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Novel Methodology to Include all Measured Extension Values per Defect to Improve Defect Size Distributions

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Abstract **— Defect size distributions play an important role in process characterization and yield prediction. To reduce time and costs of defect size extraction procedures the paper presents a novel methodology to determine defect size distributions. For that, we use all measured defect extension values per inspected defect compared to known methodologies just using one size value per defect. Our approach enables a reduction of the sample of defects to be inspected in semiconductor manufacturing fabs. Nevertheless, the novel methodology will provide even better accuracy of defect size distributions.**

1 INTRODUCTION

Defects (e. g. particles) can become the cause of electrically measurable faults (killer defects) dependent on the chip layout and the defect size. These faults are responsible for manufacturing related malfunctions of chips. So, defect size distributions are important for yield prediction and to control quality of process steps and product chips. For that, optical wafer inspection systems like KLA or Tencor will mostly provide two size values per inspected defect. One size value will be measured parallel to the x-axis of the wafer and the second value will be measured parallel to the y-axis of the wafer. Today, several models will be used to reduce these two measurement values to a single size value per defect. Doing this for a large sample size of inspected defects will be the basis to determine a defect size distribution.

If a defect inspection system provides multiple size values per defect, we get some information about the variety of defect outlines that occur in reality. But, if this information will be reduced to a single size value per defect, we delete all the outline information that we just have measured. So, a long measurement time that costs a lot of money will be wasted, because part of the measured information will be deleted in later data analysis procedures. So, our goal is to keep all the measured size values per defect that are offered by any kind of defect inspection equipment and taking into account **all** these measurement values when determining a defect size distribution. This will either increase the accuracy of defect size distributions or decrease the sample size needed to determine a defect size distribution.

So, the paper will discuss the following issues. First, Section 2 will present methods to determine defect size distributions based on a single size value per inspected defect. Then, Section 3 describes our novel methodology to calculate defect size distributions that include more than just a single extension value per inspected defect. In Section 4 we present some experimental results comparing both methodologies to get defect size distributions. Finally we conclude our approach.

2 METHODS TO EXTRACT DEFECT SIZE VALUES

Defect size distributions are required to predict chip yield. For that, today each inspected defect will be given exactly one size value. This means, that the outline of such a defect will be modeled as a circle. But, most defects are not circular that occur in semiconductor devices as can be seen in Figure 1 (also ref. [HeSt94], [HeWe96a], [LeML97]).

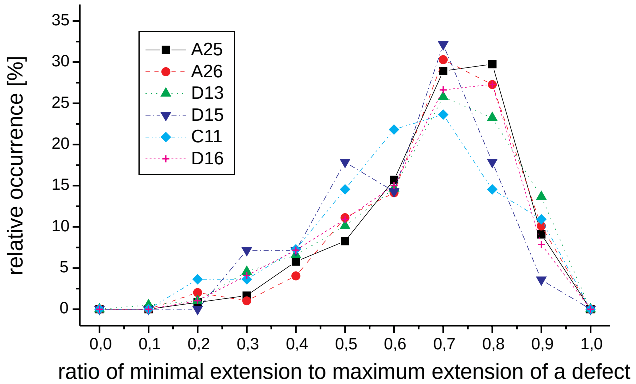

Fig. 1: Ratio of the minimal extension value to the maximum extension value of defects inspected inside multiple test chip designs. If defects are all circular that occur in reality, the ratio should be 1.0 for each defect.

So, optical measurement systems initially provide several extension values that later will be summarized to a single defect size value using different calculation models (ref. Figure 2).

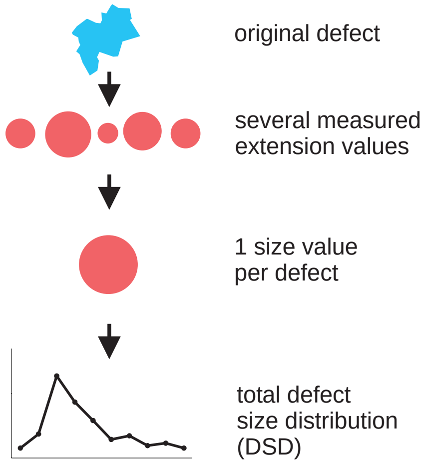

Fig. 2: Known methodologies to determine a defect size distribution (DSD) based on just one size value per inspected defect.

