Sub 20 nm Particle Inspection On EUV Mask Blanks

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SUMMARY

The Rapid Nano is a particle inspection system developed by TNO for the qualification of EUV reticle handling equipment. The detection principle of this system is dark-field microscopy. The performance of the system has been improved via model-based design. Through our model of the scattering process we identified two key components to improving the inspection sensitivity. The first component is to illuminate the substrate from multiple azimuth angles. The second component to improve the sensitivity is to decrease the wavelength of illumination. A shorter wavelength increases the total scattering and reduces the background scattering relative to the defect signal. A new Rapid Nano particle detection system (RN4) will be completed mid 2016. It combines the multi-azimuth illumination mode with a 193 nm source. This system will have a sub 20 nm LSE sensitivity, in-line with the requirements of the ITRS roadmap for defects on EUV masks.

The Rapid Nano inspection system makes use of dark-field imaging, in which an area of a substrate is imaged on a camera. Previous generations of the Rapid Nano system made use of commercially available optics for the imaging step. In the DUV wavelength regime diffraction limited imaging over a large field is more challenging and suitable optics were not available off-the-shelf. Therefore TNO designed and fabricated an objective lens specifically for the Rapid Nano 4 inspection system.

Other challenges in changing the illumination to the DUV include handling the high peak power of the pulsed laser source and the lifetime of the optics. The design of the Rapid Nano 4 and first results comparing it to the model predictions will be presented.

1 INTRODUCTION

Reticle defectivity is one of the issues that still needs to be addressed in order to prepare EUV lithography for high-volume manufacturing. Particle contamination before, during and after the production of a reticle is a source of reticle defects. For this reason, there are strict requirements on the cleanliness of all reticle handling equipment that interact with a reticle over its lifetime.

In order to qualify the particle cleanliness of equipment for the reticle infrastructure, particle inspection equipment is needed. In 2011 TNO introduced the RN1, which was capable of detecting 59 nm particles on a full reticle substrate [1]. The ITRS roadmap gives the critical defect sizes for wafers and EUV reticles (see Figure 1). We aim to increase the sensitivity of our particle scanner to match the requirements set by the ITRS roadmap. By modeling the scatter process a road forward to increase the sensitivity were identified [2]: decreasing the background variance by multi azimuth illumination and use light at 193nm wavelength. The multi azimuth illumination mode averages out the variance in the background scattering, allowing for a lower detection threshold to be used. Two years ago, this illumination mode was implemented in our existing particle

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detection system [3], RN3. This resulted in a decrease in lower detection limit from 59 nm to 42 nm PSL particles on silicon. According to the ITRS roadmap [5], the critical defect size for EUV reticles will be around 20 nm (see Figure 1). With the next generation particle inspection equipment, the RN4, we are building a system that will be capable of measuring sub 20 nm particles, which matches with the defect size roadmap of ITRS.

