CDO Budgeting

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ABSTRACT

The Critical dimension off-target (CDO) is a key parameter for mask house customer, affecting directly the performance of the mask. The CDO[1] is the difference between the feature size target and the measured feature size. The change of CD during the process is either compensated within the process or by data correction. These compensation methods are commonly called process bias and data bias, respectively. The difference between data bias and process bias in manufacturing results in systematic CDO error, however, this systematic error does not take into account the instability of the process bias. This instability is a result of minor variations - instabilities of manufacturing processes and changes in materials and/or logistics.

Using several masks the CDO of the manufacturing line can be estimated. For systematic investigation of the unit process contribution to CDO and analysis of the factors influencing the CDO contributors, a solid understanding of each unit process and huge number of masks is necessary. Rough identification of contributing processes and splitting of the final CDO variation between processes can be done with approx. 50 masks with identical design, material and process. Such amount of data allows us to identify the main contributors and estimate the effect of them by means of Analysis of variance (ANOVA) combined with multivariate analysis.

The analysis does not provide information about the root cause of the variation within the particular unit process, however, it provides a good estimate of the impact of the process on the stability of the manufacturing line. Additionally this analysis can be used to identify possible interaction between processes, which cannot be investigated if only single processes are considered.

Goal of this work is to evaluate limits for CDO budgeting models given by the precision and the number of measurements as well as partitioning the variation within the manufacturing process. The CDO variation splits according to the suggested model into contributions from particular processes or process groups. Last but not least the power of this method to determine the absolute strength of each parameter will be demonstrated.

Identification of the root cause of this variation within the unit process itself is not scope of this work.

Keywords: CDO, CDO budget , CDO stability, MTT; ANOVA; multivariate analysis;

INTRODUCTION

Each manufacturing process contributes through its natural spread to the final CDO value of the product. Since this spread varies from process to process a maximum CDO budget is attributed for each process step, where each process consists of multiple parameters, each of them having a specific CDO_i. Usually these contributions are assumed to be independent and so they are summed quadratic according to the central limit theorem (Eq.1).

$$CDO = \sqrt{\sum_{i=1}^{n} CDO_i^2} \qquad [1]$$

Typical approaches to split the final CDO into budgets are:

- equally distributed CDO amongst all (major) processes or
- CDO calculated according to process CD bias.

Both approaches take a simplified view, e.g. they can not account for interactions between subsequent processes like resist development and subsequent Cr etch process.

A more realistic approach – but significantly more complicated too – is to apply Analysis of variance (ANOVA) combined with multivariate analysis. This combined analysis not only allows us to differentiate between significant and nonsignificant contributions from different process parameters (CDO_i) e.g. plasma gas pressure or humidity but also enables us to determine the strength of each of these parameters. The huge benefit of this approach is to explain the final

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[1] CDO is often referred to as mean-to-target (MTT) as well

CDO variation through variation of basic parameters which allow us to verify the model including e.g. assumptions on the independency of unit processes, checking of the central limit theorem and last but not least estimate the limits of CDO budgeting given by metrology.

Using real product data is one way but it complicates the analysis since the products show a large intrinsic spread already[2]. Easier and still valid is to restrict the data to a specific mask set e.g. a standardized design that is used for monitoring line stability. In the existing publication the latter approach was applied. Data sets[3] from approx. 70 masks combined with all kind of different parameters - including e.g. process parameters, equipment used, time stamp …- were analyzed. The data was collected over an extended period in order to cover long term instabilities and avoid misinterpretation because of lack of degrees of freedom.

OVERVIEW OF THE MODELS

In this publication three different models will be discussed:

a) equal CDO budget approach for (major) processes (only 4x major processes are taken into consideration),
b) CDO budget according to the CD bias of each (major) process and
c) Combination of ANOVA and multivariate analysis to determine the CDO budget.

In addition a couple of generic questions need to be validated or proven:

- Are all processes and factors influencing CDO known?
- Is the quadratic sum of the CDO_i budgets correct?
- Are CDO_i contributions independent?
- Is the available metrology performance good enough to identify CDO budgets and help to improve processes with respect to their stability?