To compare our novel approach to existing models we first have to define some measurement basics. A single defect extension value *d* will be measured between two points of its outline as can be seen in Figure 3.

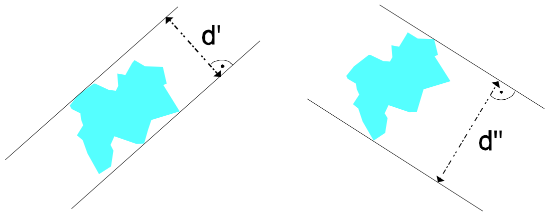

Fig. 3: Measurement of the extension of a defect in-between parallel lines.

So, there is a straight line (*d'*, *d"* in Figure 3) between these two points, where the angle φ is defined between the straight line and the vertical die border lines as can be seen in Figure 4.

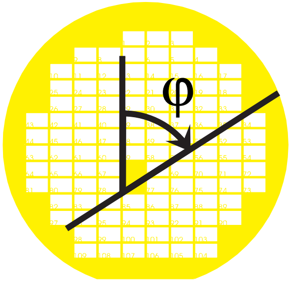

Fig. 4: Definition of the measurement angle φ on a wafer.

Today, most calculation models give the defect size as the radius *r* of the resulting circular disc model that corresponds to the original defect providing several extension values *d*. To prevent any calculation errors we will always use the "diameter like defect extension" *d* and not the "radius like defect size" *r* here (*d=2r*). Furthermore the defect extension *x* will be defined as the defect extension *d* measured at φ=90° and the defect extension *y* will be defined as the defect extension *d* measured at φ=0°. Followed are several calculation models having in common that modeling defect outlines should provide the correct diameter of a circular defect model in a way that its probability to cause a fault (= fault probability) fits to the probability that the real defect causes a fault.

2.1 *Circle Based on One Specific Measurement Value*

Generally, the diameter of the circle to describe a defect will be calculated based on the maximal defect extension [StRo95]. Also the minimal defect extension will be used to get the diameter of the circle [LeML97]. But, to really get the maximum or minimum defect extension it is required to collect many extension values per defect. Poor accuracy of these two models does not justify such extensive measurements [HeWe96a]. In contrast to that, it is more suitable to take just one measurement value per defect each measured at a constant measurement angle φ [HeWe97b]. For instance, most optical measurement systems provide defect extension values at φ=0° (extension value *y* (y-dimension) at [LeML97]) and φ=90° (extension value *x* (x-dimension) at [LeML97]). The following Figure 5 shows such angle specific defect size distributions.

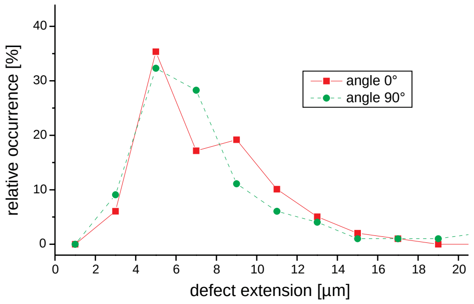

Fig. 5: Total defect size distributions (DSD) based on defect size values each measured at the same measurement angle φ.

2.2 *Circle Based on Mean Defect Extension*

Here, the defect will be modeled in a circle, where both should have the same area. So the mean value of individually measured defect extension d_i will be calculated as

$$\bar{d} := \frac{1}{n}\cdot\sum_{i=1}^{n} d_i \tag{1}$$

where *n* is the number of measured values. If only the two extension values *x* and *y* are measured, we get:

$$\bar{d} := \tfrac{1}{2}\cdot(x+y) \tag{2}$$

2.3 *Circle Based on Elliptical Defect Extension*

[HeSt94] introduced the elliptical model to describe real defect outlines. There are two ways to "reduce" the mathematically complex ellipse to the circle required in yield prediction models:

