Cleaning and inspection of EUV reticles: specifications and prospects

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Abstract:

Due to large absorption of EUV light, EUV reticles are not expected to have pellicles for particulate contamination protection. The lack of a pellicle means that having a means of cleaning and inspecting pellicles that could be adapted to in-situ use is of great interest. Even nanosize particles could result in fatal defects in every die of the wafer. Consequently, measures must be taken to detect and remove any particle above a certain critical size, accidentally deposited on the reticle.

Here we present the issues and challenges we are facing in the detection and removal of particles from EUV reticles. Very stringent specifications are required to ensure that practically no particle is present at the time of exposure. We will then give an overview of the technologies that ASML is investigating in order to meet these specifications. These include laser scatterometry techniques for the inspection part and different dry cleaning techniques. For the former, the challenge is the detection of sub 50nm particles on patterned reticles within minutes, while for the latter, the main challenge is to remove any type of particle (organic/inorganic) in the same timescale and without damaging the pattern. Results, including cleaning of 50-nm PSL spheres using dry techniques, will be discussed.

Key words:

EUV reticle, EUV mask, mask cleaning, mask inspection

I. Introduction

The IC market growth is driven by both the exponential shrinkage of the component size on the chip and the exponential cost reduction per component. The key technology to enable this shrinkage is optical lithography. The current mainstream technology is based on the 193nm (wavelength) immersion technology, employed to print features with a lateral critical dimension (CD) of 45nm (which corresponds to half pitch, hp, in dense lines). This technology can be extended to the 32nm node (CD=32nm) with a significant increase in complexity involving, i.e., double-patterning technology [ref1]. Beyond the 32 nm node a major change in technology is required and the most dominant candidate is Extreme Ultraviolet lithography (EUVL). This technology is based on 13.5nm wavelength. This dramatic decrease in wavelength will bring a straightforward gain in resolution, but several issues have to be addressed for the commercial success of EUVL. These include the generation of radiation at the EUV wavelength (100W of in-band radiation at intermediate focus will be required) and the difficulties due to the high-absorption of this radiation by virtually all materials, including gases (of the order of percent per nanometer of thickness for solid materials). Because of this, the optical path must be in vacuum and all optics must be reflective (e.g., mirrors instead of lenses), including the reticle. Contamination also becomes a critical issue, especially for reticles. In fact, contrary to DUV reticles (used for 193nm), because of high material absorption EUV reticles do not have a protective pellicle in proximity of the surface to prevent particles to accidentally fall on the patterned area, especially during handling and exposure. Because of the pellicle DUV reticle contamination is important only at particle sizes relatively large (>~5 μm), since smaller particles on the pellicle are not imaged during exposure and do not result in a defect. However, in the EUV case, the particle is in direct contact with the pattern, thus the critical particle size is comparable with the CD (as illustrated in the next Section). A single particle on the reticle may result in a fatal defect in every die of the wafer (batch), corresponding to zero-yield.

For this reason, contamination of the reticle during all phases of its lifetime must be addressed. An industry-wide collaboration resulted in the Dual-Pod carrier system, which was demonstrated to be very effective in preventing particle contamination during handling of the reticle[2]. The Dual-Pod consists in two “boxes”, one inside the other. This double protection system proved that contamination of less than 0.1 particles/reticle over the entire lifetime is possible (where lifetime is defined as round-trip shipment, vacuum pump/vent and storage, inspected at 53nm minimum size).

The other critical phase of the reticle lifetime is inside the lithography tool, during exposure. Although the reticle will be in an ultra-clean vacuum environment, because during exposure it cannot be protected with the Dual-Pod, there is still a small risk of particle contamination. Exposed wafers will have to be checked for defects off-line and, if necessary, the reticle will have to be removed from the machine and cleaned. Although no cleaning technique currently exists that meets the requirements for EUV reticles, there is significant effort worldwide in this direction. For example, Sematech, in collaboration with Hamatech Gmbh, achieved cleaning of >10nm particles from reticle blanks (=without pattern) using a combination of wet/dry techniques [3].

Although inspection and cleaning can be done off-line, ASML is investigating techniques that can be employed to inspect and clean the reticle inside the lithography tool. Integrating such functionalities in the machine should decrease the risk of fatal defects due to particles on the reticle and should increase the throughput. The main issues of reticle cleaning/inspection will be illustrated in Section II, while the requirements that these techniques must satisfy will be detailed in Section III. These techniques have to be compatible with vacuum environment, which means that only dry techniques can be employed. In Section IV we will review some of the cleaning techniques investigated and their current status. In Section V we will discuss the more challenging problem of inspection.

