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Spatial frequency breakdown of CD variation

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ABSTRACT

Controlling the Local CD Uniformity is important for the implementation of EUV lithography in high-volume production. Spatial frequency breakdown of stochastic effects and identification of stochastic noise contributors may help us to understand the current performance and suggest possibilities and pathways for future improvement. In this work, we look for potentially hidden sources of systematic local variability by collecting and analyzing CD metrology data over lengths greater than a single SEM field of view (FOV). Fourier analysis of the CD data is used to identify any systematic variability. This work will enable a more accurate breakdown of local variability. Additionally, using the length scale of any observed systematic signal we can attempt to trace back the origin and reduce or eliminate its source.

Keywords: CD variability, Fourier analysis, LCDU breakdown, Scanning electron metrology, Extreme ultraviolet lithography

1. INTRODUCTION

CD variability occurs across wafers, across dies, and locally within a die. Local CD variability is one of the dominant components of Edge Placement Error EPE.[1] Metrology to characterize the CD variability at various scales has typically relied on measuring samples in widely separated locations across the dimension of interest.[2] While this enables statistical analysis to extrapolate variability on to massive feature scales it does not provide clarity on potential non-random variability at those length scales. Hidden non-random variability on the sub-millimeter length scale is potentially masked within random stochastics due to the widely separated sampling.

Figure 1 shows that when breaking down the observed local variability (Local CDU and/or Line Width Roughness) the largest component is classified as random stochastic noise. Systematic variability is commonly associated with printed mask variability that repeats on every printed die. Metrology noise is of course a limitation that all measurement methods suffer. The accuracy of such a breakdown is determined by the metrology and sampling used. Local variability is commonly defined as the observed variability within a single field-of-view (FOV) of a SEM or similar metrology tool, typically $0.5 - 2\mu m^2$ in size. Making measurements of multiple field-of-views across a die can help improve the statistics and reduce the error in the systematic and metrology components of the breakdown.

Variability on a length-scale larger than a single FOV but smaller than what typically separates multiple FOV measurements within a die would appear as random. As a result, this variability would be grouped in the stochastic component of local variability. If such a signal existed, it would only be visible if measurement data was available over a longer length scale.

In this work, we look for potentially hidden sources of systematic local variability by collecting and analyzing CD metrology data over lengths greater than a single SEM FOV. When treating the CD data we will use Fourier analysis to identify any potential systematic variability. This work will enable a more accurate breakdown of local variability. Additionally, using the length scale of any observed systematic signal we can attempt to trace back the origin and reduce or eliminate its source.

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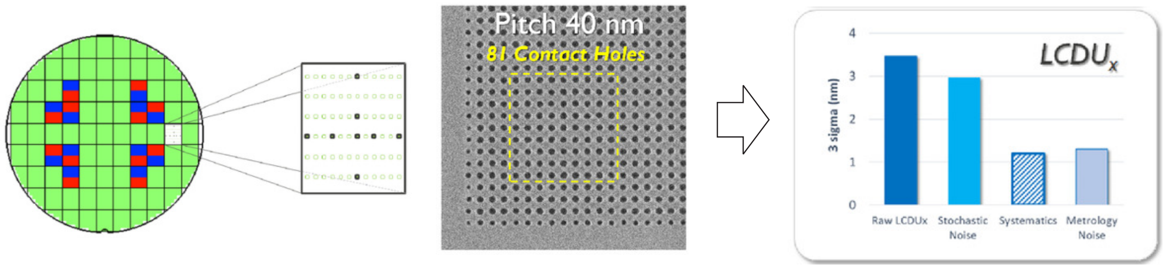

Figure 1. Example of wafer layout and LCDU breakdown for the CDx of the P40 CHs.[2]

2. EXPERIMENTAL SETUP

For our experiment we chose a dark field EUV mask that provides a large uninterrupted area of contact holes (CHs). Such pattern choice allows us to consider every feature separately when necessary. On the mask we have 2.9x3.2mm^2 areas covered with hexagonal CHs. Different mask areas have different pitch and CD variation. Those areas also have several repeats on the mask. In this study we select $P_x = 46nm$ and $P_y = 80nm$ hexagonal CHs with mask CD of 24nm. We first expose a targeting focus exposure matrix (FEM) wafer using imec NXE3400B system. We use a pupil that is optimized for our pattern of choice. The resist stack consists of 20nm underlayer and 40nm of positive tone chemically amplified resist. This FEM wafer shows that we need 71mJ/cm^2 dose to print CHs to 23nm target CD.