1. The circular diameter $\bar{d}$ should be the mean extension of the ellipse dependent on the measurement angle φ. So, [HeSt94] proposed the approximation

$$\bar{d} \approx \tfrac{1}{2}\cdot\sqrt{min\cdot max} + \frac{min\cdot max}{min+max} \tag{3}$$

based on the maximum extension *max* and the minimum extension *min* of the real defect. If only the two extension values *x* and *y* are measured, we get:

$$\bar{d} \approx \tfrac{1}{2}\cdot\sqrt{x\cdot y} + \frac{x\cdot y}{x+y} \tag{4}$$

2. The area of the modeled ellipse (¼ π *x y*) should be the same than the area of the resulting circle (¼ π $\bar{d}^2$). So, [LeML97] uses the equation

$$\bar{d} = \sqrt{x \cdot y} \qquad \textbf{(5)}$$

based on the two measured extension values *x* and *y*.

The probability that a defect causes a fault is based on the defect extension and not on its area. So, we prefer to use equation (4) in this paper.

3 NOVEL METHOD TO DETERMINE A DEFECT SIZE DISTRIBUTION

As we've seen before, just one size value will be calculated for each inspected defect. Based on these values, a total defect size distribution (DSD) will be determined. To accurately include the irregular outlines of defects that occur in reality, we introduced a DSD based on individual so called Micro Size Distributions (MSD) for each inspected defect [HeWe96a] (ref. Appendix). So far, this methodology is based on extensive measurements per defect (e. g. 36 extension values per defect). To be competitive in time and measurement procedures described in Section 2 we will use the Micro Size Distribution methodology in a way that just two measurement values will be required per inspected defect. Figure 6 briefly describes our approach. The two measured extension values *x* and *y* will be collected in a Micro Size Distribution (MSD 2). Then, these Micro Size Distributions will be summarized to a total defect size distribution (DSD).

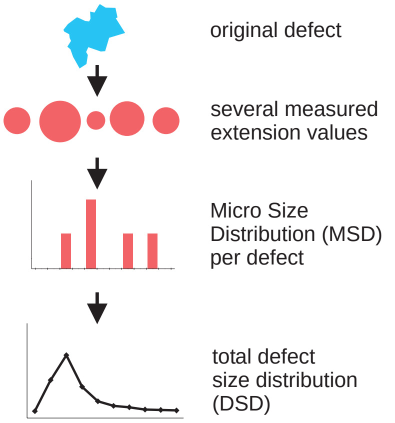

Fig. 6: Novel methodology to determine a defect size distribution (DSD) based on a Micro Size Distribution (MSD) per inspected defect.

To keep the number of originally inspected defects, it is obvious that each measured size value per defect has to be weighted by the total number of measurement values per defect. If in this case the **2** size values *x* and *y* are measured per inspected defect, we will determine a DSD based on all these values. If the final DSD is displayed in a chart as "number of defects" per "size interval", each occurrence value has to be divided by **2**. To get a relative size distribution, where the sum of all occurrence values will be normalized to 100%, we even don't need the extra division by 2. The following Figure 7 compares the MSD 2 to the measurement angle specific defect size distributions of Section 2.1 (ref. Figure 5). It can be seen that the MSD 2 based DSD is equal to the mean values of the DSD at φ=0° and the DSD at φ=90°.

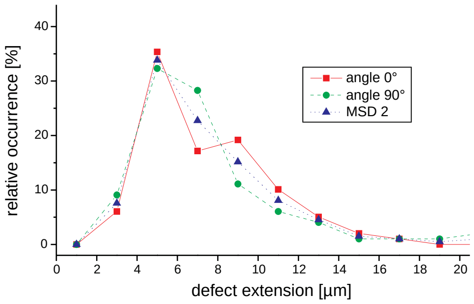

Fig. 7: Total defect size distributions (DSD) based on differently modeled size values per inspected defect.

4 EXPERIMENTAL RESULTS

Since 1991, numerous test chips containing checkerboard test structures that include various subchip designs in interconnection layers were manufactured at the Institute of Microelectronics Stuttgart (IMS) in Germany, ALCATEL SEL in Germany, National Semiconductor (NSC) in Santa Clara CA, THESYS in Germany, and ELMOS in Germany [HeSt94], [HeWe95b], [HWLS96], [HeWB97a]. Due to the easy defect localization facilities inside checkerboard test structures, we provide an image data base describing the size and outline of hundreds of inspected defects.