II. Overview of cleaning/inspection issues

A EUV reticle consists in a 6”x6”x1/4”quartz or low-thermal-expansion material substrate with a reflective multilayer (ML) coating and an absorber pattern on top, as shown in Figure 1. The coating consists of ~40, Mo/Si, $\lambda/4$ pairs of about 200nm total thickness. A capping layer (like Ru or Si) is often used. The pattern is defined into an absorbing layer (i.e., TaN/TaNO). The size is 4 times larger than the CD (because of 4x demagnification factor between wafer and reticle) and the thickness is about ~70nm. The pattern is in principle arbitrary and can be composed of (dense) lines, contact holes, periodic and non-periodic patterns.

Because the lithography tool is extremely complicated and utilizes many different materials, we can “in principle” have any type of particle deposited on the reticle (i.e., organic, inorganic, metallic, such as Al, Fe, Al_2O_3, ceramics, etc.) and thus we must be able to remove any type of particle. The particles could be conductive or insulating, they can be of any shape and any size and could be deposited on the (conductive) coating or on the (insulating) absorber.

A first challenge in reticle cleaning consists in removing the particles without damaging the substrate. Damage either to the ML or to the pattern has to be absolutely avoided (see Section III). Because the reticle is composed by different materials and has a complex structure, it is very fragile. For example mechanical stress could peel off the coating from the substrate or heat could cause interdiffusion of the Mo/Si layers, reducing the reflectivity. A second challenge lies in the presence of the pattern: particles can in fact get trapped in trenches or holes, which would make the removal by physical means (fluids, shockwave) very difficult to apply.

The pattern constitutes also the main challenge in reticle inspection. Typically, laser scatterometry or dark field techniques are used to inspect bare surfaces, exploiting the fact that particles scatter light isotropically, whereas a flat surface specularly reflect light. These techniques, however, are not applicable to structured surfaces, because of the strong scattering of the pattern itself (see Section V). The main challenge in reticle inspection is then the ability to distinguish a particle from the background pattern within the required amount of time and with the required sensitivity (see next Section).

III. Cleaning and inspection specifications

A certain number of specifications (listed in Table 1) have to be met for a cleaning/ inspection technique to be integrated in the lithography tool.   The minimum particle size to remove/inspect is defined by the following equation:

$$Size = \frac{1}{2} CD \cdot Mag / MEF \,, \qquad (1)$$

where *Mag* is the demagnification factor between reticle and wafer (=4) and MEF is the mask error factor, which depends on the exposure parameters and is usually calculated numerically. In our case the MEF varies between 1.5 and 3.5 and, because of this, the particle size decreases more than linearly with respect to the CD. As mentioned earlier, in principle the inspection/cleaning technique should be able to handle all types of particles. The maximum number of cleanings in a reticle lifetime has been estimated as ~300, which is the estimated limiting case of intensive reticle usage over 6 months. The actual number of cleanings will vary largely in function of the specific reticle, process and customer and will be in the range ~20-300. The two main requirements for cleaning are Particle Cleaning Efficiency (PRE) at minimum particle size and damage to the reticle. The required PRE insures that every particle will be removed during the entire lifetime of the reticle. We assume that at the time of cleaning only a few particles (ideally only 1) will be present on the reticle. These requirements translate in a PRE of 99.5% for the limiting case of 300 cleanings and of 95% for the best case of 20 cleanings. The damage to the reticle is primarily measured as reflectivity loss ($\Delta R/R$ in %) of the ML and as damage to the absorber pattern. Up to 1% loss in reflectivity (over the lifetime of the reticle) can be tolerated, but reflectivity loss cannot vary more than 0.1% over the entire reticle surface in order to maintain dose homogeneity. The faster the cleaning, the higher the productivity, so a cleaning time smaller than 12 minutes is desirable, although a longer time may be accepted initially.

For reticle inspection, it is important that no particle will be missed, which means less than 1 false negative every 300 scans. The number of false positive is less critical and not yet specified. For the inspection time, the same considerations for cleaning are applicable. It is important to note that the knowledge of particle size and location are not required.

IV. Cleaning techniques

In this section we will review the status of the techniques investigated by ASML for reticle cleaning. As mentioned earlier, these must be “dry” techniques in order to maintain compatibility with the vacuum environment of the lithography tool. These techniques include Laser Shockwave Cleaning (LSC), developed at ASML and in collaboration with an external partner, and High Voltage Cleaning (HVC), developed at the Institute of Spectroscopy RAS (ISAN), Troitsk, Russia, also in collaboration with ASML.

