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Metrology of Chrome on Quartz Photomasks using Low Voltage Scanning Electron Microscopy II: Optimized Machine Usage

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METROLOGY OF CHROME ON QUARTZ PHOTOMASKS USING LOW VOLTAGE SCANNING ELECTRON MICROSCOPY

II: OPTIMIZED MACHINE USAGE

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ABSTRACT

This is the second of two reports based on work done under the JESSI T8 Project. It describes how computerised SEM measurement facilities were optimised for chrome on quartz photomasks, and discusses SEM usage and stability. Optical and SEM measurements are compared and systematic differences explained.

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1. INTRODUCTION

This is the second of two RAL Reports describing work done under the JESSI T8 Project on SEM metrology of chrome-on-quartz photomasks. The main aims of this Project, and its collaborators, are described in a companion Report, RAL-95-011. In summary, the photomasks are really 5X reticles designed to give 0.35μm minimum linewidths on silicon after fivefold reduction in a wafer stepper. The need in the Metrology Subproject, therefore, was to measure chrome and quartz lines in the range 1-4μm with a precision of 0.050μm (3σ).

For metrology of Cr/quartz, two "Deliverables" were required : the first ("C1") covered SEM *physical* parameters, was issued in June 1992 and forms the bulk of RAL-95-011. The second Deliverable ("C2") covered optimised use of SEMs at RAL and IMEC, was issued in April 1994 and forms most of this publication. In addition, a discussion on all the work (in both reports) appears below.

To distinguish the original JESSI Deliverable from the rest of this Report, its pages are numbered C2-i, C2-ii etc. Tables are interspersed throughout the text and Figures are collected together at the end.

Actual work on SEM metrology started a little late, in October 1991 with a redefinition of the tasks in the low voltage SEM Subproject. At RAL some time was spend in improving the ambient conditions of the Hitachi S4000 SEM by elimination of electromagnetic interference and reduction of extraneous light.

2. DISCUSSION

2.1 SEM Conditions

The main SEM *physical* parameters were determined first. Use of SEM image analysis was studied only briefly for Deliverable "C1", but is dealt with in more detail here. For the Hitachi S4000 at RAL, effective use of the *measurement parameters* was hampered by their complexity and inadequate information from the SEM manufacturers. This publication explains how they are used - and how mis-use can lead to false indications of precision (eg 3σ values of zero).

Comparison of the two available profile analysis methods was particularly relevant in view of current world discussions in SEM metrology (cf Reilly, SPIE Vol 1673, p 48, 1992). In fact, we showed that, for Cr-quartz the 50% threshold method gives better agreement with optical measurements than the linear approximation ("LA") one, and this lead to further work where the value of 50% for the "isofocal threshold" was confirmed experimentally.[1]

Work at IMEC on *resist metrology* showed that the LA method handled the various secondary electron profiles better, and is recommended for process control but an appropriate standard is needed before such measurements can be assessed for absolute accuracy.

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[1] Bracher & Jonckheere, "Profile analysis and the isofocal threshold in SEM Metrology", MNE '94 Conference, Davos, Switzerland 1994

2.2 Stability

One essential part of metrology is to show that the measuring machine is stable over a suitably long period. Allied to this is the fact that operators are human and, when setting up an SEM for measurement, can easily overlook one of the many machine variables. This is particularly true of RAL's general-purpose S4000 SEM, compared to the S6100 at IMEC which is dedicated to metrology and run on a production-line basis.

For both S4000 and S6100, operator set up procedures were defined in writing and attention paid to operator training. At RAL, daily measurements of a chrome line were taken for three weeks. The results - well within the precision required by the Project - demonstrated the importance of good machine maintenance and, especially, rigorous operational procedures.

A written SEM setting-up procedure is recommended for any project where regular measurements are needed.

2.3 Contamination

RAL's S4000 SEM has an oil diffusion pump and some oil vapour tends to "back stream", leading to carbon contamination in exposed parts of the specimen. The machine has a "foreline trap" which should be filled with liquid nitrogen but this is a slow and tiresome practice : most users prefer to minimise contamination in other ways - eg by allowing adequate pump-down periods and minimising beam exposure times at high magnification.

Good practice required that the effects of contamination be quantified and this is described below in "C2" Section 3.4. Even extreme contamination showed only a surprisingly small change in linewidth as the predominant signal changed from backscattered material contrast to secondary emission caused by sample topology (ie the edges of the chrome lines).

This experiment demonstrated the greater consistency of the "linear approximation" method compared with the threshold one. This is due to differences in implementation, and could be removed if the threshold method, for example, also included a straight line fit to the SE profile edges.