Based on the analysis of the FEM wafer, we exposed our final uniform (CDU) wafer at target dose and focus conditions. The experimental setup is shown in Fig. 2. While exposing the final CDU wafer we collect high speed real time energy data from the EUV source (corresponds to $1-6\mu m$ sampling frequency on wafer), in order to link CD variations to dose fluctuations. For data analysis we study 81 full field dies, that are present on the wafer.

3. METROLOGY

The main method of our study is to secure uninterrupted measurement and data acquisition. Therefore, we collect 228 images with 819x819nm^2 field of view, which cover a length of 164μm. The zigzag way of image collection, as shown on Fig. 3, allows us to secure spacial continuity in Y direction. We also measure the 2^{nd}

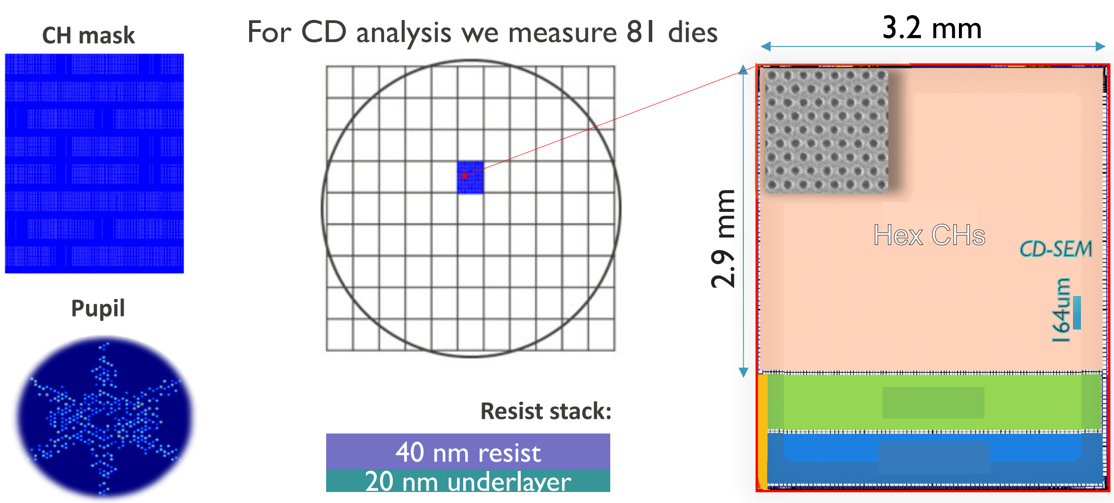

Figure 2. Illumination pupil, P46x80 mask, resist stack and wafer layout used in the experiment.