Laser shockwave cleaning

With the Laser Shockwave Cleaning (LSC) technology particles are blasted away from the substrate by exposing them to a fast moving shockwave, resulting from laser induced breakdown (LIB) of air (or of another buffer gas), due to focusing of a high energy laser pulse. Figure 2 shows the basic setup: a high-energy (~100mJ), Q-switched laser pulse is directed parallel to the substrate to clean and focused close to the surface (~mm). The intense focus will produce a small plasma pocket that will almost instantaneously expand generating the shockwave. The physics of LSC has already been explained elsewhere [4], so here we will only summarize the results.

The expression of the pressure jump across the shockwave can be written as:

$$\Delta p \sim \frac{8}{25}\left(\frac{1}{\gamma+1}\right)Y^{5}(\gamma)\left(\frac{W}{R^{3}}\right), \tag{2}$$

where W is the energy of the laser pulse, R is the distance from the center of the plasma, and γ the specific heat ratio of the gas. The dimensionless parameter Y is an empirical constant, which depends on the specific heat ratio. Typical values of Y are listed in Table 2.

Equation (2) is a simplified expression valid only for strong shocks (e.g., Mach number >2) and thus for small values of R. . In the far–field the shockwave slows down and travels at the speed of sound, so that its pressure attenuation is proportional to R^{-1}(instead of R^{-3}). The previous expression is important for the optimization of the laser shockwave cleaning process, since the pressure jump across the shockwave is a direct measure of the cleaning force. It shows that the largest improvement in cleaning can be made by decreasing the gap distance. The gap distance is however limited to a minimum value, to avoid damage to the surface. Another large improvement can be made by increasing the energy of the laser pulse, but then a larger gap distance is needed to avoid damage to the surface, typically due to radiation induced thermoelastic stress.

Depending on the distance of the particle from the laser focus, different removal mechanisms may take place. If the shockwave hits the particle at a shallow angle (e.g., far away from laser focus), the particle will likely be removed by the rolling or sliding mechanisms. In the case of steep angles (e.g., nearly below the laser focus), removal by saltation is more likely to occur.

A particle can roll or slide if the cleaning momentum is larger than the resisting momentum associated with the adhesion forces. This model is described, i.e., by Lammers et al. [4]. If the shockwave hits the particle at a steep angle, the pressure will induce a compression in the particle, which will store elastic energy. This energy will be subsequently released, projecting the particle away from the surface, as described by

Zhang et al. [5]. In either case the particle is dislodged and transported by the turbulent flow following the shockwave.

At ASML, we built an automatized LSC setup capable of handling samples of any type and size, up to 300mm wafers. Although EUV reticles are the main target, 300mm wafers are preferred for particle removal efficiency (PRE) measurements. In fact, with these samples, fast and accurate inspection is possible using commercial particle scanners, such as the KLA-Tencor SP2.

We were able to show removal of PSL (Polystyrene-Latex) particles from Silicon wafers as small as 40nm (limited by the inspection tool), with PRE larger than 95%. Figure 4 shows point and line cleaning of nominal 60nm PSL particles. For point cleaning 15 and 20 shots were applied in the same spot and 100% PRE was achieved locally. For line cleaning, the sample was moved in steps and PRE of 95% was obtained. Note that the particles in the central part of the line are mostly redeposited. This unusual redeposition pattern can be explained by the turbulent flow of air following the shockwave, as illustrated in Jang et al. [6]. This redeposition can be avoided by adding a gas flow parallel to the surface, which cancels the turbulent flow of the shockwave, as described in [6]. If we now look at the size histogram of particles before/after line cleaning, we see that, because of spread in nominal size, a considerable number of 40nm particles were removed. So we can conclude that this technique can remove at least 40nm PSL particles (on silicon) with high PRE.

The second crucial test is damage to the ML coating. For this test we employed ML-coated Silicon and Quartz substrates. Qualitative damage tests were performed in order to explore the parameter space of pulse energy and gap distance. The results are shown in Figure 6. As expected, for large energy and small gap distance, we obtain catastrophic damage, due essentially to detachment of the ML from the substrate. We believe that this caused by thermoelastic stress induced in the ML film. By comparing the results for silicon and quartz substrates, we see that the substrate material and the adhesion between it and the ML play a critical role in the damage threshold. For parameters that do not cause visible damage (by optical microscope), reflectivity at 13.5nm was measured before and after cleaning and showed no reflectivity loss. In locations where "discoloration" (slight change in color) of the ML was observed, a small decrease in reflectivity was observed (< 1%), but XPS (X-ray Photoelectron Spectroscopy) analysis showed that no sputtering of the Ru capping layer took place. This means that the damage is of thermal or thermo-mechanical nature. Notice finally that no direct laser damage is observed if precautions are taken to keep the laser beam as parallel as possible to the surface.