The following Figures and Tables give some experimental results where we compare the MSD 2 based DSD that takes into account the two size values *x* and *y* per defect to those generally used DSDs that are based on reduced single defect size values. Such models are the measurement angle specific DSD at 0°, the measurement angle specific DSD at 90°, the elliptical DSD, and the mean DSD. As reference distribution we also included a MSD 36 based DSD that takes into account 36 measured extension values per inspected defect. The following Figure 8 gives these distributions based on 100 defects inspected inside 72 test chips "A26-1".

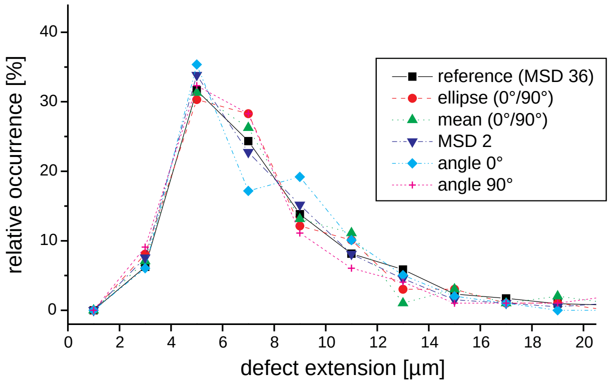

Fig. 8: Model specific defect size distributions (DSDs) based on 100 defects inspected inside 72 test chips "A26-1".

Table 1 compares the error of the different models to describe the outline of defects. The error *err* is defined as the difference between the relative occurrence of defects within a size interval (e.g. ≥2µm - <4µm) for a defect model and the relative occurrence of defects within the same size interval for the reference MSD 36. In Table 1 we summarize the maximal positive error (over estimation), the maximal negative error (under estimation), and the mean error of the different models defined as (ref. [Bart84]):

$$\overline{\text{err}} = \pm \frac{1}{n} \cdot \sqrt{\sum_{1}^{n} \text{err}^2} \qquad \textbf{(6)}$$

It can be seen that the mean error of ±0.39 of the MSD 2 based DSD is about 40% less than the mean errors of the elliptical DSD and the mean DSD.

model	mean	ellipse	MSD 2	angle 0°	angle 90°
max. neg. error	-5.11	-3.04	-1.67	-7.71	-2.71
max. pos. error	3.02	3.56	2.33	5.46	4.50
mean error	±0.65	±0.62	±0.39	±1.04	±0.70

Tab. 1: Maximal and mean error of model specific defect size distributions (DSDs) based on the defects inspected inside all test chips "A26-1". The reference DSD is based on a micro size distribution of 36 measurement values (MSD 36) per defect inspected inside the test chips.

The following Figure 9 gives the results of 212 inspected defects inside 7630 test chips "D13". Again, the MSD 2 based DSD provides the lowest mean error of ±0.31 (ref. Table 2).

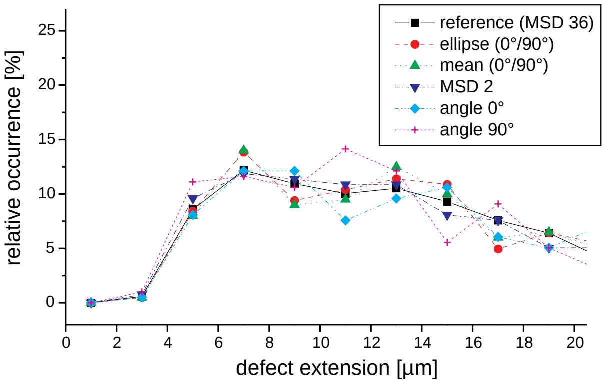

Fig. 9: Model specific defect size distributions (DSDs) based on 212 defects inspected inside 7630 test chips "D13".

model	mean	ellipse	MSD 2	angle 0°	angle 90°
max. neg. error	-2.53	-3.45	-1.77	-2.62	-5.29
max. pos. error	2.62	2.19	1.36	2.58	4.43
mean error	±0.50	±0.52	±0.31	±0.50	±0.81

Tab. 2: Maximal and mean error of model specific defect size distributions (DSDs) based on the defects inspected inside all test chips "D13". The reference DSD is based on a micro size distribution of 36 measurement values (MSD 36) per defect inspected inside the test chips.