2.4 Instrument Correlation

It is obvious that different linewidth measurement instruments should give similar results when measuring the same sample, and for that reason various Standards Laboratories (eg the National Physical Laboratory) provide accurately measured photomasks for instrument calibration. Such a standard was bought for the T8 Project. Its chrome and quartz lines were used to check the (optical) OSI video linewidth measuring system, while its 4μm pitch grating was used to check a grating written at IMEC and used as a "secondary standard" for SEM calibration.

Optical measurement of a photomask provided by Compugraphics International revealed systematic differences between the T8 Standard and the one used by CMF Division's Production Group. Both were re-checked by NPL and the T8 one recalibrated. The resulting measurement changes (9nm for chrome and 29nm for quartz lines) were acceptable for optical work but represented values of almost 1σ and 3σ for typical SEM measurements. This error was never explained, although the T8 standard had been remeasured several times at NPL before sale.

In deliverable C1, very good correlation between optical and SEM measurements was reported. Later work - especially using other substrates and resists in various projects (eg MoSi/quartz, Cr/quartz using dry-etched PMMA) showed that systematic errors between the two methods could emerge.

Quite often these errors were statistically significant and close inspection showed that they were due largely to non-vertical chrome wall angles. (Such inspection was a severe test of both SEM and operator). The problems of measuring these angles are discussed below in C2 Section 4.2, while Section 4.3 gives a simple correction to SEM measurements. Identification of such errors is vital as it can be a first clue to problems in lithographic processing - especially during process development.

3. ACKNOWLEDGEMENTS

Thanks are due to the JESSI organisation for approving the T8 Project, to Compugraphics International for organising it and to the various member governments (UK, Belgium and Germany) for funding it. At RAL, the assistance and ideas of Conrad Langton (Sheffield Hallam University) was greatly appreciated.

Sub-Project Name : Mask and Reticle Technology Development
Project Number : T8
Programme : 3 - Low Voltage SEM Inspection and Metrology
Project Leader : R Jonckheere, IMEC vzw
Participants : IMEC, RAL

DELIVERABLE C2 April 1994

OPTIMIZED LV SEM METROLOGY OF CHROME ON QUARTZ

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1. INTRODUCTION

This report completes the work done under Task "C", to provide optimized parameters for low voltage SEM metrology of chrome on quartz photomasks. A previous report (Deliverable C1: June 1992), defined the physical SEM parameters for photomask metrology, showing good correlation between SEM measurements and those from an OSI Optical System calibrated with an NPL Standard.

This second report describes how optimised use of the SEMs and their measurement software was achieved, and gives details of long-term SEM stability. The correlation between optical and SEM methods is considered and one reason for systematic differences explored.

2. SEM CONDITIONS

Optimising the use of a low voltage SEM for metrology requires the setting of a large number of parameters, and these must be determined in a logical way (eg. there is little point in optimising image analysis on a charged sample).

The strategy was to fix accelerating voltage, working distance and beam size to give the highest kV for charge free operation and maximum contrast between the chrome and quartz. This process - together with general information on the Hitachi S4000 and S6100 SEM's - was described in Deliverable C1. The most important parameter values (for Cr/quartz linewidths around 1.5 µm) are shown in Table 1.

To measure a linewidth the SEM saves the image in a framestore and the user chooses (a) how blocks of scan lines should be summed to give measurable line profiles (S4000) or block size (S6100), and (b) the profile analysis method.

MACHINE	S4000	S6100
Magnification	20 K	20 K
Acc volts	0.8 kV	0.8 kV
Tilt	0 deg	-
WD	5 mm	fixed
Objective aperture	30 µm	-
Scan speed	10 secs	-
Integrated no of TV scans	-	64

Table 1. Optimum SEM conditions for LV metrology.

2.1 S4000 Measurement Conditions

Four parameters control how an imaged line is split into blocks for analysis, as shown in Fig 1. These are:

Summing.Line :	block length
Meas.Pitch :	distance between scan lines within block
Meas.Point :	number of blocks
Mult.Pitch :	pitch of blocks

The only sensible value for "Meas.Pitch" is unity, but some care is needed with other parameters. Originally we used 25 blocks of 32 scan lines at a pitch of 8 - as suggested by other users - but realised that this caused block overlap. It could also lead to meaningless 3σ values since most of the scan lines were "counted" several times in averaging.