A comparison of the no-damage parameters with the parameters used to assess the PRE on silicon shows that the setup "as is" will not be able to clean sub-100nm particles from our ML samples in air. However, planned upgrades to the current setup (including using a different gas than air and a device to protect the surface) and the fact that in a vacuum environment there is no capillary force (which is dominant and much larger than van der Waals forces when deposition and cleaning is done in air), should enable LSC to meet the required specifications (removal of sub-30nm particles with high PRE and no damage).

Finally, cleaning of a piece of real EUV reticle contaminated with real-life particles was also attempted. An analysis by optical miscrocope of the reticle surface before and after cleaning (Figure 7), provided evidence of removal of at least >100nm particles from trenches without visible damage (obviously 100nm particles cannot be resolved in a optical microscope, but they can be detected). Reflectivity measurements were not possible because of the nature of the sample. Moreover, SEM analysis of the pattern showed no damage. Notice that the parameters used in this case would have produced catastrophic damage on the previous ML samples. This indicates that real EUV reticles seem more resistant then our ML samples and that more experiments are necessary to properly characterize LSC's capabilities on real EUV reticles. In conclusion, we believe that, although more experiments and upgrades will be necessary, LSC is a very promising candidate for in-tool, dry-cleaning of EUV reticles.

High voltage cleaning

Among the other techniques investigated by ASML, we mention here High Voltage Cleaning (HVC), developed at ISAN. This technique, illustrated in Figure 8a consists in applying (in vacuum) a High Voltage pulse to a flat electrode in close proximity (~0.1-1mm) of the (grounded) surface to clean. Because of the high electric field at the surface, particles are charged and attracted towards the electrode. If the E-field is large enough, the electrostatic force overcomes the adhesion force and the particle is removed from the surface.

In order for the particle to be charged, the charging time, given by the product of the resistance times the capacitance of the particle has to be smaller than the pulse length. This in turn sets a limit to the maximum practical resistance of a particle to about ~ 10^{10}-10^{11} Ohm. Consequently this technique will work with different efficacy on different particles types, e.g., better with metallic or conductive particles than with PSL or highly insulating particles.

Figure 8(b-d) shows experimental results of removal of metallic particles from a TiN-coated silicon wafer. Removal of metallic particles larger than 50nm was demonstrated. Tests are currently carried on with other particle types (silica, PSL). Damage experiments on ML-on-silicon samples were also carried on and did not show any detectable reflectivity loss.

Because it operates in vacuum and because it has proven to be damage-free, this technique is also a very good candidate for EUV reticle cleaning. The disadvantage is the lower efficacy in removing insulating (organic) particles, but this limitation could be overcome, i.e., by combining this technique with other techniques that are very effective in removing organics, such as H_2 or He metastable etching.

V. Reticle inspection

Commercial tools exist for inspection of wafers and reticles (i.e., Lasertec, KLA-Tencor, Applied Materials), both for blank and patterned surfaces. In the case of blank surfaces (bare wafers, mask blanks), the dominant technique is laser scatterometry (similar to dark field imaging in a microscope). With this technique, illustrated in Figure 9a, a light source (typically a laser) is shined on the surface at an angle. A sub-wavelength particle present on the surface will scatter light isotropically. An optical system is arranged in such a way that it captures a portion of the scattered light, without collecting the reflection of the light source from the surface. Tools based on this technique are capable of very fast and sensitive measurements (such as the KLA SP2, capable of scanning a 300mm wafer in ~minutes with sensitivity down to 40nm PSL equivalent size). However, laser scatterometry cannot be used on patterned surfaces, since the particle signal will be overcome by the light scattered from the pattern.

For patterned surfaces a different method is used. The surface is imaged at very high resolution (i.e., sub-100nm pixels using 193nm UV light) and the image is compared to the image of a nominally identical location of the wafer/reticle (die-to-die analysis) or to a calculated (or reference) image (die-to-database). In this way, it is possible to detect and distinguish defects due to a particle on the wafer or on the reticle (repeaters). This method is very effective but typically very slow (~hours) compared to laser scatterometry.

The main challenge for fast, in-tool reticle inspection is the detection of particles on a patterned surface and with the same efficacy and speed of laser scatterometry. The difficulty lies in the fact that a particle on a reticle, from the scattering point of view, will look exactly like a pattern feature (i.e., a contact hole) when the illumination wavelength is larger than the particle size. However, the last statement is not true in the case of periodic patterns. Research has been conducted by TNO Delft, in collaboration with ASML, in the development of an extension of laser scatterometry to periodic patterns. If the pattern is periodic (i.e., memory banks), scattering is highly directional (while the scattering of the particle is isotropic) and can be filtered out, recovering the particle signal. Figure 9b shows a schematic of this principle. Using this technique particles as small as 50nm were detected in patterned areas, even in the case of particles located on top of a feature, as shown in Figure 10. However, such approach fails in presence of non-periodic patterns (i.e., periphery of memory chips). For this reason, other techniques based on spectroscopy (which would allow discrimination of the particle based on material signature) or fast imaging at EUV wavelength are currently investigated.

