radius, \( \lambda \) is the wavelength of the incident beam, \( R \) is the distance between the particle and the position where the scattered intensity is measured, \( n \) is the complex refractive index of the particle, and \( \theta \) is the scattered angle or the angle between the directions of incidence and observation. The 1 in parentheses is the term for the incident light polarized perpendicular to the plane in which the scatter is measured, and \( \cos^2 \theta \) is the term for light polarized in the measurement plane [10].

It should be noted that, in this equation, the scattered light intensity is proportional to the sixth power of the particle diameter. This means that, as the particle size to be detected decreases, the scattered light intensity from the particle becomes significantly lower. This makes it very difficult for the light-scattering wafer inspection system to detect finer particles with significantly small scattered light intensities.

The methodologies on how to increase the sensitivity of the particle detection systems are summarized in Fig. 3. Those are:

• reducing the wavelength of the laser as the light source,
• increasing the power of the laser,
• shrinking the diameter of the laser-beam spot to illuminate the wafer surface, and
• reducing the noise level of the system.

The former two items related to the improvement of the light source are the most promising approaches from a practical point of view, while the latter two will result in lowering the inspection speed of the system. As the scattered laser intensity varies inversely proportional to the fourth power of the laser wavelength while it linearly varies with the incident light intensity or the laser power, as can be seen in Eq. 1, reducing the laser wavelength is the most effective way to increase the sensitivity of the system.

Table 1 lists the trend in the lasers used as a light source for the unpatterned-wafer inspection system. Presently, \( \text{Ar}^+ \) ion lasers with a wavelength of 488 nm have been widely used in commercially available models for more than 10 years. The second harmonic generation (SHG) of a Nd:YAG laser have also been used for some models. Recently, blue-violet GaN lasers with a wavelength of 405 nm or shorter are available, originally developed for the next-generation high-capacity optical disc recording applications. More recently, we have developed, at Sony, a high-output (100 mW) all-solid-state laser capable of a continuous-oscillation deep-ultraviolet beam at a wavelength of 266 nm [11]. This laser unit employs the fourth harmonic generation (FHG) of a Nd:YAG

<table>
<thead>
<tr>
<th>Laser Source</th>
<th>Wavelength</th>
<th>Availability</th>
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<tbody>
<tr>
<td>Semiconductor (GaAs)</td>
<td>780 nm</td>
<td>Past</td>
</tr>
<tr>
<td>HeNe</td>
<td>633 nm</td>
<td>Past</td>
</tr>
<tr>
<td>Nd:YAG (SHG)</td>
<td>532 nm</td>
<td>Present</td>
</tr>
<tr>
<td>Ar*</td>
<td>488 nm</td>
<td>Present</td>
</tr>
<tr>
<td>HeCd*</td>
<td>442 nm</td>
<td>Past (Unreliable)</td>
</tr>
<tr>
<td>335 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semiconductor (GaN)</td>
<td>405 nm</td>
<td>New</td>
</tr>
<tr>
<td>Nd:YAG (FHG)</td>
<td>266 nm</td>
<td>New</td>
</tr>
<tr>
<td>? + ? (SFG)</td>
<td>1xx nm</td>
<td>Future</td>
</tr>
</tbody>
</table>

SHG = Second Harmonic Generation
FHG = Fourth Harmonic Generation
SFG = Sum Frequency Generation
laser and a beta-barium-borate (β-BaB₂O₄ or BBO) nonlinear crystal as the wavelength converter [11]. It should be noted that deep-UV light can cause photochemical deposition of air-borne contaminants on the optical surfaces, thus a chemical-contamination-free clean air or nitrogen purge will be necessary in the optical system. If we employ a such shorter wavelength laser (266 nm or below) as a light source for the particle detection system, its sensitivity level can potentially be raised to the range of a 20 to 30 nm diameter.

At the ITRS 2002 Update Conference held in December 2002 in Tokyo, a problem with the present particle inspection system was pointed out, that is to say, “extra reflection from SOI wafers impacts optical measurements and light scattering [12]”. Indeed, the incident light penetrates into the silicon-insulator layer of the SOI structure depending on the laser wavelength, as shown in Fig. 4. The penetration depth of light (or the light intensity falling to 1/e) in a silicon crystal is approximately 500 nm for the 488 nm laser but only 5 nm for the 266 nm laser. Therefore, if the 266 nm laser is used, problems due to the light penetration into a silicon layer will virtually be eliminated, while the 488 nm laser generates the extra reflection problems. As a result, the minimum detectable defect size of the system for SOI wafers will remain in the range of 0.1-0.2 μm, under the optimum conditions, much larger than the nominal minimum detection size.