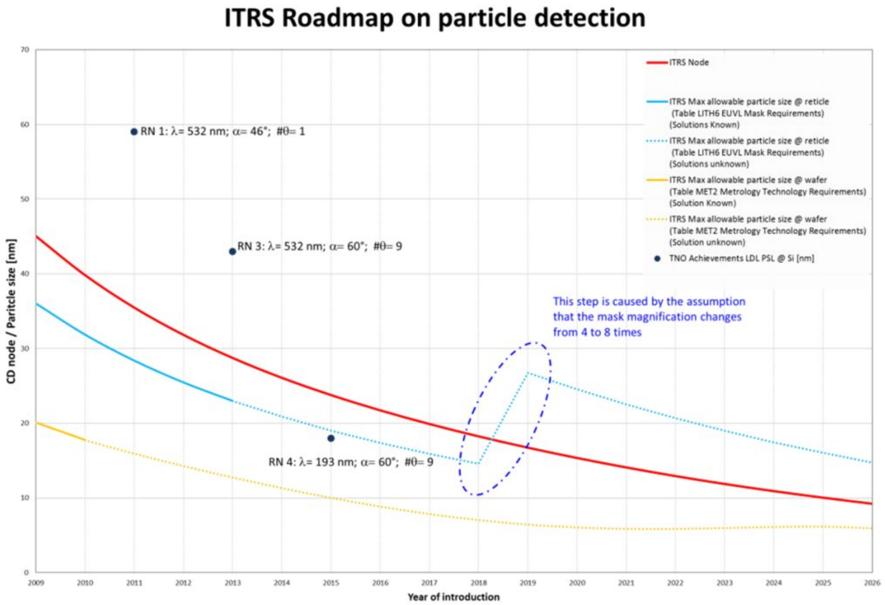

Figure 1: ITRS roadmap for critical defect size on EUV masks.

Before equipment from the reticle infrastructure can be used in production, it should pass a qualification test in which the cleanliness is proven to meet the specifications. In such a qualification test a reticle blank is used. This blank is inspected on particles before and after the test. The difference between these two inspections shows the particles that were added by the equipment during the test. The test itself consists of a number of reticle passes through the tool. The minimum number of cycles for a statistically significant result depends on the cleanliness specification and background noise present in the measurement [4].

The Rapid Nano 4 (RN4) will become one of the instruments that is part of an larger TNO infrastructure for handling an qualifying EUV equipment (pods, handling equipment, backside particle detection unit (OCT). See Figure 2). The basic infrastructure is build and qualified, consisting of an atmospheric reticle handler, load port, exchange ports and reticle flipping tools. At this infrastructure, the RN4 will be attached for automated inspection of reticles. Customers of TNO can have access to this unique facility to qualify their products or systems.

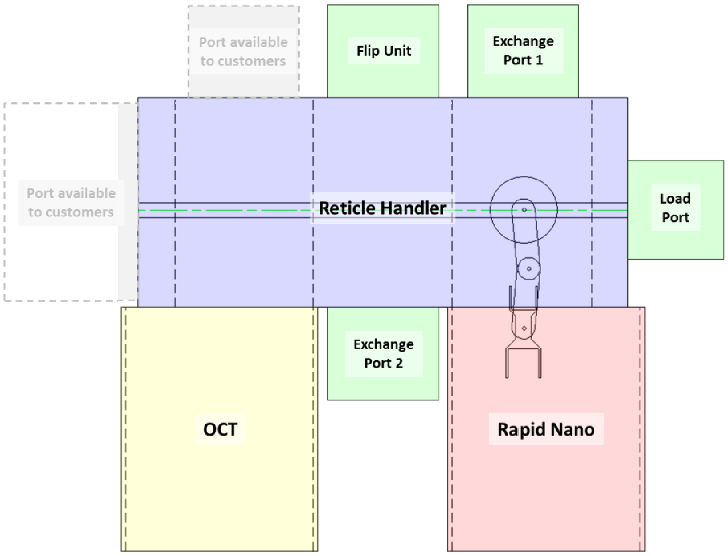

Figure 2: Particle qualification test facility

2 RAPID NANO 4 DESIGN

The RN4 system is an improved redesign of the predecessors. The basis of the system is a dark field imaging technique (see Figure 3). The substrate is illuminated outside the numerical aperture of the objective used (dark field). If the substrate would be perfectly flat without any particle or roughness, all the light will be specular reflected and no light will be captured by the objective.

If a particle is present on the substrate, the scattered light of the particle will be captured by the Schwarzschild objective and imaged on a camera using the tube lens. As the smallest detectable particles will be much smaller than the feature size the objective can image (resolution), the particle will end up as a small bright dot at a black background. The size of the bright dot is determined by the diffraction limit of the system (assuming a diffraction limited system).

The substrates used are not perfectly flat and will have some roughness. This roughness will produce scattered light, and will also be imaged at the camera as a speckle pattern. The challenge in this system is therefore to discriminate the particle from the speckle induced background noise.

Note that this effect is different from optimizing normal camera based systems, where the camera noise is usually the limiting factor. Also note that the problem cannot simply be solved by increasing the amount of light. In that case both the particle signal and the background signals will increase simultaneously.