VI. Conclusion

For the success of EUV technology, the challenge of reticle contamination control must be addressed. The Dual-Pod carrier system has shown to be very effective in preventing particle contamination during handling (0.1 particles/reticle in average over reticle lifetime). In order to reduce the risk of defects due to contamination inside the lithography tool, off-line inspection of printed wafers and eventual cleaning is a solution. However, to increase productivity, it is highly desirable to have reticle cleaning and inspection capabilities integrated in the lithography tool. In order to be compatible with the vacuum environment of the lithography tool, dry cleaning techniques must be employed. Currently ASML is investigating several dry-techniques for cleaning and for inspection. Laser Shockwave Cleaning showed very promising results in terms of PRE (removal of 40nm PSL on silicon), and with modification of the setup, this technique should be able to avoid damage of the ML. High Voltage Cleaning also shows promising results in terms of PRE and no damage of the ML, although the efficacy is particle-type dependent.

On the other hand, fast, in-tool reticle inspection still requires effort and currently can be performed only on periodic patterns. For this reason ASML is exploring several new techniques based, i.e., on spectroscopic detection of particles.

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Table 1. Reticle cleaning and inspection specifications

Specification	Value	Comment
Minimum particle size to remove/inspect	36 nm 18 nm 9 nm	27 nm node (2010) 22 nm node (2012) 16 nm node (2015)
Particle types to remove/inspect	Organic, inorganic, metallic	i.e., Al, Fe, Al_2O_3, Fe_xO_y, ceramics, organics
CLEANING		
Max number of cleanings in lifetime of reticle	300	The actual number of cleanings will be 20-300, depending on process, customer, etc…
Maximum number of particles NOT removed larger then min. particle size	<1 every 300 reticles/ cleanings	At ~1 particle/reticle.
Reticle reflectivity change (ΔR/R)	< 1 % in 300 cleanings <0.1 % in 300 cleanings	global average local variation
Number of cleaning steps	1	Preferably
Cleaning Time	< 12 min	Longer times, up to 1 hour, will be accepted initially
INSPECTION		
Number of false negative @ min particle size	<1 particle / 300 scans	At ~1 particle/reticle
Inspection time	<12 min	Longer times, up to 1 hour, will be accepted initially
Particle size required	No	
Particle location required	No	In principle, practically may be useful for cleaning purposes

Table 2. Typical values of the dimensionless parameter *Y*.

γ	7/5	5/3
$Y(\gamma)$	1.03	1.15
$Y^5(\gamma)/(\gamma+1)$	0.48	0.84

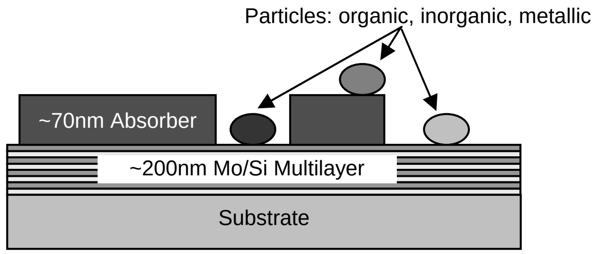


Figure 1. Schematic of EUV reticle and overview of particle cleaning/inspection problem.

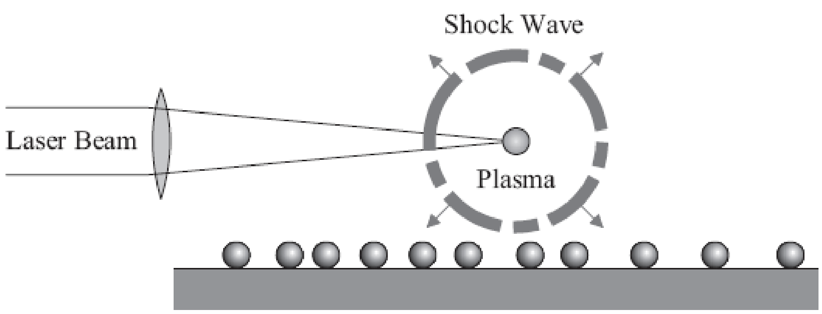


Figure 2. Laser shockwave cleaning principle.