Figure 10 shows the results of just 61 inspected defects inside 300 test chips "C11-1". Nevertheless, the MSD 2 based DSD just has a mean error of ±0.55. As expected, a small sample like this provides worse results for such models that take into account just a single size value per inspected defect. Those models require about 200 inspected defects to get a competitive DSD providing a mean error of just ±0.55 as can be seen in the results of Table 2.

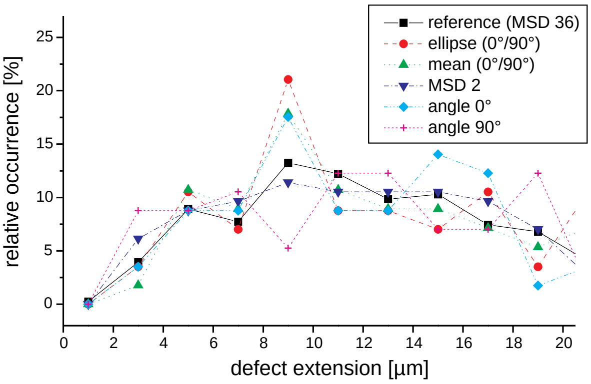

Fig. 10: Model specific defect size distributions (DSDs) based on 61 defects inspected inside 300 test chips "C11-1".

model	mean	ellipse	MGV 2	angle 0°	angle 90°
max. neg. error	-2.66	-4.27	-2.88	-6.34	-10.17
max. pos. error	5.80	9.66	2.41	5.36	6.16
mean error	±0.77	±1.29	±0.55	±1.14	±1.44

Tab. 3: Maximal and mean error of model specific defect size distributions (DSDs) based on the defects inspected inside all test chips "C11-1". The reference DSD is based on a micro size distribution of 36 measurement values (MSD 36) per defect inspected inside the test chips.

Finally Figure 11 gives the DSDs for just 28 inspected defects inside 1308 test chips "D15-1". But, such a small sample cannot provide accurate results if defect models are used that take into account just one or two extension value per inspected defect. Only, the MSD 36 based reference DSD takes into account more than 1000 measurement values even in this case of just 28 inspected defects. So, only the MSD 36 based DSD may provide a relatively smooth curve.

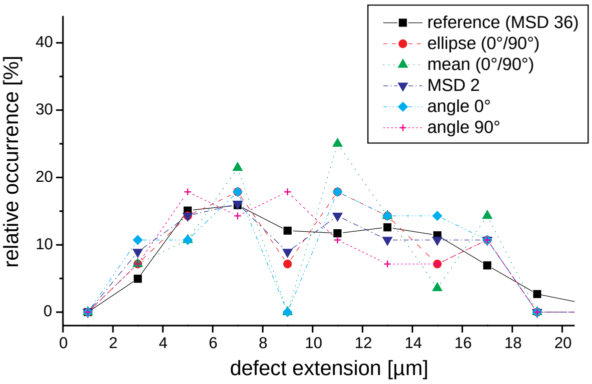

Fig. 11: Model specific defect size distributions (DSDs) based on 28 defects inspected inside 1308 test chips "D15-1".

model	mean	ellipse	MGV 2	angle 0°	angle 90°
max. neg. error	-12.96	-5.56	-3.53	-12.96	-5.80
max. pos. error	13.39	5.98	4.12	5.98	6.27
mean error	±2.33	±1.10	±0.81	±1.72	±1.17

Tab. 4: Maximal and mean error of model specific defect size distributions (DSDs) based on the defects inspected inside all test chips "D15-1". The reference DSD is based on a micro size distribution of 36 measurement values (MSD 36) per defect inspected inside the test chips.

In summary, we can conclude from the experimental results presented here:

- For a given small sample of inspected defects (<100) the MSD 2 based defect model results in a significantly better defect size distribution than those defect models based on one size value only.
- To ensure the same accuracy of a total defect size distribution (DSD) defect models based on just on size value per inspected defect require larger samples than those models based on two or more extension values per inspected defect.