The experienced reader might know already that models a) and b) are not correct partially because of the underlying assumptions but also because they do not account for interactions between parameters. Nevertheless it is still important to show that both models are incorrect and can not be used to calculate the final CDO. This is done briefly in the two subsequent chapters. The following chapters then focus solely on the ANOVA/multivariate analysis combination.

"EQUAL CDO BUDGET" MODEL

The 4 major processes affecting final CDO are pattern generation (PG), resist development, Cr etch and MoSi etch. Adding additional processes does not change the discussion so for simplification we will restrict the discussion to these 4 processes. If each of the aforementioned processes equally contributes to final CDO the numbers would increase from RCD to INCD to FICD (see Fig.1), where:

- RCD is measured after resist development. It includes the litho steps pattern generation, post exposure bake and resist development,
- INCD is measured after Cr etch and resist strip. Since resist strip has no or at least no measurable impact INCD is dominated by Cr etch and
- FICD is measured on the final mask. This measurement is impacted by MoSi[4] etch and the entire second level process. Again we assume that the second level process has minimal impact, so MoSi etch is the main driver for CDO contribution to FICD.

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[2] E.g. blank material, design, Cr clear field, main feature size etc. All of these factors need to be covered by additional factors within the ANOVA analysis.

[3] consisting of Resist CD (RCD), Internal CD (INCD), Final CD (FICD)

[4] MoSi stands for the phase shift layer

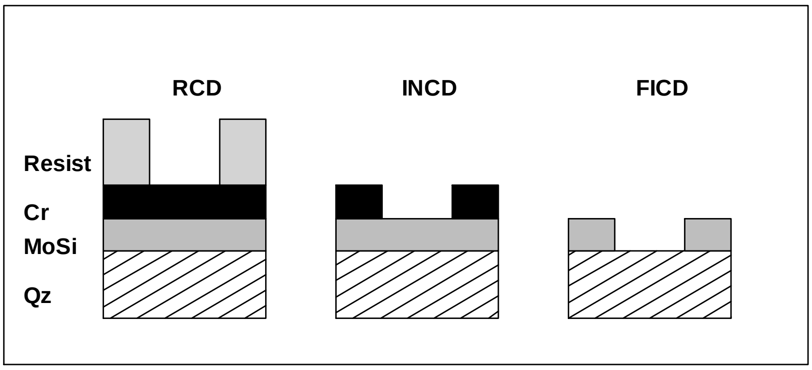

Fig.1 *– mask at RCD, INCD and FICD measurement.*

Fig.2 shows the variation for all three CDO measurements and their respective differences. The corresponding numbers for the variation (CDO 3σ) and the variation per step (CDO/step) are summarized in Tab. 1.
It is obvious that both the unit process contributions CDO/step calculated from INCD and FICD are smaller than from RCD and - most notably - the CDO/step values for each of the differences ("Delta Measurements") are much smaller than expected. One could argue that additional "major" processes contributing to RCD were not taken into account thus the given number of steps for RCD mentioned in Tab. 1 is significantly higher than expected. This hypothesis will be checked later on in the ANOVA part. Nevertheless the small CDO/step values for the "Delta Measurements" ≤ 2nm would be hard to explain.

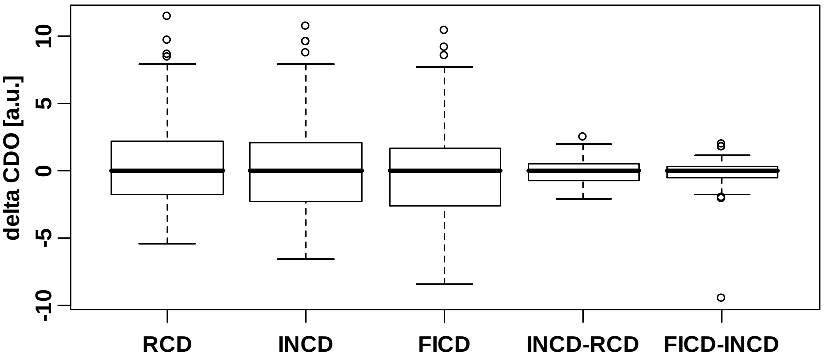

Fig.2 *– CDO - variation of RCD, INCD and FICD as measure of CDO propagation; variation of RCD, INCD-RCD and FICD-INCD differences demonstrate the contributions from RCD- 2process steps, INCD-RCD – 1 process step, FICD-INCD – 1 process step according to our previous assumptions. All these contributions contain also the measurement budget, for RCD once, in other cases 2 times, due to two measurements involved in difference.*