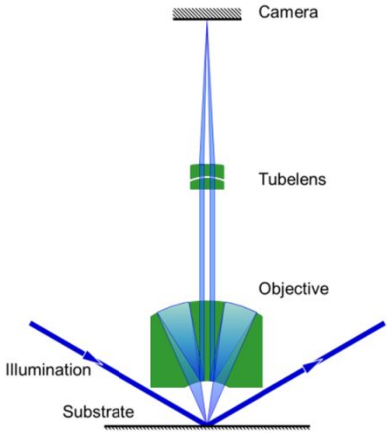

Figure 3: Schematic of the Rapid Nano 4 system. The substrate is illuminated at a grazing angle, while scattered light is imaged on a camera.

As described in previously [2], [3]. there are a several ways of increasing the contrast of the particle and the background. One of the implemented methods is polarization. The incident polarization is P-polarized. This will result in a lower scattering of the background compared to the particle.

The other important improvement, already introduced in RN3, the illumination of the substrates for different azimuth angles [3].

Both of these methods are also implemented in the Rapid Nano 4 design. The main difference between the previous Rapid Nano generations is de decrease in wavelength. As the intensity of particle scattering is strongly related to the wavelength as $\sim\lambda^{-4}$ and particle diameter $\sim d^6$(Rayleigh scattering approximation) where the scattering of the background due to roughness is related to the wavelength, it really helps to decrease the wavelength. For Rapid Nano 4, the design wavelength is 193 nm. For this wavelength, there is a good source available (ArF excimer laser), can still be used in atmospheric pressures and still have some different glass types available to design the optics with.

However, changing the wavelength to 193nm has quite an impact on the system. Contamination of optics due to hydrocarbons becomes an important issue as well as the poor transmission of the 193 nm through air. Also the availability hardware that can be used at 193nm is more limited than for larger wavelengths.

The Optical system of consists in total of 9 modules: (See Figure 4)

1) Laser
2) Beam shaping and delivery
3) Pulse Stretcher
4) Light guide
5) Illumination branch
6) Beam Dump
7) Detection Branch
8) Level Sensor
9) Scan Box

Next to these 9 optically oriented modules, there are also stages, metro frames and other supporting equipment needed to keep the system clean and safe.