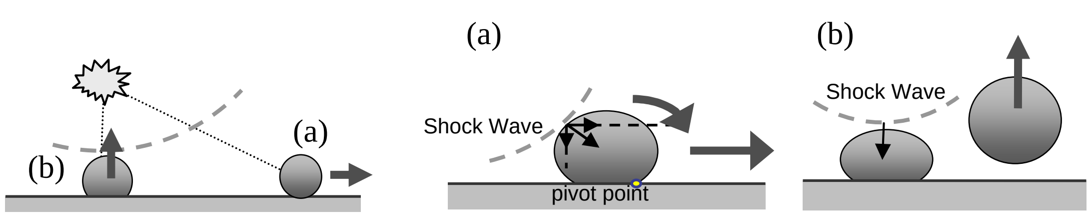
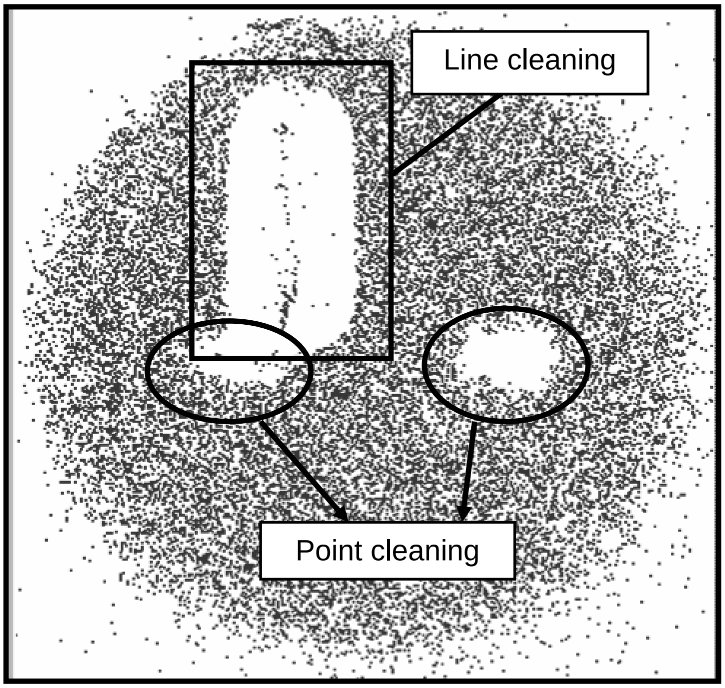


Figure 3. Removal mechanisms for LSC depending on distance of particle from laser focus: rolling/sliding (a) and saltation (b).



Point Cleaning (20 shots)	
Deposited	256
Removed	256
Re-deposited	0
PRE	100%
Line Cleaning	
Deposited	2423
Removed	2400
Re-deposited	90
PRE	95.3%

Figure 4. Cleaning results for point (15 and 20 shots) and line cleaning of 60nm PSL on Silicon. The deposited area is ~4cm in diameter.

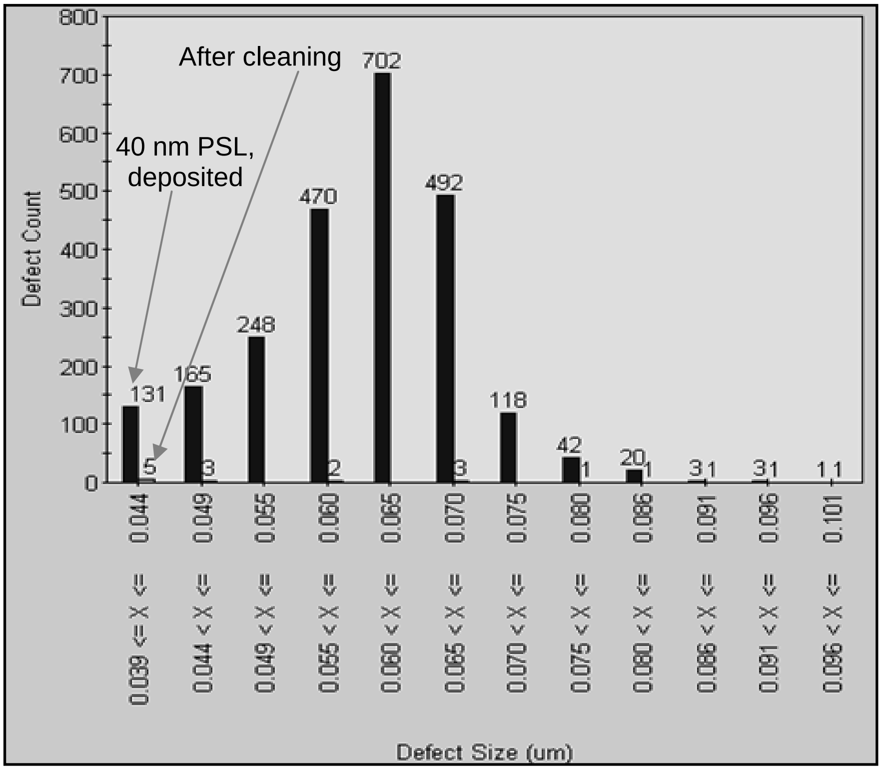


Figure 5. Histogram of (nominal) 60nm PSL inside the cleaned area before and after line cleaning of Figure 4.