Tab.1 *– Summary of CDO contributions per unit process. Numbers were calculated according to Eq.1 assuming independent processes, equally distributed error and long term CD metrology error of 1.5 nm for each metrology step.*

	Single Measurements			**Delta Measurements**	
	RCD	**INCD**	**FICD**	**INCD-RCD**	**FICD-INCD**
CDO 3σ - metrology subtracted [a.u.]	10.45	11.36	10.49	1.88	1.43
Major Processes included (assumption)	2	3	4	1	1
Metrology steps contained	1	1	1	2	2
CDO/step 3σ []	**7.39**	**6.56**	**5.25**	**1.88**	**1.43**

“BIAS BASED CDO BUDGET” MODEL

Another commonly used model is based on the CD bias contribution, i.e. processes with a higher CD bias get a higher CDO budget assigned. To check this assumption CDO and Process Bias were calculated from the 70 mask data set and plotted in Fig.3[5]. In order to support the “Bias Based CDO Budget” model one would expect a linear correlation between both parameters which is not the case! Therefore we draw the following conclusions:

- Process Bias and CDO Contribution are independent variables. Knowledge of any of them does not allow us to make estimation of the other one.
- The Process Bias can not be used to calculate the CDO Contribution.
- A higher Process Bias does not require a higher CDO budget. The point is valid unless the increase of Process Bias is coupled with decrease of the process stability.

All three items show that the “Bias Based CDO Budget” model is not representative of the real situation we see by analyzing the collected data.

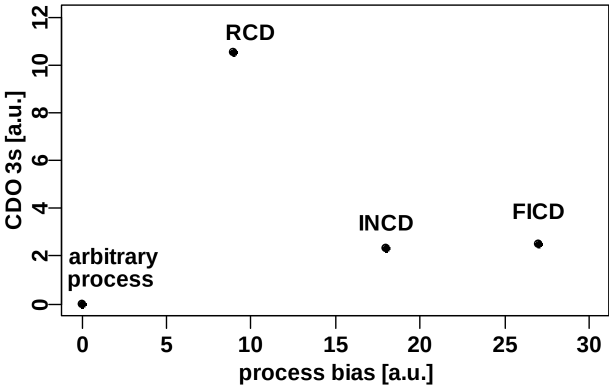

***Fig.3** – correlation between process bias and CDO contribution for 3 different process parts- litho process till RCD measurement, the process steps between RCD and INCD measurement and process steps between FICD and INCD measurement. The viewgraph demonstrates the lack of correlation between CDO and process bias, leading to conclusion, that the process bias does not allow us to judge the CD stability of the process. CDO contribution is taken from Tab. 1- CDO 3σ– metrology subtracted; process bias is estimated as average difference on the same data. Arbitrary process is e.g. clean, Pellicle mounting or any other process with 0nm process bias.*

ANOVA – CDO CONTRIBUTORS ESTIMATION

The commonly used “Equal CDO Budget” and “Bias Based CDO Budget” models have been dismissed in the preceding sections so to come up with a better approach for CDO budgeting a combination of ANOVA and multivariate analysis has been tested instead.

The analysis of variance - ANOVA is a well established statistical method for analysis of relations between several input variables - factors and one dependent variable - response. For CDO, the contributing factors were assumed to be 2 litho, Cr and MoSi etch process. All other processes are considered to be CDO neutral. Metrology is contributing to CDO due to the uncertainty of the measurement; even so it does not influence the mask performance directly. Therefore Metrology is included as separate factor in the ANOVA.

Due to limited number of data points- (masks involved into the experiment) we have to limit the number of degrees of freedom, to avoid overestimation of the model. This requirement reduces the number of factors we may introduce and successfully test as statistically significant for CDO. Since this rule applies to factors as well as their interactions only 2nd order interactions are kept. Additionally the entire process is split into three subcategories - RCD, INCD and FICD. Through this trick the degrees of freedom in all litho processes should decrease to one factor, the RCD measurement when building an ANOVA model for INCD. This is valid unless there are interactions between factors in different parts of the process.

