In-die Mask Registration for Multi-Patterning

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Abstract

193nm immersion lithography is the mainstream production technology for the 20nm and 14nm logic nodes. Considering multi-patterning as the technology to solve the very low k1 situation in the resolution equation puts extreme pressure on the intra-field overlay, to which mask registration error is a major error contributor. The International Technology Roadmap for Semiconductors (ITRS) requests a registration error below 4 nm for each mask of a multi-patterning set forming one layer on the wafer. For mask metrology at the 20nm and 14nm logic nodes, maintaining a precision-to-tolerance (P/T) ratio below 0.25 will be very challenging. Mask registration error impacts intra-field wafer overlay directly and has a major impact on wafer yield. We will discuss a solution to support full in-die registration metrology on reticles.

1. Introduction

Logic device manufacturing at the 20nm node is either already introduced into high volume manufacturing or will be very soon. Leading edge semiconductor manufacturers have already started 14nm development. Because EUV lithography is not yet ready, immersion lithography will continue to be the production workhorse for these nodes.

As the ITRS Roadmap [1] indicates, the wafer overlay requirement will soon be tighter than 4nm, driving mask registration below 4nm as well. This very tight specification requires significantly better control of the e-beam mask writer. In the past, the principle registration metric, measurement repeatability, simply followed the ITRS from technology node to technology node, but previously presented papers [2] show some hints that mask lithography systems may have inherent placement errors which are not captured by standard OQC (outgoing quality check). Other evaluations have demonstrated, at least on test masks, that registration errors transfer to the wafer [3].

Fig. 1: Excerpt from the ITRS roadmap 2012 update, lithography section (orange means double patterning, light blue means triple patterning)
Several test masks and product masks were comprehensively evaluated and the mask registration errors classified into three major groups: global errors, local errors and pattern dependency. This is the first time that this evaluation becomes possible since in the past metrology tools were not capable of measuring accurately on any feature. It turned out that all masks demonstrated residual registration imperfections. Especially pattern dependent registration errors may become very critical considering overlay between poly layer and contact layer masks or between two adjacent DPL (double patterning lithography) masks.

The key question with regards to registration metrology today is: “What critical components are we missing with standard metrology approaches?”

2. Experimental

Test reticles manufactured from various suppliers using the latest generation e-beam system have been evaluated. Today typically between 50 and 400 measurement sites are evaluated for advanced masks. We increased the number of measurement to 700 sites distributed over the mask. In addition, we evaluated 1600 neighbouring sites in order to check local distortions and random e-beam error. We show also the results of pattern dependent placement error measurement and report a successful measurement of in-die structures. We demonstrate the effect of the sampling size on the 3 sigma value of the mask.

In addition, a mask from Toppan Printing with various product-like in-die features (fig.2) was evaluated for pattern dependencies. A model-based correction including the metrology tool’s remaining optical imperfections was applied to ensure accurate measurement results on various in-die features. The measurement results were evaluated using IPRO evaluation software, DEVA.

Fig. 2: Examples of in-die pattern on Toppan’s test mask

3. Results and discussion

3.1. Global signatures

Figure 3 shows a contour plot of a reticle measured on a 104x132 mm² array. We measured and displayed registration error of approx. 700 features. Based on these 700 sites, the registration performance of the mask is 4.9nm (3sigma), (fig.3).

Systematic error was further analysed by measuring lines with dense features across the mask in x and y direction and performing a Fourier analysis. With today’s sampling plan only the low frequency contributors can be caught (fig.4), however the investigation shows that there are higher order systematic contributors which might be worth to go after and fix them in order to improve overall mask registration.
3.2. Local noise

The performance of main-deflector and sub-deflector corrections of the e-beam system determines the shot placement noise and stitching error. We investigated the performance of a large array (40 x 40) of dense contact holes in order to determine local noise contribution of the e-beam system. This kind of evaluation can provide two different types of information:

1. the amount of shot placement noise, and
2. the performance of residual stitching error between writing stripes and other systematic errors

Fig.3: Registration plot of a high end mask clearly displays a residual global signature

Fig.4: Registration error frequency analysis shows that several higher order systematics are not captured by today’s sampling. Global signature contributes 3.8nm to total mask error in our example.
Conventionally, the shot placement noise and the local distortions are measured on test masks only. These test masks are prepared and evaluated on a weekly or even bi-weekly schedule. During the periods between the regular checks, the e-beam performance is assumed to be stable. Considering that the safety margin is further decreasing, it becomes quite important to monitor local registration performance on each product plate to lower the risk of image placement yield loss. As of today, this type of measurement can take several hours which is not compatible with mask production flow. Therefore significant improvement in throughput is required to enable this measurement for products.

This evaluation on any product plate provides important base line information on the shot placement noise impact to pattern placement all over the mask, impacting also the validity of registration measurement result of a fairly small sample. If, for example, the noise on a product mask becomes too high, then the measurement of a small sample has a higher risk of being not valid and far off the real registration performance of the mask (see below in section 3.4). The systematic local error needs to be understood and minimized in order to achieve best mask registration quality.

Figure 5 shows a plot of the measured distortions. In order to verify that accuracy fulfills a P/T of 0.2, the measurements have been performed on exactly the same array after reticle rotation by 90 degree. Both the 3sigma values as well as signatures rotate with the reticle. In conclusion, the measurement results are not induced by a metrology artefact.