It was evident that the maximum block size (summing line = 64) gave the smoothest line profiles, both from observation and from computer simulation in Deliverable C1. Parameters were therefore changed to give the largest blocksize with minimal block overlap:

Summing.Line :	64
Meas.Pitch :	1
Meas.Point :	4
Mult.Pitch :	63 (max value)

An experiment with deliberately interleaved scan lines is described in Section 2.4 below, but the above values were used for all further metrology in the Project.

2.2 Line Profile Analysis Method

Both Hitachi SEMs offer two methods for computing linewidths from stored images - "threshold" and "linear approximation". They use different methods of line edge detection as explained in Fig 2. Each requires a parameter from the user - either the % threshold value or, for the "LA" method, a differentiation factor whose value depends (vaguely) on the smoothness of the profile.

For the same SE profile the "LA" method will, in general, give higher linewidths than the 50% threshold one and initial work on Cr/quartz suggested that the latter agreed better with optical measurement.

To confirm this, three chrome lines of width 1.5, 2.0 and 2.5 µm were measured for a range of SEM beam diameters using both techniques, and the results plotted as shown in Fig 3. For all three linewidths it was evident that:

(a) LA linewidths were about 50 nm higher than the corresponding 50% threshold ones;

(b) LA linewidths increased more with beam diameter;

(c) the 50% threshold method agreed best with OSI results.

From the intercept values between the "OSI" and "50% threshold" lines it seemed that the best agreement would be obtained with a "Cond.Lens" setting (beam width) of 12, and so this became the standard value for uncoated Cr/Qz metrology.

2.3 Optimum Threshold Value

Up to this point the only reasons for choosing a value of 50% for the threshold were our own experimental evidence and some Monte Carlo studies by Nunn [1]. These implied that, for backscattered profiles, the 50% threshold value was "isofocal", ie. minimally affected by small errors in SEM focusing. Automatic focusing on the S4000 never achieved the same quality as manual adjustment, but this depends on the skill of the operator, and such effects must be minimised. (With fairly small beam sizes, the S4000 images are predominantly from backscattered electrons, though largely through tertiary interactions.)

To determine the "isofocal threshold" the same line is measured over the 20% - 50% range of threshold values, with different fine focus settings, the same stored image being remeasured in between focus adjustments. Linewidths for each focus setting are then plotted against threshold values.

This should give a set of straight lines intersecting at a single point with the "in-focus" line having the lowest gradient, as its line profile has the steepest sides. As shown in Fig 4a, statistical variations cause complete confusion. If these are removed by plotting fitted straight lines (Fig 4b) then an area of "minimal confusion" is evident. If, for each threshold value, the vertical distance between the maximum and minimum values is now plotted, then a simple curve (Fig 4c) is generated and the minimum value of this should be the isofocal threshold.

In practice, the results were analysed in a VAX computer using a short FORTRAN program. Values of the minimum (cf Fig 4c) were determined by numerical differentiation using Newton-Gregory interpolation [2]. The results of the experiment, using 6 chrome lines, are given in Table 2, and the mean % value, 51.6 ± 4.8, agrees with Nunn's theoretical prediction of 50%.

Linewidth µ	Run	Min % value
1.4	1	50.2
1.4	2	56.0
1.5	1	43.5
1.5	2	49.7
1.6	1	55.8
1.6	3	54.5

Table 2. Isofocal threshold results: mean % value is 52 ± 5

2.4 Interleaved Blocks and "3σ"

As mentioned above, four parameters control how the image of a measurable line can be divided into blocks of scan lines. The SEM software reports the values of the mean, minimum and maximum linewidth together with a "3σ" value.

The 3σ values arise from variations in both noise and linewidth. A study of the measurement conditions suggested that interleaving the scan lines should be possible. If so, it would give 3σ values which depended purely on noise, and from the equation

$$\sigma_{(total)}{}^{2} = \sigma_{(line)}{}^{2} + \sigma_{(noise)}{}^{2}$$

we could derive noise-free values of $\sigma_{(line)}$.

To do this we kept

Meas.Pitch = Summing.Line

and set Mult.Pitch to 1. We then measured a line using 4 different sets of conditions. These are shown below in columns B-E of Table 3, compared with the "standard" set in column A.

Conditions	A	B	C	D	E
Meas.Point	4	4	8	16	32
Mult.Pitch	63	1	1	1	1
Summing.Line	64	64	32	16	8
Meas.Pitch	1	4	8	16	32

Table 3. S4000 measurement conditions (cf. Fig 5)

The resulting SEM images are shown in Fig 5, where the distance between the two horizontal dashed lines should remain constant (256 scan lines or 2.2 µm). It seems that the SEM software is overlapping the blocks rather than interleaving them, and the measured distance between the dashed lines can only be explained if the SEM software resets "Meas.Pitch" to 1. Note that one measurement gives a zero 3σ value. The "expected" and "actual" summations are illustrated in Fig 6.