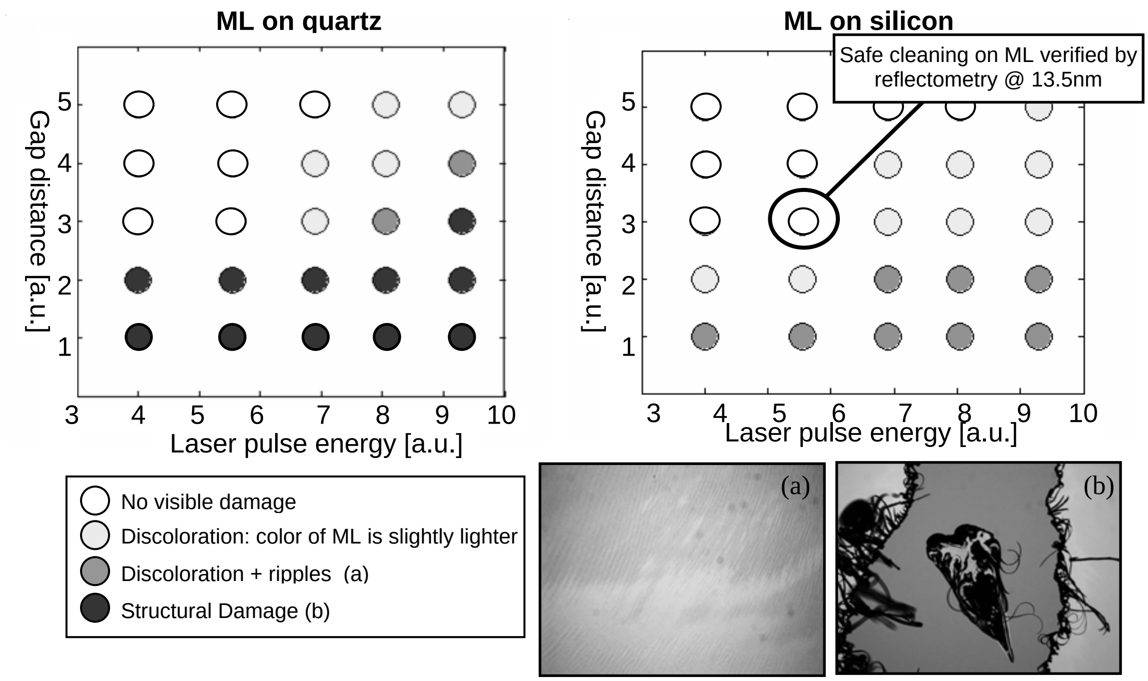


Figure 6. Qualitative damage assessment of LSC on ML on silicon and on quartz. The insets show example of observed damage.

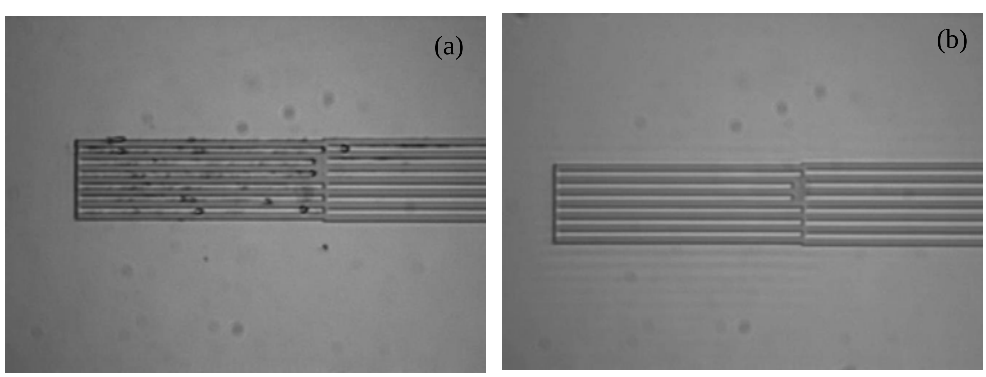


Figure 7. LSC cleaning of a piece of real EUV reticle. The images before (a) and after (b) cleaning are taken at the optical microscope (150x) with 50μm horizontal field of view. The spots appearing on both images are dirt on the microscope lens.