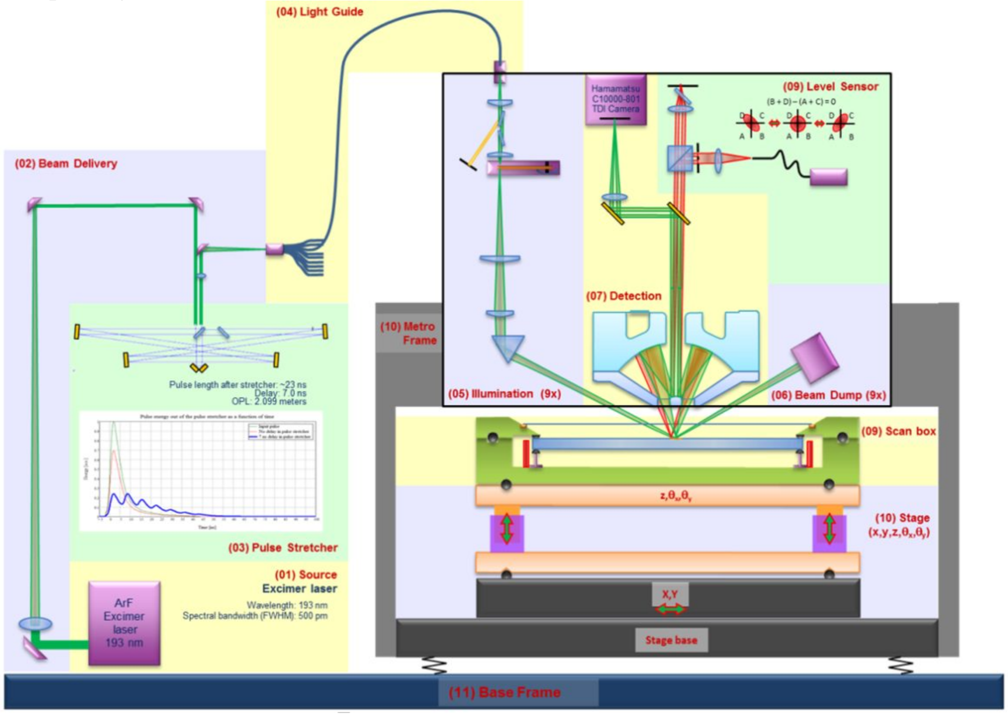

Figure 4: Schematic overview of the RN4 system

2.1 DETECTION BRANCH

The very heart of the system consists of the objective and tube lens. Objectives suitable for 193 nm are not available off the shelf . They are almost always custom designed objectives. The objective for RN4 is a custom, diffraction limited infinity corrected Schwarzshield design. The objective has a NA of 0.4 and a field diameter of 200 µm. The central obscuration is about 17%.

This objective is designed and build within TNO and does not need any alignment after fabricating the mirrors. In this way, we were able to build an objective against relatively low costs.

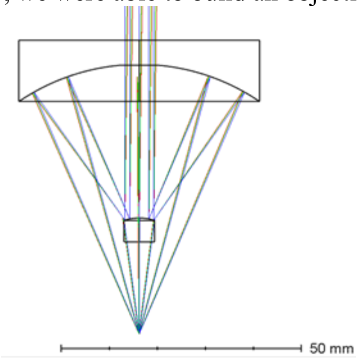

Figure 5: Ray trace of the 193 nm objective

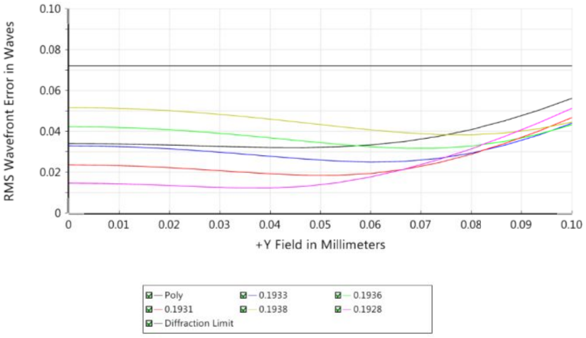

Figure 6: Wavefront error as a function of field

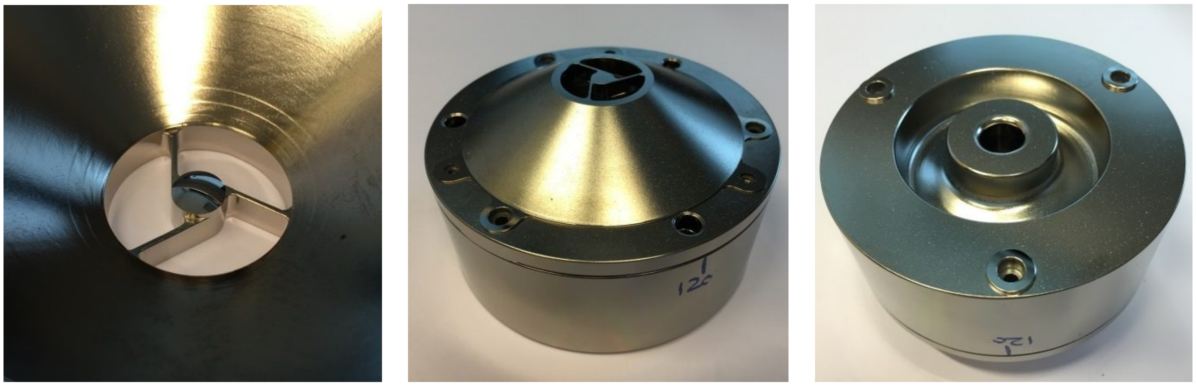

Figure 7: Realization of the objective

The detection branch tube lens images the substrate on the camera. A level sensor is needed to have a feedback signal of the actual substrate height and keeping the substrate in focus of the objective. As the level sensor uses a different wavelength (785 nm), 2 dichroic mirrors are used to couple the level sensor light into the objective. At the same time, the spot of the level sensor is located just outside the back projected image of the camera. The light of the level sensor can be blocked by using an aperture just in front of the camera.