This experiment highlights two facts about the S4000 measurement software:

(a) it does not work as suggested by Hitachi
(b) overlapped blocks give artificially low - or meaningless - 3σ values.

2.5 Measurement Conditions Summary

The work described above led to several conclusions which were not obvious at the start of this Project. For that reason, they are summarised below:

(a) Linewidth measurements should use the highest possible value of "Summing .Line" to minimise the "random noise" part of 3σ.

(b) Avoid overlapping of measurement blocks: set

Meas.Pitch ≥ Summing.Line

otherwise 3σ values may be meaningless.

(c) Do not set "% threshold" so that the measured SEM linewidth agrees with that from optical methods. This can introduce errors from focusing, which have a surprisingly large effect on measured linewidths.

(d) Calibrate SEMs using pitch measurements on the central lines of a grid of 5 or more lines and spaces. Repeated checks using a calibrated OSI have shown that such grids - written by an E-beam Microfabricator - are quite satisfactory providing the outer lines (which may suffer from proximity effects) are ignored.

A traceable standard would be better for calibration but possible contamination precluded the use of the NPL Standard Photomask in the S4000 SEM.

3. SEM PERFORMANCE

Consistent measurements from an SEM which is used for metrology depend on several factors, including rigorous machine maintenance. For a general purpose SEM such as RAL's S4000, operator errors must be minimised by operator training and using a well defined measurement procedure. A written check list was very helpful, especially for the long-term stability study reported below.

3.1 S4000 Operator Set-up Sequence

The basic items in an operator set-up sequence, for a general purpose SEM, are outlined below. In practice, at RAL, a more detailed list was used while a much simpler procedure is needed for IMEC's dedicated metrology S6100 (cf. Section 3.2).

(a) Initial checks

Objective aperture
Stage lock
Air lock(s)
Image adjustments (off, = 0) eg. raster rotation, tilt correction

(b) If kV > 0.8 then insert conductive sample for initial tuning:

Set W.D. and find feature
Set kV and beam size: align beam and focus

(c) Insert sample

Set W.D. via menu
Focus (adjust Z)
Rotate sample if necessary **
Check calibration and measurement parameters
Lock stage
Final focus (including stigmators)
Freeze image
Measure

(d) Reset machine; remove sample

** *If an in-chamber SE detector is used, lines to be measured should point at this. Raster rotation may lead to incorrect measurements.*

3.2 S6100 Operator Set-up Sequence

The S6100 is used in a "production-line" environment which minimises the amount of setting-up compared with the S4000.

Reset tip current to 2 μA
Optimize beam alignment on calibration grid (on wafer chuck)
Focus and stigmation wobbling

Replace wafer holder by mask holder, load mask
Set system to "MASK" (switches chuck-in-position check off)
Find pattern at small magnification using continuous scanning
Tune scan rotation if required (range of 5 degrees)
Fine tune focus at double the magnification used for metrology
Position measurement site at low magnification
Freeze image
Increase desired magnification for measurement (line to be measured should cover about one third of the CRT)
Store integrated image of 64 TV scans
Measure

3.3 Long Term SEM Stability

The stability of the S4000 was checked by measuring the same chrome and quartz lines on an IMEC sample, every working day for 3 weeks. Measurements were done in the middle of the day, and when necessary the SEM was switched on an hour or more in advance to let the source settle down. Each day 3 successive measurements were recorded and plotted as shown in Fig 7. The required σ was ± 17 nm (to give a 50 nm 3σ precision) and, out of 45 measurements, only 3 were outside the "mean ± 17 nm" limits.

The *long term RMS* 3σ values were:

Chrome line	31 nm
Quartz line	27 nm

ie. well within the bounds required by the Project.

As a comparison, 15 successive measurements were made on each line to assess short term stability, and the resulting *short term RMS* 3σ values were

Chrome line	39 nm
Quartz line	31 nm

ie. broadly agreeing with the long term values above.

3.4 Contamination

One minor problem encountered with RAL's S4000 is carbon contamination. This was evident on the sample used for long-term stability tests and care was taken to use different areas for focusing and measurement. Analysis of the results showed no perceptible change in linewidth, but the effects of severe contamination were of interest. To that end, the S4000 was allowed to image a single area of a clean sample, in slow scan mode, for over 15 minutes, broken only by linewidth measurements every minute.