5 CONCLUSION

Defect inspection tools are commonly used to determine defect size distributions for process control and yield improvement. Several methodologies are used to calculate total defect size distributions (DSD) based on the measured extension values of an inspected defect. Compared to known calculation models resulting in just one size value per inspected defect, we presented a novel methodology to include all measured extension values per inspected defect in a so called Micro Size Distribution (MSD). The total defect size distribution (DSD) will then be calculated using the MSDs of all inspected defects, even if each MSD is based on just two measurement extension values per defect.

Our experimental results clearly show that whenever more than just one extension value is measured for a single defect, the accuracy of DSDs significantly increases, if the measured data will not be reduced to a single size value per defect. Furthermore, also the sample size of inspected defects may be decreased, because the number of extension values taken into account will increase when determining a DSD based on a Micro Size Distribution MSD 2 per inspected defect. This approach will help to optimize the usage of defect inspection tools.

APPENDIX
MICRO SIZE DISTRIBUTION (MSD)

To provide an image data base describing the size and outline of hundreds of inspected defects, the defect extension will be measured between parallel lines (ref. Figure 3). Image-processing based tools provide curves to describe the defect extension (y-axis) dependent on the measurement angle (x-axis: 0°-180°) as can be seen in Figure 12.

Generally, just one size value will be calculated for each inspected defect. Based on these values, a total defect size distribution (DSD) will be determined. To also include the irregular outlines of defects that occur in reality, we introduced a total defect size distribution based on individual size distributions for each inspected defect [HeWe96a].

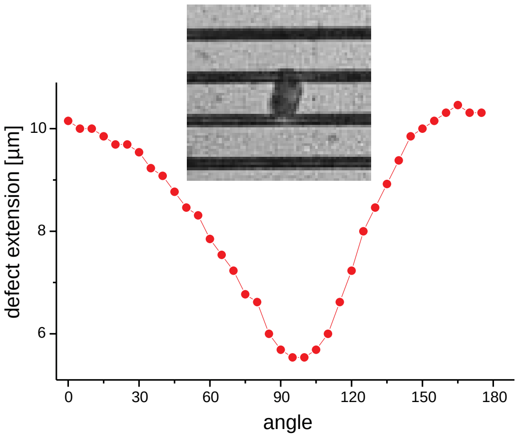

Fig. 12: Extension of a defect dependent on the measurement angel.

Our intention is to model each defect as a so called **Micro Size Distribution (MSD)**. Then, these distributions will be summarized in a total defect size distribution. For this reason, we measure the defect extension between parallel lines as described in Figure 3. We select equivalent measurement steps Δφ that we get

$$w = \frac{180°}{\Delta\varphi} \qquad \mathbf{(7)}$$

measurement values. Now, we replace each original defect by *w* imaginary defects each with its individual size value (e. g. Δφ=5° results in *w*=36 imaginary defects). Each imaginary defect has to be weighted with *1/w* because all *w* imaginary defects represent just one original defect. So, the absolute occurrence of inspected defects remains unchanged, if and only if for each defect

$$\sum_{i=1}^{s} \frac{1}{w} D_i = 1 \qquad \mathbf{(8)}$$

where *s* is the total number of size intervals and D_i stands for the number of imaginary defects per size interval. For example, the defect of Figure 12 results in a Micro Size Distribution as can be seen in Figure 13.

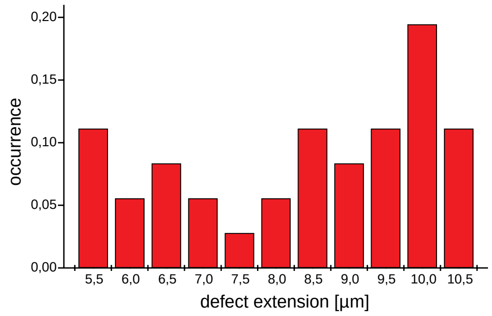

Fig. 13: Micro Size Distribution of imaginary defects based on one real defect.

Then, we determine a total defect size distribution based on all Micro Size Distributions of the imaginary defects, where the total number of all original defects is identical to the sum of all imaginary defects. Using the Micro Size Distribution (MSD) per inspected defect results in a very accurate total defect size distribution (DSD) because this procedure takes into account all variety of defect outlines that occur in reality [HeWe96a].

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