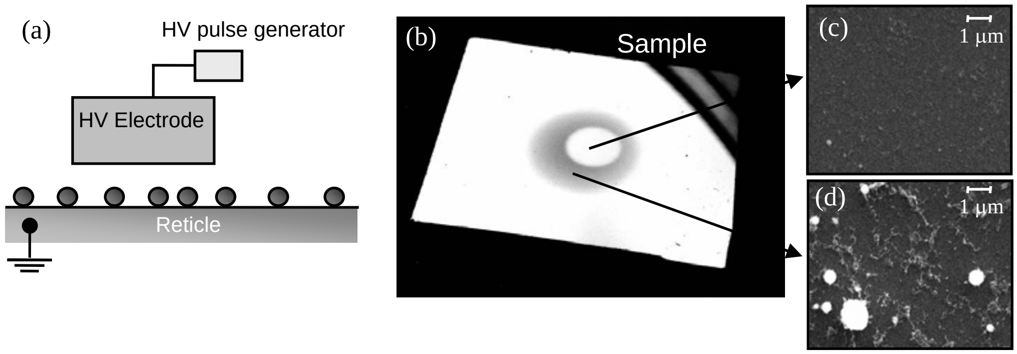


Figure 8. HVC principle (a) and cleaned sample (b). The SEM pictures show the central cleaned area (c) and the outer reference (uncleaned) area (d).

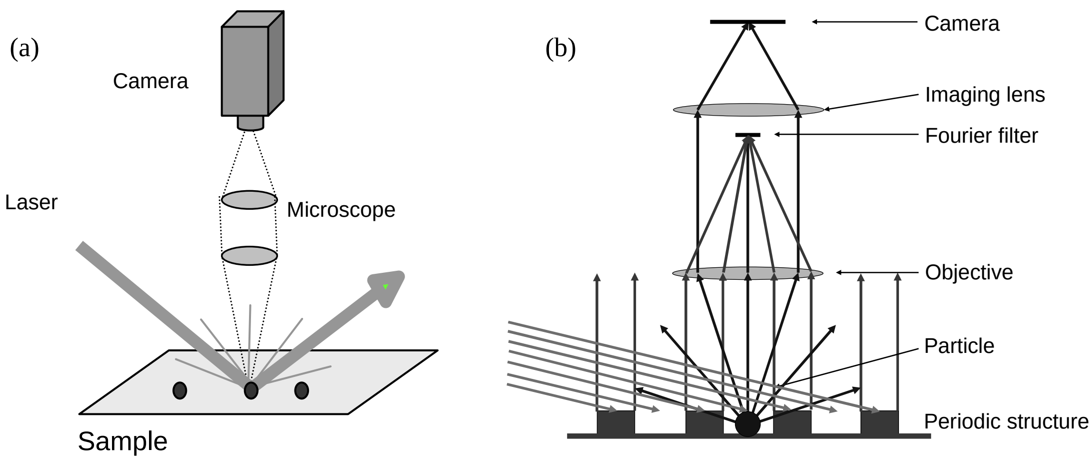


Figure 9. Laser scatterometry principle (a) and extension to periodic patterns (b)

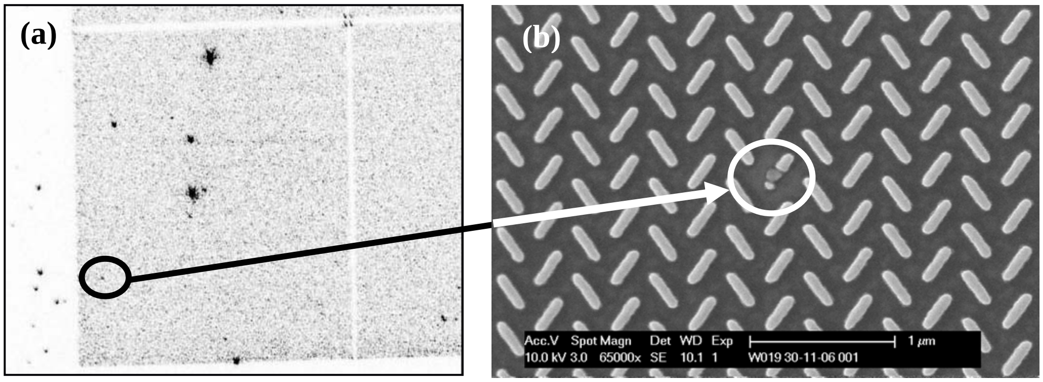


Figure 10. Detected particles by laser scatterometry with filtering (a) and SEM image of one of the particles (b). Notice that the particle lies on top of the feature.