The experiment was repeated to compare both "50% Threshold" and "Linear Approximation" methods, as shown in Fig 8. Both show a slight (but statistically insignificant) increase in linewidth for extremely heavy carbon contamination. The final few measurements relied more on secondary emission from edge slopes than chrome- quartz contrast.

The graphs show how the "LA" method gives more consistent results than the "Threshold" one - but this is a consequence of its implementation, which relies on 4 least squares fits per measurement. (Similar techniques could be applied to the Threshold method to improve its consistency).

The conclusion from this experiment was that even deliberately severe contamination - far more than would occur in practice - did not have a disastrous effect on linewidth measurement for Cr/quartz samples. This deliberate contamination far exceeded anything seen on other samples during the entire 3 year project.

4. OPTICAL-SEM CORRELATION

4.1 NPL Standard Recalibration

Optical line width measurements at RAL used an OSI system, as described in Deliverable C1. This is calibrated with an NPL Standard Photomask owned by the CMF Production Group. A second NPL standard, bought especially for the T8 Project, was found to give systematic linewidth errors on the OSI. Conversion equations in microns for the 1 - 6 μm range were:

Cr : (T8) = 1.004* (OSI) + 0.032
Qz : (T8) = 1.002* (OSI) - 0.060

The systematic error for quartz prompted NPL to recalibrate the T8 standard and this led to:

Cr : (T8) = 1.004* (OSI) + 0.023
Qz : (T8) = 1.002* (OSI) - 0.031

ie. changes of 9 nm and 29 nm in linewidths.

A separate check used sets of linewidths on a photomask supplied by Compugraphics International, and results of these measurements are shown in Table 4. The overall RMS linewidth difference is only 0.015 μm, ie. ¼ of the original systematic error observed.

This eradication of systematic errors between calibration standards, together with work on a 0.2 μm Photomask Standard [3], showed one possible cause of systematic error in photomask metrology - ie variations in wall angle of the absorbing layer, for which high-resolution high-kV SEM imaging was needed.

Nominal Microns	Chrome Lines		Quartz Lines	
	Comps	RAL	Comps	RAL
0.9	0.81	0.80	1.01	1.02
1.0	0.91	0.89	1.10	1.11
1.2	1.09	1.08	1.30	1.31
1.4	1.28	1.26	1.52	1.51
1.6	1.49	1.48	1.73	1.71
1.8	1.69	1.68	1.93	1.92
1.0	0.91	0.91	1.10	1.12
2.0	1.88	1.88	2.15	2.13
3.0	2.86	2.86	3.12	3.11
4.0	3.89	3.90	4.11	4.12
5.0	4.87	4.90	5.14	5.12
6.0	5.87	5.89	6.17	6.16

Table 4. Compugraphics and RAL OSI measurements compared

4.2 Physical Profile

A previous ESPRIT Project [4] suggested a way of correlating SE line profiles with the physical profile of the measured line by cleaving the sample and examining the edge in an SEM. However, no actual results were published and our own investigations have shown this to be extremely difficult for the following reasons.

(a) Cleaving quartz is very difficult and leaves nanoscopic debris along or near the edges to be examined. Even vigorous brushing does not remove this.

(b) High magnifications (50K - 90K) are needed - implying carefully coated samples and SEM voltages of 20 - 30 kV. For good results stringent control of ambient conditions is needed - ie. mechanical, sonic and electromagnetic vibrations.

(c) We found that the best technique is to cut a trench using a focused ion beam and examine this at 80 degrees tilt. A sample supplied by NPL is shown in Fig 9, compared with the end of a chrome line that has not been milled.

(d) The worst problems are those of resolution and edge roughness. Chrome lines are 85 - 105 nm thick and the SEM has a probable resolution of 20 nm, with similar sized variations in edge roughness. Wall angle measurements could therefore, be accurate to only, say, 10 - 14 degrees.

The most promising technique is Atomic Force Microscopy, especially as superfine tips with square ends are now being developed. Use of an AFM with a tilted 20 degree tip, for wall angle measurement, was demonstrated in the recent BCR Project [3].

Attempts to image physical profiles in the SEM have, however, led to a way of estimating wall angles and thus correcting one source of systematic error between optical and SEM measurements.

4.3 Correction for Chrome Wall Angle

The first Cr/Qz samples, made using CMS(EX)R resist on antireflective chrome, were slightly undercut in profile. This accounted for the good agreement between optical and SEM measurements.