On the other hand, light-scattering topography with a longer wavelength light source may be applied to monitor the structural imperfections or crystallographic defects such as stacking faults in the surface regions of silicon wafers, if the noise level from the surface microroughness can be lowered.

INFLUENCE OF SILICON-SURFACE MORPHOLOGY

If we employ a shorter wavelength laser as a light source for the particle detection system, its sensitivity level can be raised. However, so far, silicon-surface morphology, such as crystal originated pits, micro-scratches, microroughness, as well as residual contaminants on a mirror-finished wafer, prevents detector sensitivity from being raised to such a high level. For unpatterned wafers, the background noise coming from surface scattering makes it difficult to discriminate finer particle scattering from surface scattering.

Crystal Originated Pits

So-called crystal originated pits, known as COPs, are observed as a square-shaped pit or a pair of pits on the surface of a (100)-oriented Czochralski (CZ)-grown silicon crystal, as shown in Figs. 5 (a) and (b). Crystallographically, the formation of the COPs is associated with an agglomeration of supersaturated vacancies during Si-ingot growth resulting in the formation of octahedral void structures in the bulk silicon as shown in Fig.5 (c). In other words, it is associated with the “negative” crystal growth of vacancies into octahedral voids. The COPs are
Nitrogen Concentration (atoms/cm$^3$)

FIGURE 6. Schematic grown-in defect map in terms of nitrogen concentration in bulk silicon and the ratio of the pulling rate during crystal growth over the temperature gradient at the solid-liquid interface.

exposed at the surface by the wafer polishing process as well as the subsequent wet cleaning process. These octahedral void structure defects have been a problem for the wafer inspection systems because they also scatter light and can be counted as particles, although these are not really particles adhering on the surface. As oblique incidence minimizes the contribution of light scattering from the COPs and the COPs scatters primarily toward the normal, recent models of the wafer inspection systems have the capability of discriminating between particles and COPs by comparing the scattered light in vertical incidence and that in oblique incidence and/or comparing the scattered light of an oblique incident beam collected by several collectors placed in different positions.

Even the latest surface inspection systems, however, cannot distinguish COPs and particles at their nominal minimum detection levels, while they can do it at the 80-100 nm sensitivity level but with an accuracy of the 80-90 % level, according to our own review-AFM/SEM observations.

It was once believed that the number of the COPs can be reduced from the wafer by lowering the crystal pulling-up speed during the crystal growth. More recently, it was found [13] that the size of the COPs can be controlled below the detection limit, even if they cannot be completely eliminated, by controlling the ratio of the pulling rate during crystal growth (V) over the temperature gradient at the solid/liquid interface (G), or V/G, and introducing a small amount of nitrogen into a growing Si crystal as shown in Fig. 6. The size of the COPs, therefore, will be able to be minimized below the sensitivity limit of the particle detection systems, even if they cannot be completely eliminated.

FIGURE 7. Arc-shaped scratches detected by a wafer-surface particle detection system.

Micro-scratches

Scratches on the silicon surface can also scatter light and cause problems for unpatterned wafer inspection. Long arc-shaped scratches as well as small particles were detected on silicon surface as shown in Fig. 7 when a new high-sensitivity model of the wafer inspection system was introduced while the former models with lower sensitivities had never revealed this type of scratch because of their poorer light scattering nature. Optimization of the wafer polishing conditions could easily eliminate these arc-shaped scratches as well as micrometer-order scratches. More recently, it has been reported [14] that the entire surface of a mirror-polished wafer contained numerous micro-scratches whose width and depth are in the order of nanometers. These nanometer-order micro-scratches preferentially scatter perpendicular to their long dimension; therefore, these defects are often missed. If we continue to increase the sensitivity of the system, the discrimination of particles from these micro-scratches will become a difficult challenge in the future. Reconsideration of the wafer polishing process and materials, which will be discussed in the next section, will be necessary in order to reduce or eliminate these micro-scratches.