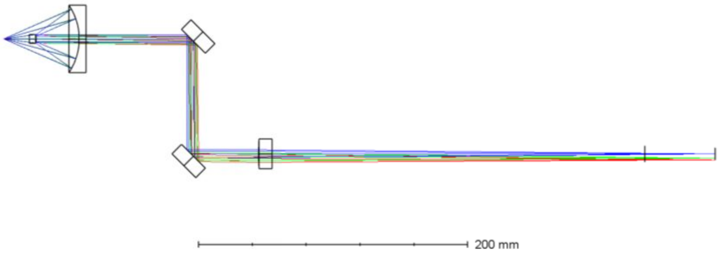

Figure 8: Design of the detection branch

The system is eventually designed to work with the TDI camera in scanning mode. As the focus is now on the detection of sub 20 nm particles the TDI camera is used in full frame mode. As a consequence the system is used in a stepping mode resulting in a lower throughput.

2.2 ILLUMINATION BRANCH

The function of the illumination branch is to illuminate the substrate. To limit light loss, the illumination spot is placed as tight as possible around the field of view of the detection branch (camera). As we illuminate the substrate under 9 different azimuth angles, the projected ellipses need to be overlapping. Furthermore, there is a significant angle of incidence (60 deg w.r.t. normal), the effect of the cosine projection also needs to be compensated. To tackle both of the problems, the illumination branch is split up in 2 parts (See Figure 9). The first part (left in picture), creates an ellipse by imaging the fiber into an intermediate field plane. By rotating the first lens pair, the ellipse can be oriented in the right direction. By orienting each of the 9 arms individually, all spots at the substrate can be overlapping. The second step is to compensate for the cosine effect due to the large angle of incidence. This is done by a second lens pair. The position (overlapping) of the spots at the substrate can finally be optimized by tip/tilt of the final prism.

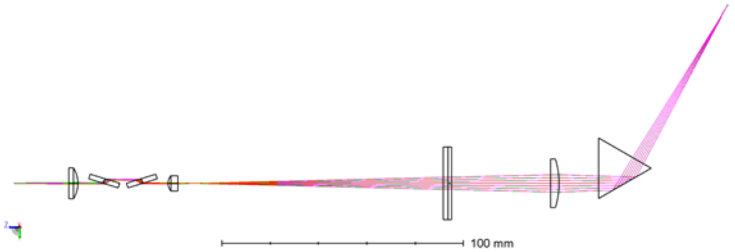

Figure 9: Design of the illumination branch (This design is copied 9 times, for each azimuth angle)

If all the 9 illumination branches would have light from the same fiber type and length, the overlapping spots will show a complex interference pattern, resulting in a inhomogeneity. The excimer laser chosen has quite a band width (about 500 pm) which means that the coherence length is already quite short. This short coherence length is used to avoid the interference pattern. Each of the 9 fiber has a difference in length larger than the coherence length of the laser.

2.3 CONTAMINATION

The contamination of the RN4 system has 2 sources:

1) Molecular contamination. The optical system of the RapidNano is exposed to 193nm light. This might cause carbon growth on the optical surfaces. Molecular contamination is controlled by purging the system with ultra clean gasses and selecting right materials and cleaning the materials in a proper way.
2) Particle contamination. This is not so much a thread for the optics, because the optical path is purged with ultra-pure nitrogen. However, it is an issue for the reticle blank under examination. To avoid substrate contamination, the substrate is placed in a protective scanbox. The scanbox is a closed box, which is on the cover closed with a polymeric window. RN4 is capable of measuring through the window. To avoid cross-contamination of the Reticle Handler, the scan compartment of the RN4 is also a very clean, particle free environment.