Other methods of preparation - eg dry etching with PMMA resist - could lead to sloping wall angles as shown in the FIB milled samples of Fig 10, resulting in systematic differences between optical and SEM linewidths (Fig 11). Such errors have been investigated by Nunn and Turner [5] who have since suggested a simpler correction based on the thickness T of the chrome and the wall angle α, by adding

$$T / \tan(\alpha)$$

to the SEM measured chrome linewidths (and subtracting from quartz lines). The improved agreement in Fig 11 demonstrates this "wall angle correction" in practice.

4.4 Correlation of Nanoline with S6100

At IMEC, the intention was to transfer the metrology optimized on the S6100 SEM to an optical system, mainly because the accessibility of the S6100 precludes its availability as a standard metrology tool for the internal mask facility. An existing tool, the Nanometrics Nanoline, was investigated for this purpose.

A test mask was used as supplied by Philips Hamburg (Dupont today) as part of a linewidth correlation exercise within Esprit JEEPS. It was found there that reasonable correlation was met with both Philips and Compugraphics optical (OSI) measurements and the threshold based S6100 measurements at IMEC.

Both chrome and quartz lines were measured in the range 0.4 to 10 µm. The Nanoline system set-up includes autofocus and manual fine focus, crosshair alignment, edge detection using threshold 35% (transmitted light) and a 1000X magnification. On the Hitachi S6100, the parameters described in deliverable C1 were used.

After plotting the Nanoline results as a function of the S6100 measurements (cf. Fig 1) a linear part of the curve was selected. In practice this was in the range 1 - 5 µm. A straight line was fitted using least squares and was used to calibrate the Nanoline. During the JEEPS correlation exercise it was noticed that the SEM image is not calibrated for magnifications below 20 kX. For this reason linewidths larger than 5 µm were not taken into account. Good correlation has been found for linewidths smaller than 1 µm, notably for 0.4 µm chrome and 0.7 µm quartz lines respectively, as detailed in Fig 12.

The above measurements were performed over a period of about 2 months. Including the linewidth uniformity on the test mask, a long term repeatability of around 20 nm 3σ was found for the S6100, and 30-40 nm 3σ for the Nanoline metrology tool, as detailed in Table 5. For quartz lines the reproducibility of the measurements seems to be inferior to that of chrome lines, but this is thought to be due to the poorer definition of the quartz lines on the mask. Note the improved repeatability for chrome lines with decreasing linewidth, which is due to the increased magnification (25 kX was used for 5 µm, increasing up to 100 kX for 0.4 µm). This trend is not noticed with the Nanoline, as a constant magnification of 1000X is used.

Nominal (μm)	S6100		Nanoline	
	Cr (nm)	Qz (nm)	Cr (nm)	Qz (nm)
5.0	10	9	9	11
4.0	9	7	15	18
3.0	7	7	8	11
2.0	5	7	10	11
1.5	7	7	14	10
1.4	5	9	14	11
1.3	8	8	14	21
1.2	6	6	14	16
1.1	8	12	12	9
1.0	6	10	15	11
0.9	6	11	12	14
0.8	5	10	11	14
0.7	5	16	9	12
0.6	5	11	11	9
0.5	5	16	7	9
0.4	3	-	16	-

Table 5. Repeatability of mask measurements at IMEC
using LVSEM (S6100) and Optical (Nanoline) methods.
Results are 1σ values in nm.

5. REFERENCES

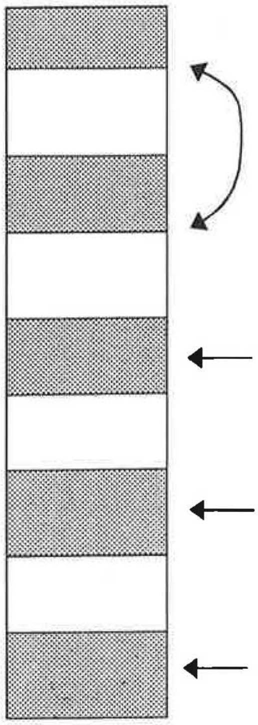
[1] Nunn J W, "Comparison between the experimental & theoretical modeling of linewidth measurements on photomasks and their insensitivity to accelerating voltage in the scanning electron microscope", Scanning, Vol 12, pp 257-263 (1990)

[2] Butler R & Kerr E, "An Introduction to Numerical Methods" (Longman, London 1966) p 219

[3] BCR Contract MT176 - "Development of a Photomask Linewidth Standard", Phase 1, February 1992 - February 1994