Microroughness

Microroughness of the silicon surface, which ranges approximately from 10 nm to 1 µm in spatial wavelength, is usually referred to as “haze” in the semiconductor industry. The microroughness also prevents detector sensitivity from being raised to a higher level. Figure 8 illustrates a light-scattering signal collected along a laser-scan line on a wafer. It can be seen from this figure that the single from a discrete defect sits on top of the background haze. If a comparatively high threshold of light-scattered intensity was defined, as shown as (a) in the figure, only comparatively big particles can be detected without any influence of noise from the surface morphology as well
Signal from a particle
Signal from a smaller particle
Noise due to surface roughness
Variation of background haze

Position
Scanning direction

FIGURE 8. Light-scattering signal collected along a scan line on a wafer (top). Particle map displays for three differently defined thresholds of scattering light intensity indicated as (a), (b) and (c) in the top figure. (bottom).

FIGURE 9. (a) Immersion-type multi-wafer RCA cleaning vs. (b) spin-type single-wafer SCROD cleaning.

as that in the optical system. At the lower threshold level as shown as (b) in the figure, smaller particles and haze can barely be discriminated. If the threshold of intensity is defined to be lower than (b), as shown as (c) in the figure, the variations of the background haze are partly counted as particles as well as real particles; therefore, it is difficult to discriminate haze and particles with such a low threshold. In other words, the minimum detection size of particles is limited by the haze background. Thus, it will be clear that the sensitivity of the wafer inspection system cannot be raised without decreasing the background haze level. Therefore, the very small particle size detection or high-sensitivity inspection is primarily restricted to super-smooth monitor wafers. Adequately optimized precision wafer-polishing using polishing pads with a lower modulus of elasticity and a slurry with uniform, smaller abrasives gives good results for lowering the haze level. For the further reduction of haze, further improvements in the wafer cleaning process as well as in the wafer-surface polishing process will be required.

It is well known that widely-used RCA SC-1 cleaning in a NH₄OH/H₂O₂/H₂O mixture efficiently removes particulate and metallic contaminants from the wafer surfaces, but it is known to enhance surface microroughness due to simultaneous oxidation/etching of the surface layers of the silicon wafers during their immersion in the chemical solution [15]. In such immersion-type wet chemical cleaning, even if ultra pure chemicals are introduced and then disposed of after cleaning, the contamination removal efficiency is dominated by the amount of impurities brought into the fresh solution by the to-be-cleaned wafers themselves [16], as shown in Fig. 9 (a). In order to meet stricter wafer cleaning requirements, new cleaning methods not to enhance microroughness will have to be employed in
which fresh chemicals are continuously supplied, such as single-wafer spin cleaning. Recently, we have developed a new single-wafer spin cleaning that alternately cycles between ozonated water and dilute HF at room temperature for a few seconds [17-19], as shown in Fig. 9 (b). Called “SCROD” (single-wafer spin cleaning with repetitive use of ozonated water and dilute HF), this process can efficiently remove particulate and metallic contaminants from a silicon surface without increasing surface roughness.

Residual chemical contamination on the surface of silicon wafers, both inorganics and organics, can also cause the formation of various kinds of haze on the surface [15, 20], resulting in reducing the sensitivity level of the inspection system. The SCROD cleaning is also very effective in eliminating this type of chemical contamination [17-19].

SUMMARY

As the size of potentially yield-limiting (or “killer”) particles has significantly decreased with the decrease in the feature size of leading-edge ULSI devices, a clear need has arisen for a system capable of measuring particles far below 50 nm in diameter. If we employ a shorter wavelength (266 nm or below) laser such as a deep-ultraviolet solid-state laser as a light source for the particle detection system, its sensitivity level can be raised to the range of a 20 to 30-nm diameter on a smooth surface, which corresponds to approximately a half of the nominal detection limit of the existing systems. However, so far, silicon surface morphology such as COPs, micro-scratches, microroughness, as well as residual chemical contamination on the silicon surface, prevents detector sensitivity from being raised to such a high level. Therefore, before raising the particle detection sensitivity of the system, we must establish technologies for obtaining super-smooth silicon surface by employing scratch-free precision surface-polishing, COP-free crystal growing annealing and microroughness/particle-free wafer cleaning. The ever increasing detrimental impact of particulate contamination in smaller feature-size device manufacturing will create future research opportunities and engineering challenges to develop finer particle/defect detection systems as well as particle/defect review, classification, and characterization systems.

REFERENCES


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