3 REALIZATION

The system is now in the assembly stage. The design allows us to build it in a modular way. This means that each module can be build and tested separately. After integration of all modules, only a minimum effort on alignments is needed.

The system is based on an existing base-frame with pre-mounted stage. The remainder of the system will be built on this base-frame. The stage is adapted with additional mounting points, at the new and existing mounting points, a stiff metro-frame is attached. The sensor head is mounted into the metro-frame. (See Figure 10, right)

The sensor head and stage system are placed in a mini environment. At the top of the mini environment ISO 1 air is supplied by a filter fan unit (FFU). This FFU is supported on the base-frame, there is a flexible sealing between the mini environment (metro frame) and the FFU to avoid vibrations to be coupled into the metro frame.

Furthermore, the minienvironment can be accessed by 2 automated doors, one is used at the side of the reticle handler and gives the Reticle Handler robot access to the Rapid Nano system. The other door is a manual feed door. This door is used to access the stage compartment in case of odd size substrates, or for maintenance.

Figure 10: Mechanical design of RN4

Outside the mini environment, the electronics racks, laser, beam delivery and pulse stretcher are located.
The laser is mounted on a carriage, for maintenance the laser can be slide outside the base frame for easy access. After the maintenance, the laser can be replaced on exactly the same position as the original without further alignment.
The base-frame and the xy stage are already build and operational. The custom designed z-tip-tilt-stage is integrated at the xy stage and is under test. The lower section of the metro-frame and mini environment is already mounted as well as the electronic racks, pneumatic cabinet and the power distribution unit (See Figure 11). May of the opto-mechanical components for the different modules are still in the procurement phase and are delivered soon. It is in the expectation that the system will be fully build in the next 2-3 months.

Figure 11: Assembly of the RN4 system, with stages and tip-tilt z-stage

4 EXPECTED PERFORMANCE

Using advanced modelling of the Rapid Nano system a performance estimation is made.
In Table 1 the performance is given. The modeling results showed a performance for RN3 of 43 nm where the measured performance of RN3 was 42 nm. The model [3] and the measurements are in good agreement. The same model type also used to predict the performance of RN4. Here the model showed a sub 20 nm PSL on Si particle detection.
The first measurement results for RN4 are expected somewhere in June 2016

Table 1: Predicted and measured performance of the different Rapid Nano generations

	PSL on Si [nm]	Al on Si [nm]
RN1: 532 nm, 1-azimuth		
Predicted	59	35
Measured	59	35
RN3: 532 nm, 9-azimuth		
Predicted	43	25
Measured	42	
RN4: 193 nm, 9-azimuth		
Predicted	18	18
Measured	June 2016	

5 NEXT STEPS

The goal of the Rapid Nano 4 system as being build today is to show that it can measure sub 20 nm particles. To reach this milestone, all activities related to automation or throughput are considered less important. Nevertheless the system is designed to inspect a full reticle substrate in ~90 min. The next step will be to improve the throughput of the system.

One of the first steps will be using the camera in TDI mode: The camera used is a Hamamatsu C10000-801 TDI camera. This camera is now used in a full frame mode which requires start/stop motion of the stage Using this camera in TDI mode the stage does not need to follow a stepping pattern. Instead, it is possible to perform a scanning motion, where the velocity of the stage is kept constant, depending on the "shutter speed" needed. The camera and the laser will be triggered using the stage position. For each trigger pulse, the charge of one row of pixels is transferred to the next row. By triggering this transfer, the speed of the stage and the camera are synchronized. Using a scanning motion instead of a stepping motion, will improve the inspection time with a factor ~35.

Furthermore the throughput is limited by the laser repetition rate. The laser will be used for the current generation has a repetition rate of 500 Hz. The RN4 system is designed such that the laser can be replaced by another laser with higher repetition rate (2 kHz). This laser replacement can be performed with minimum impact to the system.

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