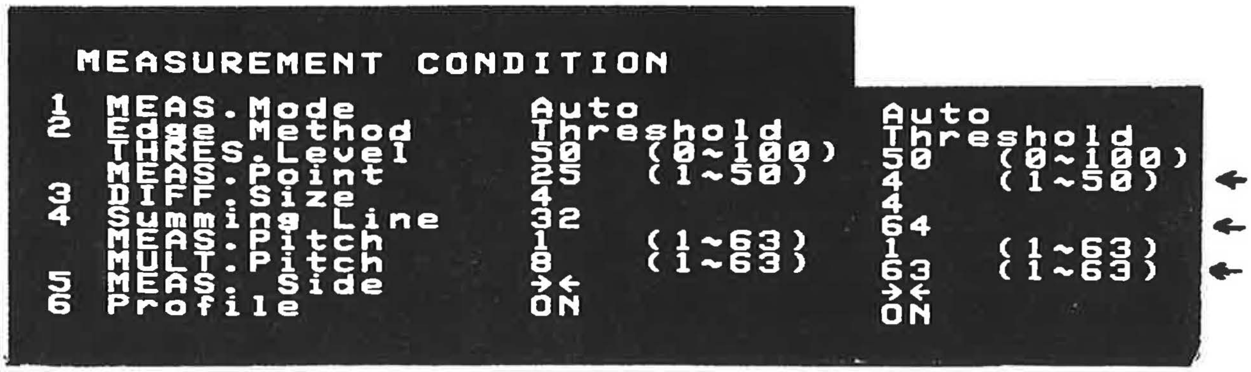
[4] Buysse P, "The initial establishment of SEM for chrome mask inspection", ESPRIT Project 1043, Task 7.1 (IMEC, Leuven 1987)

[5] Nunn J W & Turner N P, "The use of a novel image-shearing technique on a scanning electron microscope for comparative measurement of linewidths on photomasks", Scanning, Vol 11, pp 213-217 (1989)



Takes average of *'MEAS.POINT'* measurements, at a pitch of *'MULT.PITCH'* scan lines

Each measurement = sum of *'SUMMING.LINE'* scan lines .... at a pitch of *'MEAS.PITCH'* scan lines



```
  MEASUREMENT  CONDITION
1  MEAS.Mode            Auto                   Auto
2  Edge Method          Threshold              Threshold
   THRES.Level          50    (0~100)          50    (0~100)
   MEAS.Point           25    (1~50)           4     (1~50)     ←
3  DIFF.Size            4                      4
4  Summing Line         32                     64               ←
   MEAS.Pitch           1     (1~63)           1     (1~63)
   MULT.Pitch           8     (1~63)           63    (1~63)     ←
5  MEAS. Side           →←                     →←
6  Profile              ON                     ON
```

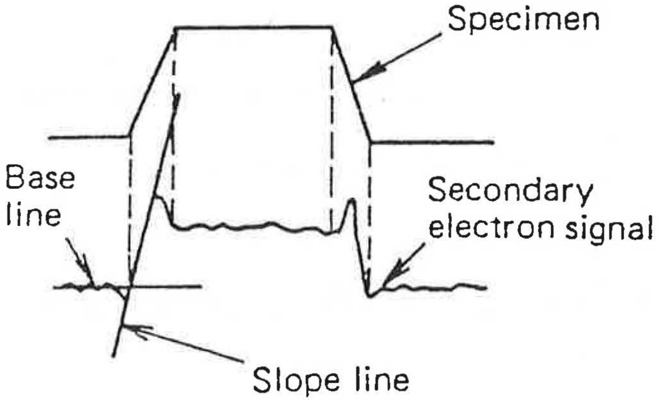
INITIAL *(LEFT)* & FINAL *(RIGHT)* CONDITIONS

Fig 1. S4000 measurement conditions including screen displays

S4000 PROFILE ANALYSIS

Linear approximation

Straight line fits to base & slope
Width = distance between base/slope intercepts



Threshold

Choose height between max & min signal levels
Width = distance between threshold/signal intercepts