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[5] At this point is not important to know the exact number of unit processes affecting the CDO since both measurements - CDO and Process Bias - are taken simultaneously during the manufacturing process.

Factors acquired before RCD are marked as L_1, L_2, L_3…; between RCD and INCD as P_1, P_2, P_3 … and metrology as M_1, M_2, M_3 …. The generic model for INCD set up is shown in Eq.2:

$$INCD = a \cdot RCD + b \cdot L_1 + c \cdot L_2 + ... + d \cdot P_1 + e \cdot P_2 + f \cdot P_3 + ... + g \cdot M_1 + h \cdot M_2 + ... + i \cdot L_1 L_2 + ... \quad [2]$$

Results for the ANOVA analysis for INCD (with factors: L_1-L_3, P_1-P_4, M_1-M_4, RCD and interactions) are given in Tab.2:

Tab.2 *– ANOVA results for investigation of INCD consisting of factors RCD, L_1-L_3, P_1-P_4 and M_1-M_3. Significant factors are marked in the last column by "XXX". Significance for relevant factors is based on probability (second last column* ***Pr>F****) at α level 0.01. Since the probabilities are either far below or significantly above the α level, choice of the criteria is not critical for main factors. Strongest interactions exhibit probabilities about 0.01-0.03, which is slightly above the α level. This drop of* ***Pr>F*** *between main factors and all interactions leads to the elimination of all interactions from the model.*

Factor	DOF	Sum Sq	Mean Sq	F	Pr>F	significant
RCD	1	48.613	48.613	1821.09	$<2.2\ 10^{-16}$	XXX
L_1	1	0.369	0.369	13.83	$5.41\ 10^{-4}$	XXX
L_2	1	0.005	0.005	0.19	0.66	
L_3	1	0.003	0.003	0.17	0.68	
P_1	1	3.021	3.021	113.16	$5.49\ 10^{-14}$	XXX
P_2	1	1.393	1.393	52.20	$4.19\ 10^{-9}$	XXX
P_3	1	0.815	0.815	30.54	$1.47\ 10^{-6}$	XXX
P_4	1	0.020	0.020	1.10	0.31	
M_1	1	0.012	0.012	0.45	0.50	
M_2	1	0.527	0.527	19.72	$5.56\ 10^{-5}$	XXX
M_3	1	0.004	0.004	0.22	0.64	
…		…	…	…	…	…
RCD:P_3	1	0.104	0.104	5.49	0.02	?
P_1:P_3	1	0.133	0.133	7.03	0.011	?
M_1:M_2	1	0.120	0.120	6.33	0.015	?
residuals	47	0.89	0.019	-		

Before we continue to further reduce the contributing factors and come up with simplified models the significant factors in Tab. 2 need to be discussed in detail. As expected the ANOVA analysis confirms the importance of factors P_1 and P_2. Significance of factor P_3 is rather surprising. As discussed before litho factors L_1-L_3 should be covered by RCD, which is true for L_2 and L_3 factors; however L_1 factor is affecting INCD directly without being completely covered by RCD. This fact is fairly surprising and will be dealt with later on. RCD is certainly a significant factor in the generic model, similar to the metrology factor M_2. Metrology factor M_1 contributes to RCD measurement but has no impact on INCD according to ANOVA. Therefore M_1 is excluded from the further discussions.

The generic model described in Eq.2 was further reduced to three different models that were tested but resulted in similar residuals as shown in Tab. 3. To determine the most appropriate model following criteria were used:

- Statistical significance of all contributing factors
- Variation explained by the model - 3σ of the fitted values
- Residuals 3σ
- Adjusted R squared of the model

Tab.3 *– Comparison of selected models using all main factors in model 1, statistically significant main factors and 3 most significant interactions in model 2 and statistically significant factors in model 3. Second model exhibits highest variation explained (model 3σ), lowest residuals and highest adjusted R^2. Disadvantage of model 2 is high number of factors involving also not significant factors and interactions. For this reason model 2 was not taken for further investigation. The significance of interactions has to be proven with more data points.*