The random distribution was calculated from an area with low systematic contribution and then the local signature was calculated supressing the noise. The random noise of the pattern placement derived by our method was determined at 1.6nm, 3 sigma and the local signature of the mask lithography tool was 1.9nm, range/2 in the measured spot.

![Signature and Random Noise Plot](image_url)

**Fig.5:** Plot of local noise based on 1600 dense contacts. The amount of the local signature and the random shot noise are separated.

### 3.3. Pattern dependent shifts

We performed an evaluation of pattern dependent placement error on several state-of-the-art reticles.

On the first reticle, four different pattern types, positioned at 121 locations each over the reticle, were investigated. The smallest pattern was an isolated cross of nominal 65nm line width. In addition, dense contact hole arrays sized between the optical resolution limit of the metrology tool and a few microns were measured. The individual displacement of a single pattern is driven by global, local and pattern dependent effects. In order to extract the pattern dependent shift, an average of the measured displacement is applied per pattern type among the 121 sites measurement. The mean shifts of the four different patterns are displayed in fig.6. We have detected about 2nm of systematic shift between the different pattern types. Keeping in mind that systematic errors do add linearly, this result easily demonstrates a risk for later mask-to-mask overlay performance of two different layers. For example, in a worst case condition patterns of a poly mask and contact mask can show a systematic shift of 4nm (mask level).
This corresponds to about 25% of the wafer overlay budget. Today’s standard registration sampling plans would not detect this pattern dependent shift and thus put risk to the wafer fab.

On the mask, manufactured by Toppan, we performed a similar test to evaluate pattern dependent registration error on device-like features. The results of pattern dependencies are shown in fig. 7. We measured ~10 different patterns, however some designs were proprietary and therefore cannot be displayed in fig. 7.

The in-die pattern could not be accurately measured using the edge detection mode. However, for accurate registration measurement of in-die features KLA-Tencor developed a novel method, called model-based registration. This new method was applied to determine the registration error of the in-die features. For reference the same grid was measured on standard registration crosses in either mode, edge detection and model-based. All features actually show very similar registration signature over the mask.

This test reveals that the new model-based registration mode demonstrates accurate measurement performance on in-die features.

**Fig 6:** Pattern dependent shifts observed on contacts of different size and density as well as isolated crosses down to 65nm linewidth

**Fig 7:** Pattern dependent shifts observed on various in-die pattern on a test mask from Toppan evaluated and compared to a registration cross. The registration cross was measured in edge detection mode for reference.
3.4. Sampling impacts mask quality result

Mask manufacturers today use between 50 and 400 registration measurements on a product reticle for final outgoing quality report. We evaluated the impact of sampling on the traditional quality metric of 3 sigma error of the reticle. The evaluation was based on 700 data points. The result displayed in figure 8 demonstrates that the accuracy of the registration result depends strongly on the sample size. Taking sub-samples of 170 sites may lead to a mask registration performance of 3.9nm or 6.1nm depending on which 170 sites were selected from the 700. This means a significant risk of mis-qualification, leading to a yield risk for both the mask shop and the wafer fab.

Fig.8: Contour plot of a registration measurement on the LMS IPRO5 on a reticle patterned by a state-of-the-art e-beam system. The mask performance evaluated on 700 measurement points is 4.9nm. If sub samples of 170 sites are evaluated then the performance might vary depending on the site selection (left and right).

4. Conclusions and Outlook

Mask metrology for the 2xnm node requires enhanced metrology schemes to secure the tight reticle registration budget derived from wafer intra-field overlay requirements. Multi-patterning lithography may even require tighter control of the mask contribution to intra-field wafer overlay.

It was demonstrated that state-of-the-art e-beam mask writer exhibits systematic error contributions on different spatial scales, as well as pattern dependent registration performance (figure 9). Today’s sampling plans do not cover a significant portion of mask registration error. The situation of mask registration today is similar to critical dimension (CD) metrology done number of years ago. CD metrology developed from single pattern type based CD Mean-To-Target and 3 sigma for CD-Uniformity (CDU) reporting, towards error separation such as CD linearity among several pattern types, CDU high-sampling mapping and line width roughness.

Similar to the trend in CD metrology, registration metrology needs to be expanded in order to keep up with wafer intra-field overlay challenges. Monitoring different error sources on products enables the mask maker to improve registration capability by improved process learning and derived process control (figure 10). In addition, the separation of error components enables the wafer fab to better control the intra-field wafer overlay budget.

The required information on reticle registration uncertainty can be achieved by
1. Significantly higher sampling, and
2. Identifying pattern dependent placement errors.
A natural consequence of increased sampling is the need to measure in-die patterns. Customers would like to be able to sample the whole mask, but are unwilling to dedicate real-estate to special targets. In cooperation with Toppan model-based registration capability on in-die features was successfully evaluated.

Fig.9: Mask registration error can be divided into systematic and noise components.

Fig.10: The new approach of registration metrology enables monitoring and control of individual error components which can be used to improve and stabilize registration process capability. In addition, the separation of error components allows creating more detailed intra-field wafer overlay error budgets in the waferFab.

References: