Time Resolved Evolution of the Etch Bias

Pavel Nesladek, Jan Paul
Advanced Mask Technology Center, Rähnitzer Allee 9; 01109 Dresden, Germany

ABSTRACT

Increasing demand for high end masks with ever-narrowing specifications for critical dimension uniformity (CDU), CD linearity, etc. is the major driver for the further process development. Decreasing the main feature size and increasing the complexity of sub-resolution assist features (SRAF) are restricted by the resolution limit of the mask manufacturing process, which is determined by the resolution limit of the mask lithography process and the widening of the clear structures in etch processes – etch bias.

In order to be able to compare and develop new etch processes, a reliable and well reproducible method for etch bias estimation has to be established. Previous investigation shown, that there is a gap between etch bias estimation by mean of CD SEM and AFM methods. The measurement of the CD value in resist was identified as the major problem of the etch bias estimation for several reasons. We searched for a measurement method that minimized the disadvantages of the resist CD measurement; ideally making the resist CD measurement obsolete. Since the widening of the features can be observed at the Cr edge as well, our experiment focuses on the measurement of the upper Cr edge shift as function of time which provides the information about the etch bias as well as the time evolution of the CD and side wall angle. In our work we present a method for measurement, one can adopt as etch bias measurement and use it as a way for calibration of the easy to use etch bias measurement methods like AFM, CD SEM and optical CD measurement. The understanding of the process of structure widening gives us a confidence, that the method suggested is correct and explains well, what the limitations of the etch bias are. Last but not least the proof is given, that there is no Cr etch process with zero etch bias possible.

Keywords: Etch bias, side wall evolution, AFM metrology, Cr etch

INTRODUCTION

The current main stream technology, the half tone PSM mask, includes 2 etch steps; the Cr and the MoSi etch processes. The etch bias of the Cr etch process is significantly higher than in case of the MoSi etch process due to significant resist removal rate by the oxygen contained in the etch gas. Since the MoSi etch process uses the previously etched Cr layer as hardmask and due to rather anisotropic ion driven physical process with high selectivity to the Cr layer shows negligible etch bias, which can be kept near 0 by appropriate choice of the etch conditions.

In order to estimate the etch bias for process development or comparison of processes, a reliable method for etch bias (EB) estimation has to be found. There are 3 methods frequently used for EB estimation:

- Optical CD measurement in reflective mode
- CD SEM measurement
- AFM measurement

Since the optical CD measurement and CD SEM measurement are similar in the way they estimate the CD, they have the same advantage of high throughput. The disadvantage of these methods is the material and side wall slope dependent reflectivity and secondary electron emission respectively.

The consequence is lower reliability in several cases as shown[1, 2]. The CD measurement by means of CD SEM on the etched Cr layer can be easily correlated to the AFM measurement. Obviously the less reliable measurement is the resist measurement. To some degree are the not well defined shape of the very top part of the resist side wall and variation in the radius of the edge measured. In addition there is no calibration for resist CD measurement available.

Clear indication of this problem with resist measurement is negative etch bias reported by some authors. Negative etch bias gives a hint, that the resist CD doesn't corresponds to the side wall in resist, but to some point at the top of the resist, most probably some rounding of the upper edge of the resist as illustrated in Fig.1.

However, there is a way to reduce the effect of the edge of the measured structure and correct the CD SEM measurement in resist for estimation of the EB. The broad range of EB values reported by different authors and our recent experience comparing etch biases obtained from different CD SEM tools and settings with AFM method forced us to decide to search for a method which may help to us to clarify what is the "real" EB and identify the offset for methods, frequently used for EB estimation.

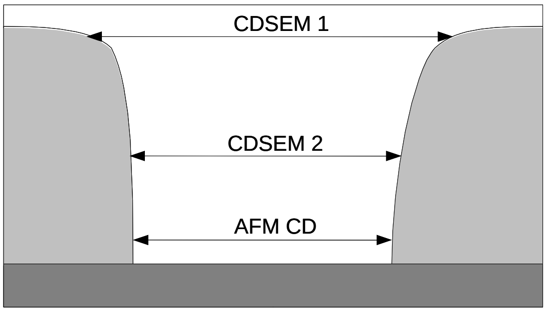

Fig.1 – schematics of CD measurement in resist by mean of AFM and CD SEM with 2 different settings. The drawing shows, that there is chance for CDSEM measurement correlating to AFM measurement (CDSEM 2). Many different CDSEM settings provides CD value, not correlating to the AFM measured value at all.

METHODOLOGY

For CD measurement by mean of AFM the question is, which point on the resist side wall corresponds to the resist CD value. Except ideal 90° side wall, the CD changes with the height on the resist side wall[1].

Variation of the side wall shape along the height increases further the uncertainty. Assuming 300nm height of the resist and side wall angle 88°, the CD varies by 20.9nm for 85° the CD uncertainty is 26.2nm. This value is comparable to the etch bias expected for modern Cr etch process. We decided to exclude the resist CD measurement from etch bias estimation and search for a method avoiding this uncertainty. Additional reason for this decision is the contribution of the resist side wall shape and the AFM measurement tip shape, which is not negligible at 300 nm side wall height.

Closer look at the expected development of the resist and Cr edge during process offers an easy method for the measurement.

Following viewgraph (Fig.2) illustrates the development of the side wall and will be used for explanation of the method selected.

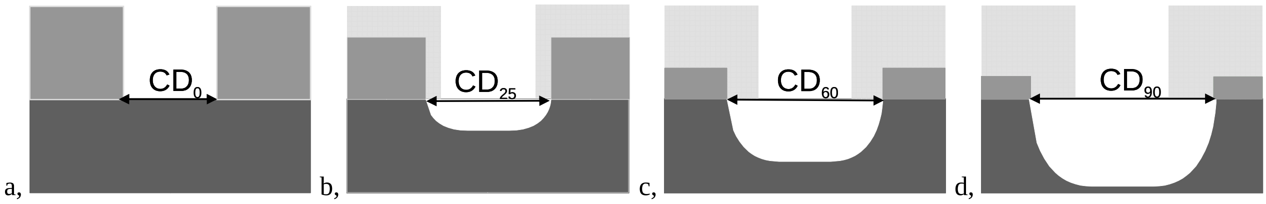

Fig.2 – evolution of the Cr trench during main etch step. Note the widening of the upper edge of the Cr trench at **a**, 0% **b**, 25% **c**, 60% d, 90% endpoint time, described as CD_0, CD_{25}, CD_{60} and CD_{90}.

Comparing pictures a, b, c and d in Fig.2, one can see, that the widening of the Cr trench, more precisely - the upper edge of the Cr trench, is responsible for the etch bias. Measuring the CD as function of the etch time gives us very precise idea about the lateral etch rate and the etch bias as the difference between the CD at time 0 and at the end of the process.

Since there is none or less pronounced trench at the very beginning of the process, we have to extrapolate the CD value at time 0 from the data measured later on during the process.

Due to change in the trench depth and side wall slope, the CD values has to be measured at several height and extrapolated to Cr surface by polynomial fit. Relatively small step is necessary at AFM in order to have precise enough data containing more data point at the side wall of Cr layer. The precision of the measurement is significantly improved by measurement after resist strip, which reduces the scattering caused by the tip contamination and changing resist thickness.

RESISTLESS ETCH BIAS ESTIMATION

We applied this method on the Cr etch process and used it to investigate the development of CD during the etch process. In order to improve the precision, we measured at several sites across the mask and proved the measurement on different masks with global clear field from 0.3 up to 75%.

Figure 3 shows the evolution of the CD value in overetch. The CD value steadily increases as expected. The slope and so the etch bias increases with increasing global clear field as expected.

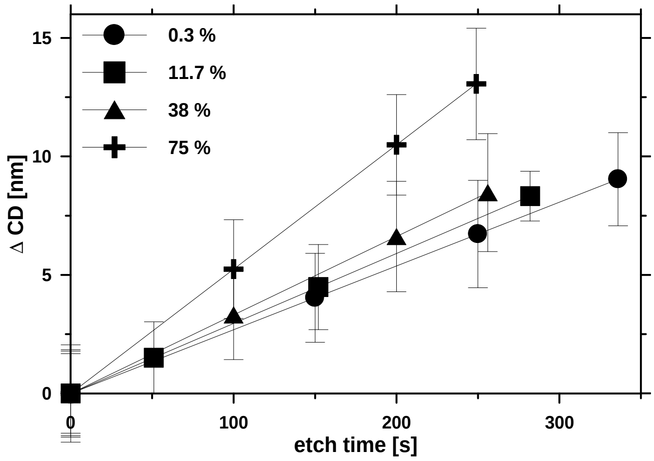

Fig.3 - CD change during overetch for global clear field of 0.3%, 12%, 38% and 75% measured by mean of AFM. The difference in slope corresponds to the lateral etch rate. The data documents the fact, that the etch bias is proportional to the global clear field.

The etch bias estimated by extrapolation from the measurement in overetch differs systematically in comparison to the value obtained as difference between Cr CD and resist CD measured by mean of CDSEM. The discrepancy can be explained by following effects:

A, Nonlinearity of the CD as function of time

B, CD in resist is different from the CD extrapolated for time=0s

Extension of the measurement into the main etch step clarifies the contribution of effect A. Assuming linear resist side wall slope, there is no reason for nonlinearity of the CD as function of main etch time. We can, however, expect difference in the lateral etch rate between main etch and overetch. At the endpoint time, the areas covered with Cr at the beginning of the process become free and the quartz surface area increases. Thus the quartz surface is not etched, the reactant consumption is dramatically reduced in the areas with high clear field. This leads to change of the resist and Cr etch rates at the endpoint.

This effect can be documented on vertical resist etch rate and the Cr etch rate respectively. Fig.4 shows the relative etch rates for resist and Cr layers for both main etch and overetch steps. Whereas the vertical resist etch rate remains high for high local clear field during the whole process, the lateral etch rate and so the etch bias flips in comparison to vertical Cr etch rate in main etch step.

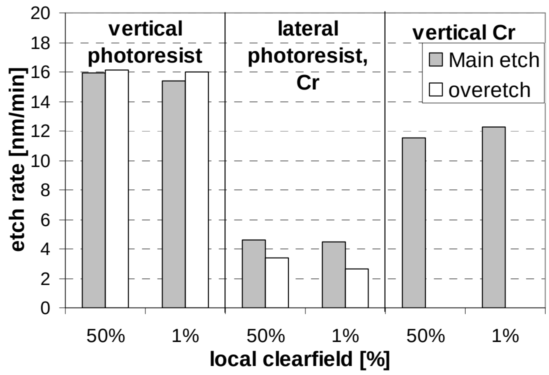

Fig.4 – Comparison of the Cr and resist etch rates during the main etch and over etch. Lateral Cr etch rates are assumed to equal to the lateral resist etch rates, since the upper Cr edge is determined by the resist side wall. Notice ratio between vertical and lateral resist etch rates, which influence the etch bias. Vertical resist etch rates increase at the endpoint time, and cause higher etch bias contribution during overetch.

These data give us clear prove of the major factor determining the etch bias. Not the Cr etch rate, but the lateral resist pull back, which strongly differs from the vertical etch rate, drives the etch bias. The only effect of the Cr etch rate is the total etch time needed for etching the Cr layer. Thicker Cr layers and chemically more etch resistant composition of the layers lead to longer etch times and so to higher EB.

Effect B is illustrated in Fig. 5 Extrapolation of Cr CD measured as function of time during the process provides clear idea of expected resist CD value. By subtracting the measured resist CD, "etch bias" can be calculated for each point in time. This, however, is not zero for process time t=0s, which is in contrary to expected behavior; this would mean, that the etch bias at beginning of the etch process is different from 0. Comparing the slope for the AFM and CD SEM measurements, we find almost perfect match. The $\frac{dCD}{dt}$ for AFM measurement is 0.077 nm/s; for CD SEM the value is 0.073 nm/s. In this way resulting EB is proven to be comparable for both measurement methods.

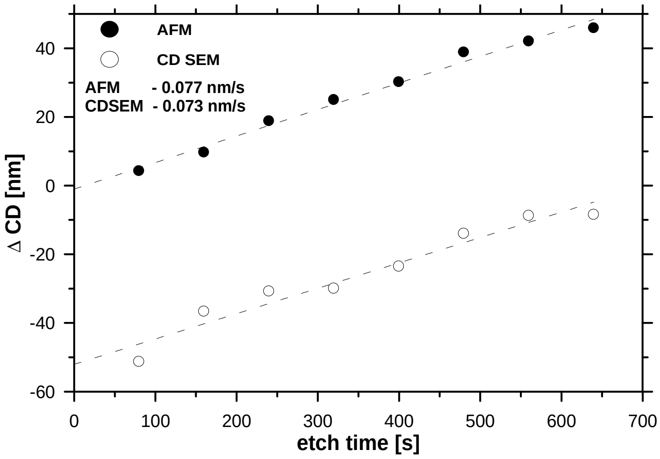

Fig. 5 – comparison of CD evolution as function of time measured at upper Cr edge measured by means of AFM and CD SEM. There is shift in absolute value, however, the slope and so the widening of clear structure is comparable for AFM and CD SEM measurement. The value extrapolated to t=0s represents the discrepancy between resist CD measured and correct resist CD expected with the Cr CD measurement used.

ETCH BIAS MODEL

The etch bias depends on several factors; we try to summarize the main factors we are able to explain by our relatively simple model:

A, Total etch time necessary for the Cr layer
B, Lateral resist etch rate
C, Resist side wall shape / slope
D, Vertical resist etch rate

The effects of factors A and B were discussed in the previous paragraph. The contribution of the remaining two factors will be estimated as follows; hence the data measured include all 4 effects and has to be separated.

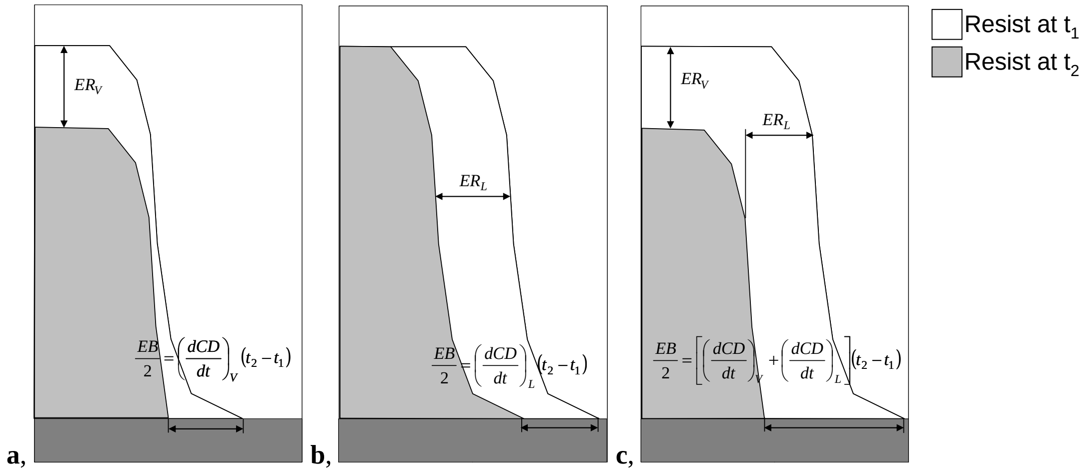

Fig.6 – Illustration of the effect of the side wall shape and vertical resists etch rate. Resist profile at time t_1 is represented by white, resist profile at time t_2 by grey color. **a**, corresponds to the case, when resist side wall is etched vertically only. Notice change of bottom of the resist side wall. **b**, represents the lateral resist etch only. This case is purely hypothetical,
c, illustrates the real etch profile change caused by both the lateral and the vertical resist etch. The drawing shows EB/2 for all cases as well, which helps us to understand the process.

Assuming 90° resist side wall angle, the effect of factor C and D is zero. When the resist side wall angle differs from 90°, which is the case for all resists we examined so far, the effect of C and D is not negligible anymore. The drawing in Fig.6 gives an idea about the contribution of the factors B, C and D in term of etch bias per second.
The lateral shift of the Cr edge measurement in previous experiment can be expressed as.

$$\frac{dCD}{dt} = \left(\frac{dCD}{dt}\right)_V + \left(\frac{dCD}{dt}\right)_L \quad [1]$$

$$\frac{dCD}{dt} = \left(\frac{ER_V}{tg(\alpha)}\right) + ER_L \quad [2]$$

And so the total etch bias

$$EB = 2 \cdot \int_0^{t_{tot}} \left(\frac{ER_V(t)}{tg[\alpha(t)]} + ER_L(t)\right) dt \quad [3]$$

Assuming linear side walls and constant etch rates

$$EB = 2 \cdot \left(\frac{ER_V}{tg(\alpha)} + ER_L\right) \cdot t_{tot} \quad [4]$$

Where $\left(\frac{dCD}{dt}\right)_V$ and $\left(\frac{dCD}{dt}\right)_L$ are vertical and lateral resist etch rate contributions to the etch bias respectively,
ER_V and ER_L are vertical and lateral resist etch rates,
α is the resist side wall slope at the Cr surface (see fig.8a) and
t_{tot} is the total process time.
Fig.7 illustrates the evolution of the resist side wall shape and checks etch bias model. The model seems to be valid for processes with remaining 70 or more nm resist at the end of the process. When the modified resist edge is etched, additional term describing the resist height dependent change has to be included. Assuming processes with remaining >70nm resist, no additional correction is necessary and the model proposed can be used.
The minimum lateral EB can be estimated by integration of resist side wall slope and vertical etch rate product over process time for specific resist type and manufacturing process as described in equation [5]. This case is illustrated in Fig. 6a.

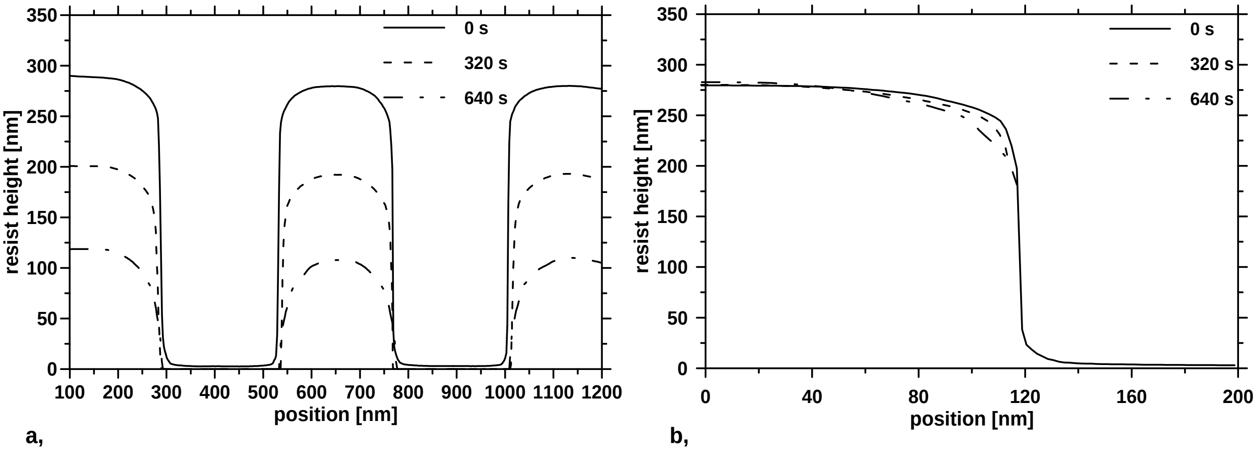

Fig.7 – evolution of the resist side wall. **a**, illustrates the resist side wall shape at beginning of the process, after 320s and 640s. **b**, provides precise comparison of the side wall. The upper approx. 70nm of the resist seems to be etched laterally faster then the remaining side wall.

Assuming non linear resist side wall, the value of $\frac{dCD}{dt}$ becomes non constant in time. For resist side wall angle of 88° with foot of 20 nm height and α=60° the value $\frac{dCD}{dt}$ changes as shown in Fig.8. The picture illustrates the $\frac{dCD}{dt}$ as function of resist side wall shape. The first term in equation [1] is the contribution of the side wall slope and vertical etch rate to the etch bias. Second part is the lateral etch rate contribution.

On that way we clarified the border conditions for EB:

- The etch bias cannot be equal 0, unless α=0 and ER_L=0, which is in our opinion not fulfilled for any process.
- The minimum etch bias for ER_L=0 is equal to:

$$EB = 2 \cdot \int_0^{t_{tot}} \left(\frac{ER_V(t)}{tg[\alpha(t)]} \right) dt \qquad [5]$$

Unless α=0 the etch bias is increased by the contribution of the side wall slope which is equal to the product of the vertical resist etch rate and the tg (α).

- In simplest case the etch bias depends linearly on total etch time and vertical resist etch rate.
- Any nonlinearity in the etch bias as function of time is caused by change of the side wall slope, except the endpoint time, at which an change in the slope can be expected due to change in the Cr coverage of the mask.

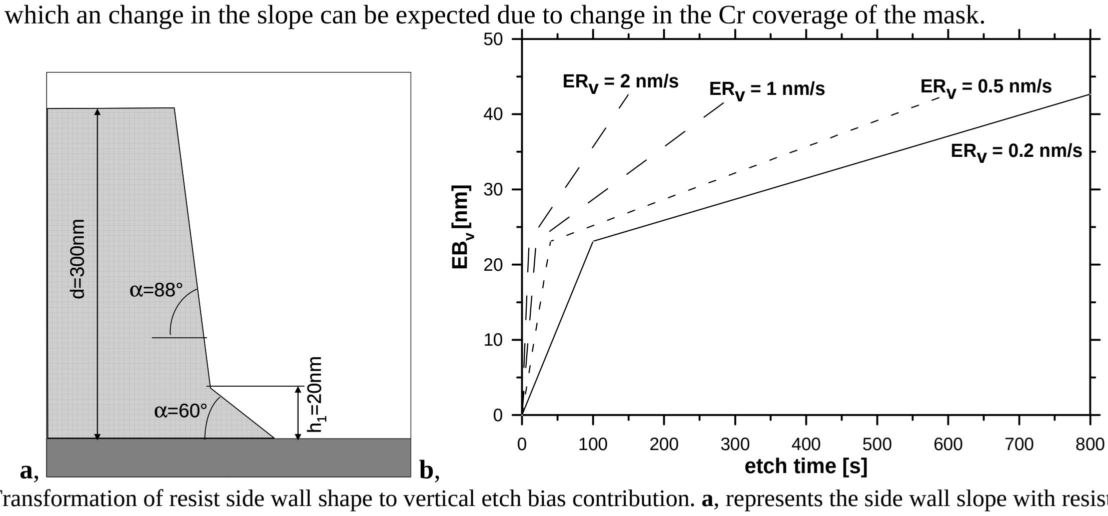

Fig.8 - Transformation of resist side wall shape to vertical etch bias contribution. **a**, represents the side wall slope with resist foot with height h_1=20 nm and slope α=60°. The slope of the remaining side wall is α=88°and resist thickness d=300nm. **b**, shows the vertical etch bias contribution EB_V according to equation [5] for vertical resist etch rate of 0.2, 0.5, 1 and 2 nm/s. The end of the line corresponds to the 300nm resist thickness.

Information about resist side wall shape as shown in Fig.7 allows us to estimate the lateral etch rate contribution to EB and split the total etch bias into lateral and vertical EB components according to equation [1]. For the data presented in Fig. 5 the result is shown in Fig.9. This figure shows that at the litho process used, the vertical EB contribution is small compared to lateral EB contribution. The main reason is the steep resist side wall.

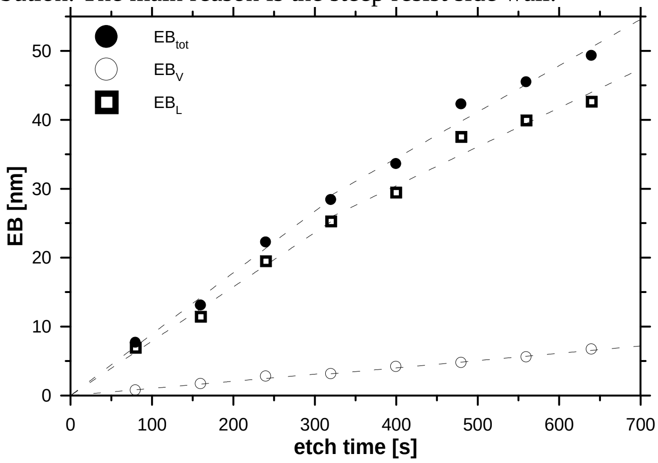

Fig.9 – EB analysis by mean of AFM. The total etch bias EB_{tot} was identified to contain lateral and vertical EB component as described in text. The vertical component EB_V is estimated as integral of resist side wall slope and vertical etch rate product process time. Difference between EB_{tot} and EB_V component is estimate for the lateral contribution EB_L.

CALIBRATION OF THE ETCH BIAS MODEL

Putting together the information about the vertical resist etch rate, side wall angle/shape and $\frac{dCD}{dt}$ from the measurement done on partly etched Cr layer, we estimate $\left(\frac{dCD}{dt}\right)_L = ER_L$ for our process. The value of $\left(\frac{dCD}{dt}\right)_L$ can be estimated also as the lowest $\left(\frac{dCD}{dt}\right)$ assuming 90° side wall angle at least at part of the side wall height. If the assumption of linear side wall shape is correct, the etch bias measured by mean of AFM as difference between Chrome CD and resist CD can be calibrated to the number obtained as $2 \cdot \frac{dCD}{dt} \cdot t_{tot}$, also the calibration to $2 \cdot \left(\frac{dCD}{dt}\right)_L \cdot t_{tot}$ is possible on that way. We leave the decision which of these values is the correct one open for public discussion. The decision depends on the approach of each experimenter, whether he makes the etch process accountable for the effect of resist side wall shape or not. There is good reason for both decisions: The side wall effect is dependent on the vertical resist etch rate – which is property of the etch process. On the other hand depends this effect on the side wall angle/shape of the resist, which has nothing to do with the etch process.

Fig.10 clarifies the difference between the AFM and CD SEM measurement. The picture **a** and **b** show the correlations between resist CD and Cr CD measurement respectively. **a** illustrates that the resist CD SEM measurement in resist correlates well with the AFM measurement for settings used, however, there is an offset caused by the CDSEM calibration as mentioned before. **b** indicates that the Cr CD measurements match very well and the results expected are comparable for methods used. **c** compares etch bias measured and proves, that the difference is caused by the resist CD measurement only.

Since the correlation is proved and the EB results estimated by suggested method are identical for both metrology tools as shown in Fig.5, the only difference is the correcting factor. The correcting factor is equal to the offset of linear fit over main etch as shown in Fig.5. For AFM measurement used the correction factor is +3.44 nm, for CD-SEM the correction factor is +54 nm. This fact explains why the EB measured common way by mean of CD-SEM exhibits significantly smaller numbers than the AFM measured.

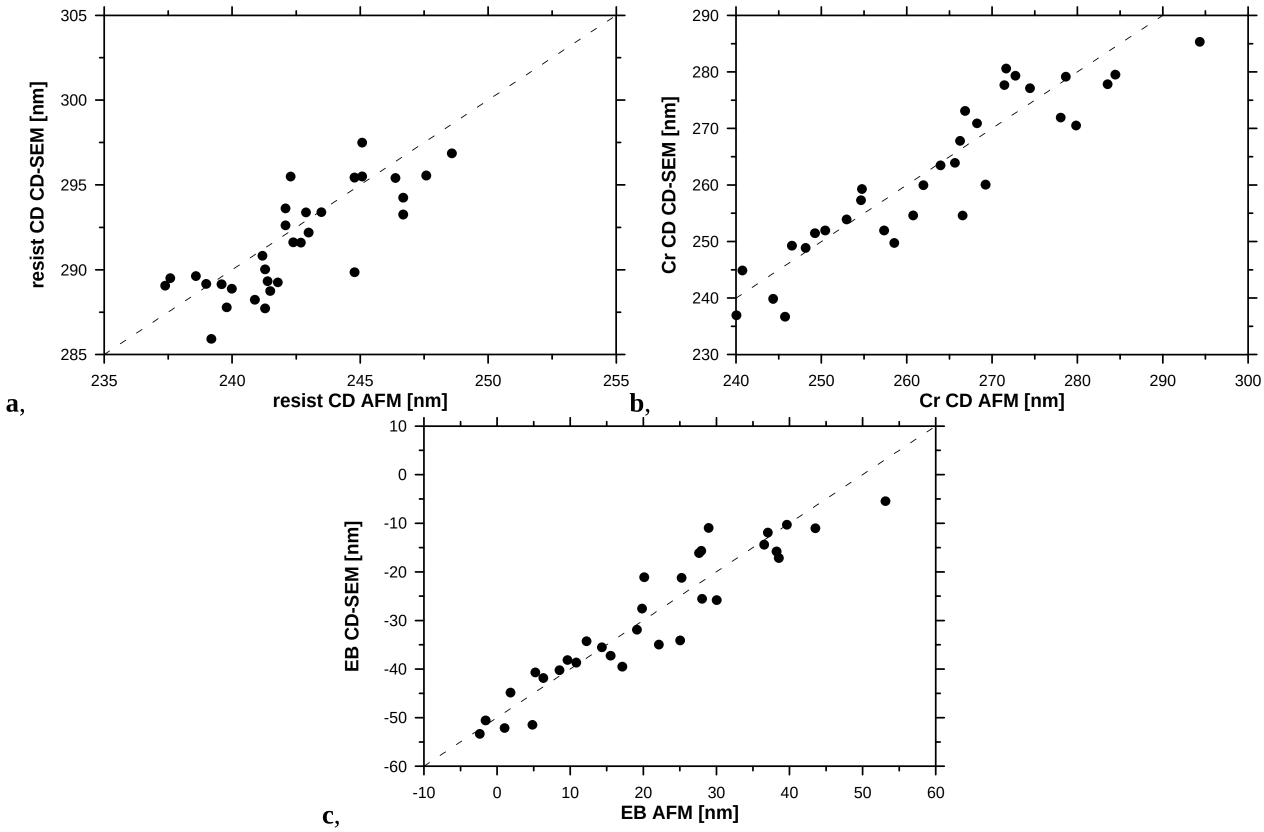

Fig.10 – CD and EB correlations between AFM and CD-SEM measurements. **a**, The resist CD correlation exhibits approx. 50nm difference between CD estimated by means AFM and CD SEM. **b**, Cr CD measurements correlate well with scattering of about ±5nm **c**, Correlation between the resulting etch biases shows offset of about 50nm.

ROLE OF SELECTIVITY

Selectivity *S* in following text is understood as vertical Cr to resist etch rate ratio. For Cr etch process with high bias power and so high resist consumption, $\left(\frac{dCD}{dt}\right)_V$ is a significant part of the total etch bias. The equation for side wall effect's contribution to the overall etch bias can be easily derived from Eq. [5], since the total etch time as well the vertical resist etch rate are related to the selectivity.

$$EB_v = 2 \cdot \left(\frac{ER_V(Cr)}{tg(\alpha) \cdot S} \right) \cdot EP \qquad [6]$$

So the contribution of the vertical resist etch rate is proportional to 1/S; Cr etch rate $ER_V(Cr)$ and the Endpoint time EP. The Cr thickness influences the EB, since the process time is given by the Cr etch rate $ER_V(Cr)$.

CONCLUSIONS

The investigations have shown, that the etch bias can be precisely estimated without the resist CD measurement. This fact improves the precision in case of AFM measurement and gives and idea of the true resist CD for CD SEM, since there are no resist CD standards available.

The model suggested is valid as long as the remaining resist thickness is higher that ca. 70 nm. The approach used allows us to confirm difference in the $\left(\frac{dCD}{dt}\right)$ term estimated for main etch and overetch steps. There are 2 root causes possible as already mentioned. With respect to the linearity of the lateral EB shown in Fig.9 we expect the etch rates differences to be the root cause of this effect. The frequency and precision of data taken, however, allows also the nonlinearity of the resist side wall as alternative interpretation. To draw more precise conclusion about linearity of the lateral etch rate due to varying resist side wall shape and/or etch rate variation is the goal of further investigations. The resistless etch bias estimation method was applied to 2 different etch processes using identical PG and Litho process. On that way the etch bias correction for CD SEM measurement and the “resist CD corresponding height” for AFM measurement were estimated.

REFERENCES

1. P. Nesladek, N. Falk, A. Wiswesser, R. Koch, B. Sass: *25th Annual BACUS Symposium on Photomask Technology*, Proc. SPIE Vol. 5992; pp. 190; (2005)
2. B. Wu, J. Chen, E. Markowitz, G. Xiao, S. Tam, A. Kumar, I. Ibrahim, W.-F. Yau: *25th Annual BACUS Symposium on Photomask Technology*; Proc. SPIE Vol. 5992; pp. 207; (2005)
3. J.D. Benson, A.J. Stoltz, P.R. Boyd, M. Martinka, J.B. Varesi, L.A. Almeida, K.A. Olver, A.W. Kaleczyc, S.M. Johnson, W.A. Radford, J.H. Dinan: *Journal of ELECTRONIC MATERIALS*; Vol. 32; No. 7; pp686; (2003)
4. B. Lee, S. Wang, T. Tian, S. Yang, R. Chen: *24th Annual BACUS Symposium on Photomask Technology*; Proc. SPIE Vol. 5567; pp. 1152; (2004)