Model	Model 3σ	Residuals 3σ	Adj. R^2	p-value
1	11.45	2.2299	0.9727	$< 2.2\ 10^{-16}$
2	11.48	1.9597	0.9798	$< 2.2\ 10^{-16}$
3	11.45	2.2569	0.9748	$< 2.2\ 10^{-16}$

Model 1: $\boldsymbol{RCD}+\boldsymbol{L_1}+L_2+L_3+\boldsymbol{P_1}+\boldsymbol{P_2}+\boldsymbol{P_3}+P_4+M_1+\boldsymbol{M_2}+M_3$
Model 2: $\boldsymbol{RCD}+\boldsymbol{L_1}+L_2+\boldsymbol{P_1}+\boldsymbol{P_2}+\boldsymbol{P_3}+M_1+\boldsymbol{M_2}+P_1{:}P_3+RCD{:}P_3+M_1{:}M_2$
Model 3: $\boldsymbol{RCD}+\boldsymbol{L_1}+\boldsymbol{P_1}+\boldsymbol{P_2}+\boldsymbol{P_3}+\boldsymbol{M_2}$

Distribution of the residuals for all 3 models is shown in Fig.4, showing that spread and distribution differ only slightly. Using all available data a spread of about 2.2-2.3 nm 3σ is remaining, which is in excellent agreement with long term stability of used metrology tools (cf. chapter “METROLOGY CONTRIBUTION”).

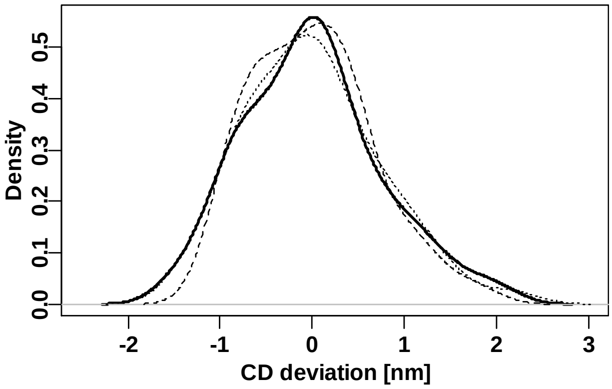

Fig.4 *–Residuals distribution for models 1- dotted line, 2- dashed line, 3-solid line. This variation cannot be explained by any of factors taken into analysis. For explanation of this variation additional factors have to be used.*

As previously mentioned, ANOVA analysis identifies RCD and 5 out of 12 tested factors as statistically significant for INCD variation ($P_1 – P_3$, L_1, M_2 factors) and indeed the simplest model – Model 3 – shows good results. So there is no need to use the more complicated models 1 or 2.
In the next chapter the multivariate analysis will be applied to quantify the effect for each factor.

EFFECT OF FACTORS BY MULTIVARIATE ANALYSIS

For statistically significant factors identified by ANOVA - model 3, quantification of the effect is performed via multivariate analysis according Eq.3. In order to avoid misinterpretation of the data due to factor covariance all pairs of factors are checked. The analysis is performed within one step, however for the purpose of simplification the effects will be discussed according to the strength their CDO contribution (Tab. 4).

$$\mathbf{INCD}= a + b\cdot\mathbf{RCD} + c\cdot\mathbf{L_1} + d\cdot\mathbf{P_1} + e\cdot\mathbf{P_2} + f\cdot\mathbf{P_3} + g\cdot\mathbf{M_2} \qquad [3]$$

Tab.4 *– Effect of factors calculated according to model 3.*

Factor	Coefficient	Effect []	Std. error []	CDO contribution [a.u.]	CDO contribution [%]
RCD	b	1.11	0.025	16.78	60.6
$\mathbf{P_3}$	f	$7.2\ 10^{-3}$	$9\ 10^{-4}$	3.638	13.1
$\mathbf{P_1}$	d	-0.89	0.188	1.970	7.1
$\mathbf{L_1}$	c	-0.011	0.003	1.523	5.5
$\mathbf{M_2}$	g	-0.7	0.114	1.400	5.05
$\mathbf{P_2}$	e	-0.058	0.174	0.107	0.4
residuals	-	-	2.257	2.257	8.1

The strongest factor with the highest CDO contribution is **RCD**. This fact is not surprising. We have to keep in mind, that the RCD variation covers all litho processes as well as the variation in the mask blank material properties, especially resist sensitivity. The effect of **RCD** is clearly visible in the raw data without any adjustment (Fig.5*a*). The dashed line represents the linear fit of the data calculated by multivariate analysis.