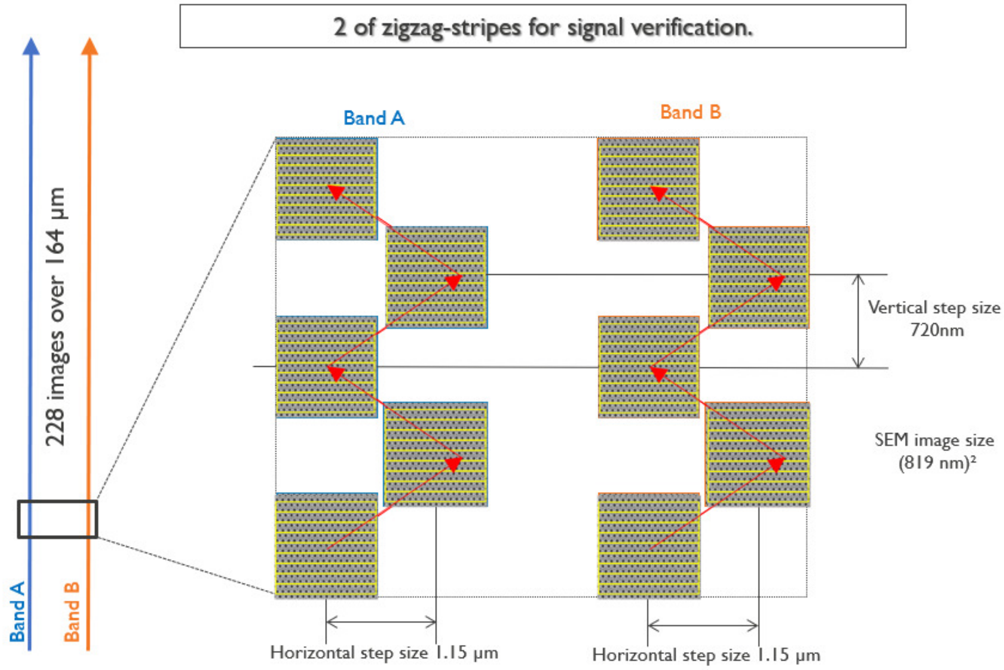

Figure 3. Metrology scheme, that enables constant sampling periodicity over the images..

zigzag stripe for signal verification. There stripes we call Band A and Band B. In each individual image we put 9 boxes. Each box frames 2 rows of contact holes (34 individual CHs) as shown on Fig. 3 and Fig. 4. The average CD of such set of 34 CHs represent one CD data point in our analysis. Therefore, each image provides 9 CD points, spaced $80nm$ apart, hence covering $720nm$. By applying a spacing of $720nm$ in Y-direction between our images, we keep the data points continuously spaced at $80nm$ also from one image to the next.This way, we collect $228x9 = 2052$ data points in total, per band of $164m$ length.

To know the systematic metrology component within the images, we average all the images (per band). For all 81 dies on the wafer we have total 18468 images per band. The averaging shows that there is a small systematic variation of $0.15nm$ over the 9 CD data points within the images (see Fig. 4). This metrology contribution per image is removed for further analysis. For this data collection, we used a CG6300 Hitachi High Tech CD-SEM under high precision stage mode, allowing to keep perpendicular electron beam incidence for each image.

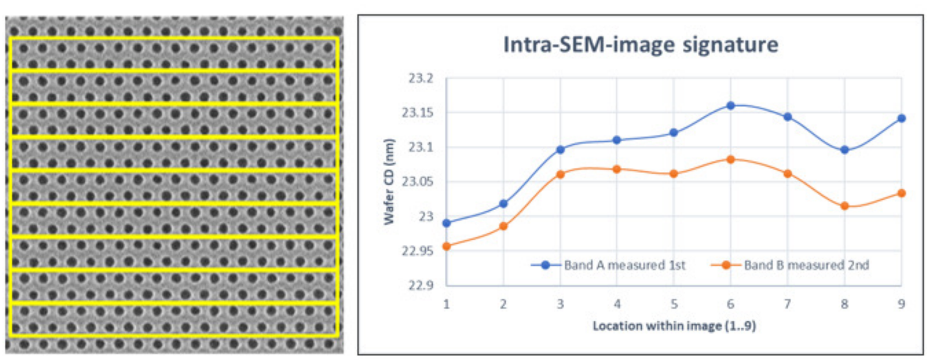

Figure 4. Metrology related signature per band.

4. DATA ANALYSIS

As a first step of our analysis we take into consideration only one die. An example of a Die(0;1) of band A is shown in Fig. 5. The 2052 raw CD data points plotted through distance along measurement direction contains **all** scanner, mask, process and metrology contributors Fig. 5a. From this limited data, it is difficult to judge if there are spatial frequencies present in the signal. Therefore, we perform a fast Fourier transform (FFT) and plot the power spectral density (PSD) as shown on Fig. 5b. The Fourier transform reveals a sharp peak that corresponds to the 720nm period.

As a second step, we look into the data of the same die, but we remove the intra-image signature by subtracting the average image from each individual one. We plot the obtained residual CD data in Fig. 5c. This data contains **random** metrology, scanner, mask and process contributions. Again, in order to obtain the spatial frequencies of the CD variation we perform a Fourier transform (see Fig. 5d). Now. the sharp peak at 720nm period is no longer visible, confirming its origin in the metrology. This demonstrates that already in a single die we can capture 0.15nm of systematic CD variation.

In order to emphasize systematically appearing frequencies and find other contributors (such as mask or scanner) more averaging is required.

Frequencies that repeat from die-to-die can be revealed by averaging many dies over the wafer.

In the next step of data analysis we: a) perform FFT for each individual die per band; b)average all 81 PSD functions per band.

The average of all 81 PSD functions for both bands (A and B) is shown on Fig. 6. The analysis of the raw data reveals 9 harmonics, that correspond to systematic metrology contribution. Those harmonics are no longer present on the PSD plots for data; where the intra-image contribution was subtracted.

In traditional LCDU analysis, spatial frequencies below 1μm are usually taken into account (as image size usually used for LCDU decomposition is about 1x1μm^2 size). The spatial frequency of our interest for this data set lies withing $1 - 10\mu m$ range. Figure 7 shows a zoom into this range of interest, where we also recalculate PSD amplitudes into half range of CD variation.

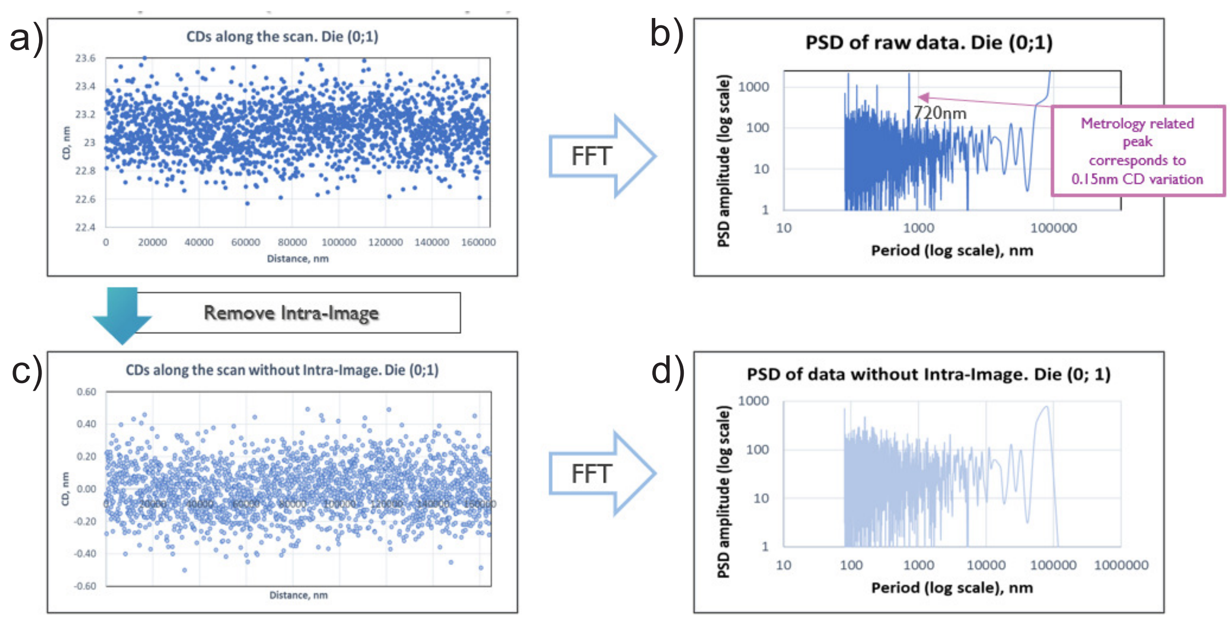

Figure 5. Band A. Die (0;1): a) CD variation along the band. Raw data; b) Fourier analysis of raw CD data; c) CD variation along the band with intra-image signature removed; d) Fourier analysis of CD data without intra-image.

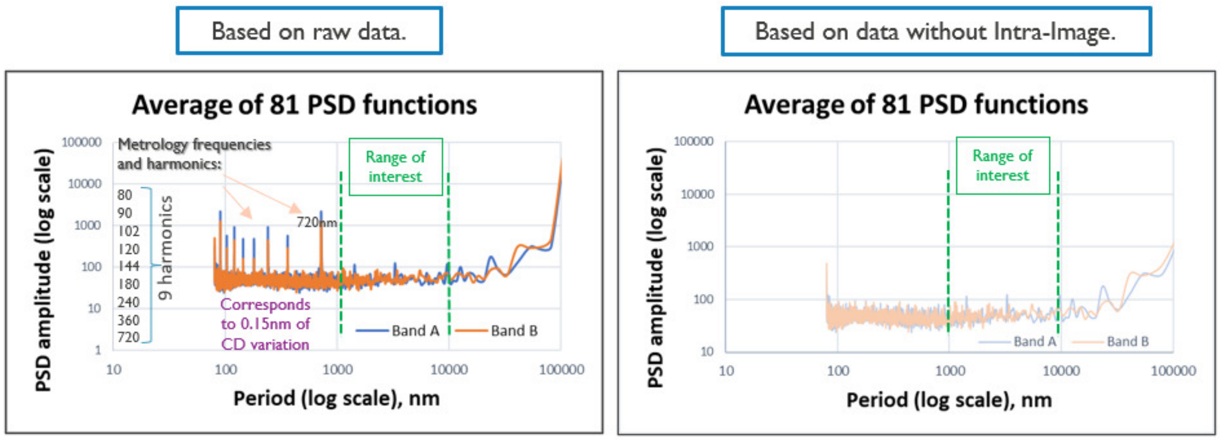

Figure 6. Average of 81 PSD functions for both band A and B. Based on the raw data and on the data without intra-image signature.

The largest contributors to the observed CD variation within the range of interest is found at 1.44μm and 3.24μm. These frequencies are associated with metrology field of view step size: 1.44μm is 2x the step size and 3.24μm is 4.5x the step size. Based on this, the expected systematic CD variations according to FFT analysis are below 0.01nm (half range).

5. CONCLUSIONS

In this work we show a developed method for frequency analysis of CH-CD variation (based on SEM data). This method was proven sensitive enough to reveal CD variations below 0.1nm. The CD-based PSD analysis confirms the observed systematic metrology contribution of about 0.15nm. After subtracting the latter, no recurrent frequencies are found in the signal.

Potentially this method can be extended to longer distances (millimeter scale). That requires large FOV metrology such as HMI eP5 (up to 8μm^2) and fast data acquisition. Additionally by using this method other features (such as lines and spaces, random vias, etc) or metrics (such as 3σ, LER, etc..) can be put under study.

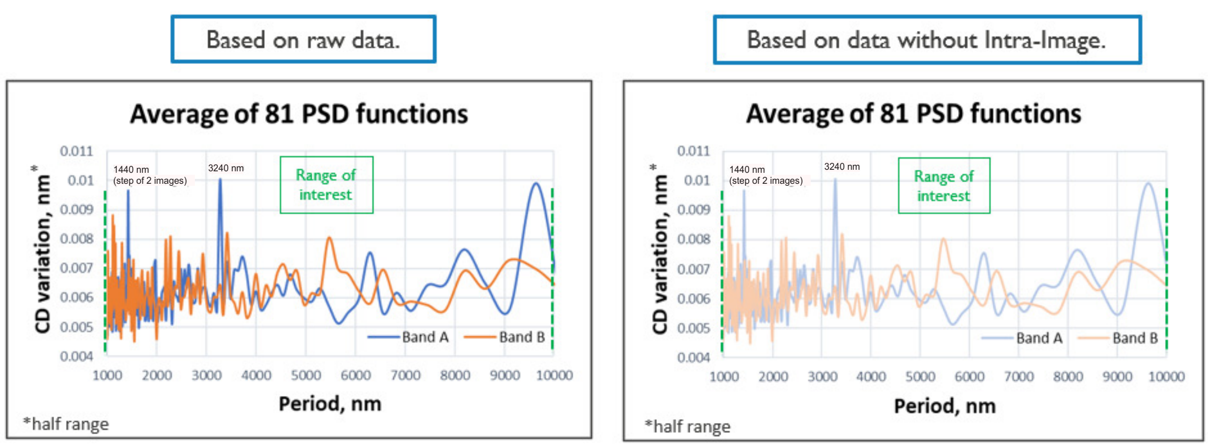

Figure 7. Zoom into the range of interest. Average of 81 PSD functions for both band A and B. Based on the raw data and on the data without Intra-Image signature.

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