To enhance trends for the following graphs in Fig.5*b*–5*f* the effect of preceding factors is subtracted, e.g. in Fig.5*c* the CDO contribution of the previous factors – **RCD** and $\mathbf{P_3}$ - are subtracted from the INCD data. This procedure is applied for Fig.5*b*-5*f*.

Second biggest CDO contribution originates from $\mathbf{P_3}$ factor (Fig.5*b*), however, the effect of this factor is very small and the CDO contribution originates mainly from $\mathbf{P_3}$ numbers larger than 200 which is fairly unusual. The INCD response is most probably not linear as supposed in the model but due to low statistics the linear model is kept.

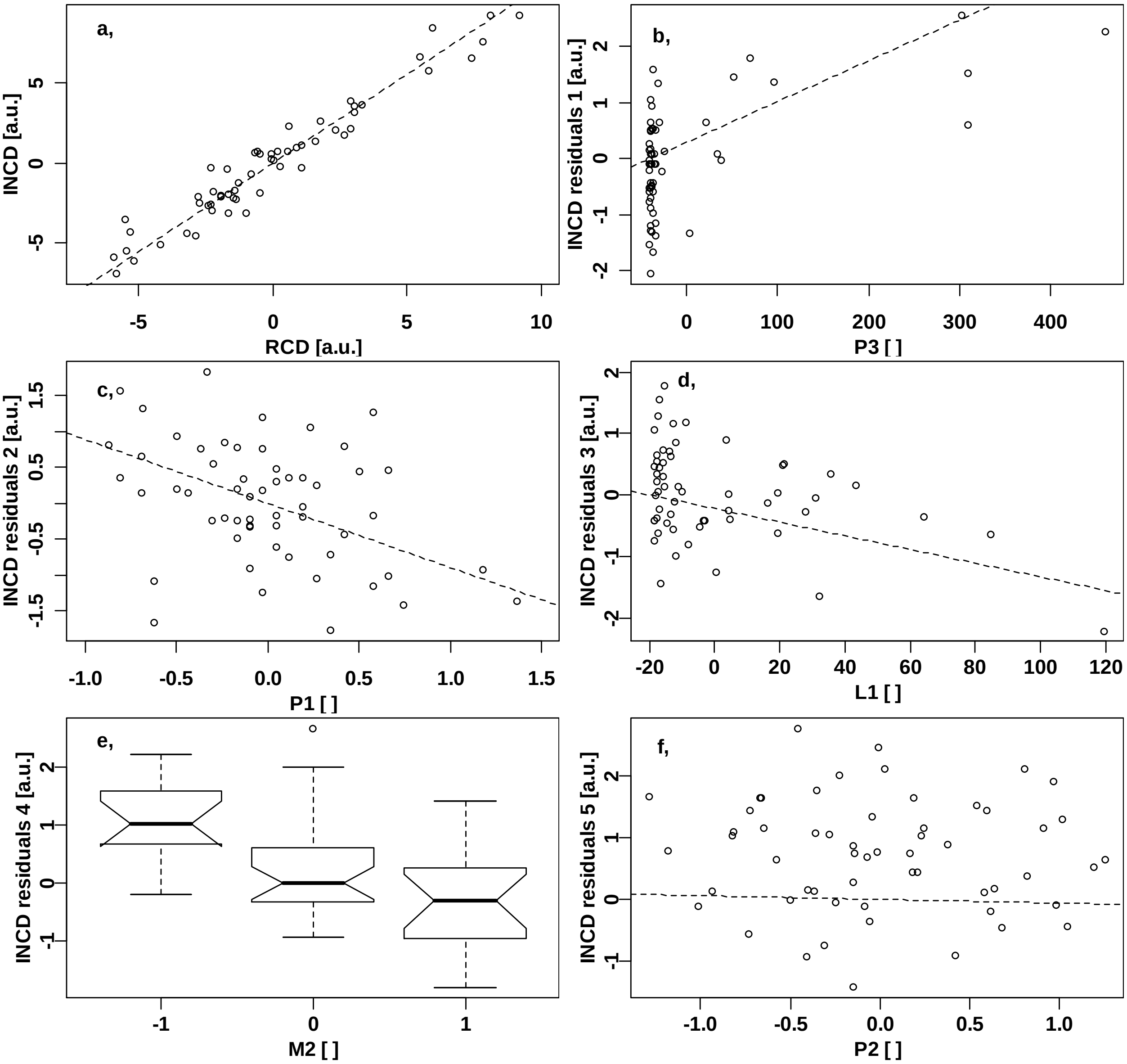

Fig.5 *– separation of factors according to the result from multivariate analysis sorted from biggest to smallest contribution to CDO. The factors are plotted as difference to the mean of the respective factor. On the y axis the INCD variation is plotted. For each plot the effect of all previous factors is subtracted to make the effect of weak factors visible e.g. for fig.5c the effect of factors plotted in fig.5a–**RCD** and 5b-$\mathbf{P_3}$ is subtracted. In viewgraphs following factors are plotted **a**-RCD, **b**-P_3, **c**-P_1, **d**-L_1, **e**-M_2, **f**-P_2.*

Next factor $\mathbf{P_1}$ (Fig.5*c*) exhibits a negative trend of -0.89, which is nominally the second strongest effect after **RCD**. Here in contrary to the previous factor $\mathbf{P_3}$, the variation of factor itself is very low and so the resulting CDO contribution is about 1.97 only (cf. Tab. 4). The INCD response to this factor is linear and we do not expect any significant change of the effect when adding new data points. The factor is almost normally distributed.

Surprising is significance of the next factor **L_1** (Fig.5*d*). As indicated by the notation, the **L_1** factor is extracted prior to RCD measurement and so we expect that this factor affects RCD, but not the INCD directly. The effect is rather weak (-0.011) and not measurable at low range of **L_1** factor. At this point in time we have no good explanation why L_2 contributes directly to INCD. The influence of the right outermost point if Fig.5*d* which seems to be responsible for the effect was tested by a separate analysis performed without this point. The strength of **L_1** was affected by about 10% - significantly less then the standard deviation of the effect estimated.

Second last factor **M_2** contributes 1.4 to CDO (Fig.5*e*). This factor is categorical factor with effect approx. 0.7 between levels. This effect is part of metrology contribution to CDO, as we will show later on. It is the only one, which can be directly attributed to each mask.

Last statistically significant factor **P_2** (Fig.5*f*) has a very low effect of about -0.06, which is not possible to estimate any other way using given precision of measurement. The effect was supposed to be significantly higher, however, the analysis shows, that this effect is negligible for CDO. It is kept in the model for the sake of completeness and in order to keep the model residuals as small as possible.

Subtracting all 6 effects from the raw data we can determine the residuals shown in Fig.6 yielding a standard deviation of σ=2.26.

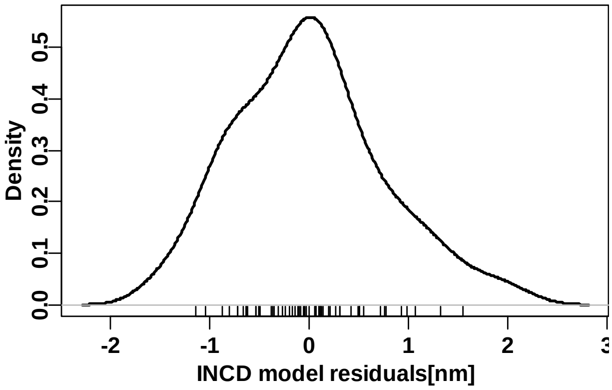

Fig.6 *– INCD residual distribution, 3σ=2.26. This INCD instability cannot be explained by any of factors tested in this work. The variation is possibly caused by the precision of the measurement; the measurement stability is not contained in any of factors mentioned so far – for this reason the variation has to be compared to the long term stability of the metrology tool used in the study.*

METROLOGY CONTRIBUTION

Using all available data a spread of about 2.2-2.3 nm 3σ is remaining, which is in excellent agreement with long term stability of used metrology tools (cf. chapter “METROLOGY CONTRIBUTION”).

As mentioned previously we have seen a distribution of INCD residual of approx. 2.26nm (cf. Fig.4 and Fig.6). In order to explain this variation a closer look at metrology stability is necessary. In Fig.7a the long term stability for RCD and INCD measurement is shown. To be able to compare the stability data from RCD and INCD with Fig.6 we convoluted both curves from Fig.7a, i.e. we need to convolute RCD/INCD. The result is printed in Fig.7b yielding a 3σ of 2.15 nm. This value easily explains the vast majority of the residuals of 3σ=2.26nm.

The consequence of this result is, that there is no way to estimate CDO more precisely than ±2 nm on single mask. This is sufficient for CDO estimation on products but it is neither sufficient for qualification of unit processes with budgets less that 2nm nor for the improvement of the CDO variation of unit process with similar budgets.

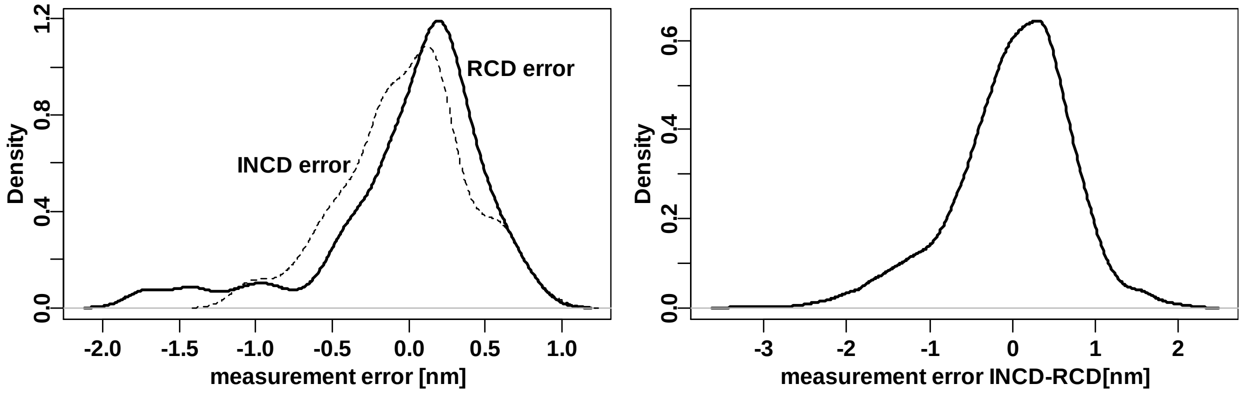

***Fig.7** – **a**, Distribution of long term stability error for RCD and INCD measurement and **b**, distribution of INCD -RCD metrology error. The data were acquired over the same period of time as the measurement used in analysis. The standard deviation of the metrology error is* $3\sigma=2.15nm$.

CONCLUSIONS

Three different CDO budgeting models were discussed with CD data from a set of 70 standard masks. In this discussion the limitations for the “Equal CDO Budget” and “Bias Based CDO Budget” models were clearly identified, concluding that neither of these two models can accurately reflect the real situation for CDO budgeting. Therefore a new approach applying a combination of ANOVA and multivariate analysis was established. This new approach resulted in a couple of very interesting findings:

- CDO budgets for RCD, INCD and FICD differ significantly and can not be spread equally,
- significant parameters were identified and their strength with respect to CDO was quantified
- hidden interaction were discovered e.g. litho parameter contributing to INCD without being covered by RCD measurement and
- The long term stability of metrology is of the same order as the residuals after subtracting all significant parameters.

Through this analysis we enable manufacturing to track CDO stability on hand of specific parameters, which can be recorded and controlled easily e.g. via SPC. This understanding should help tremendously to further reduce development costs as well as improving stability issues of entire manufacturing process.

In order to identify weaker effects and interactions a further improvement of the long term stability of metrology is required.

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