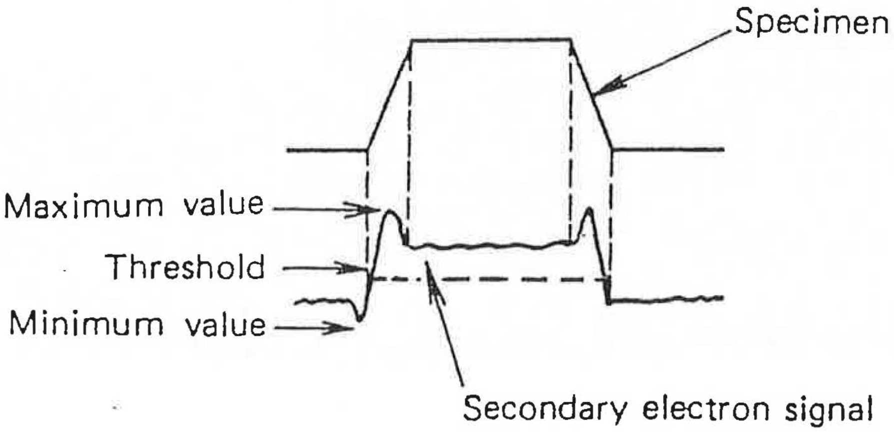


Fig 2. Linear approximation & threshold profile analysis methods

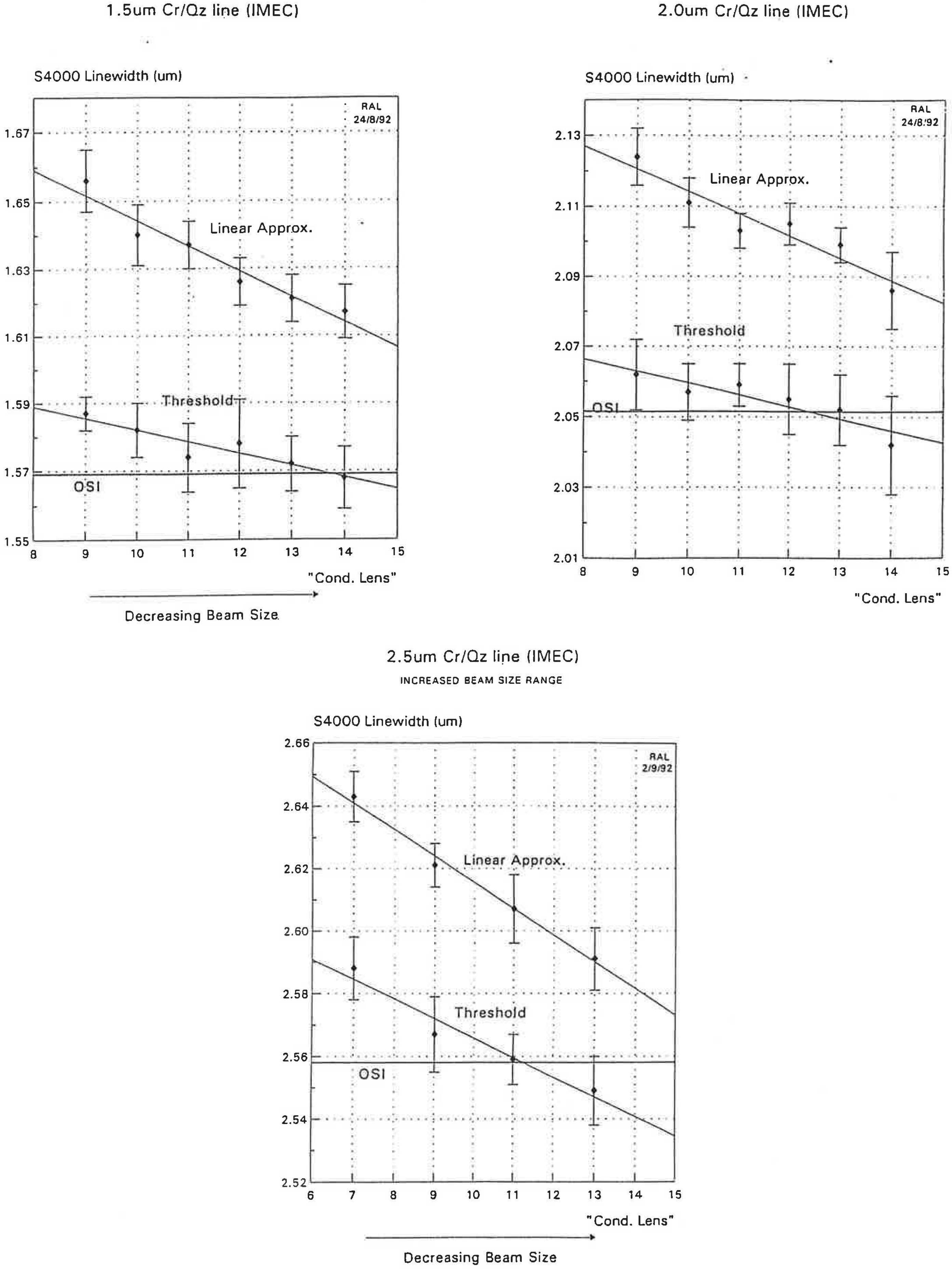
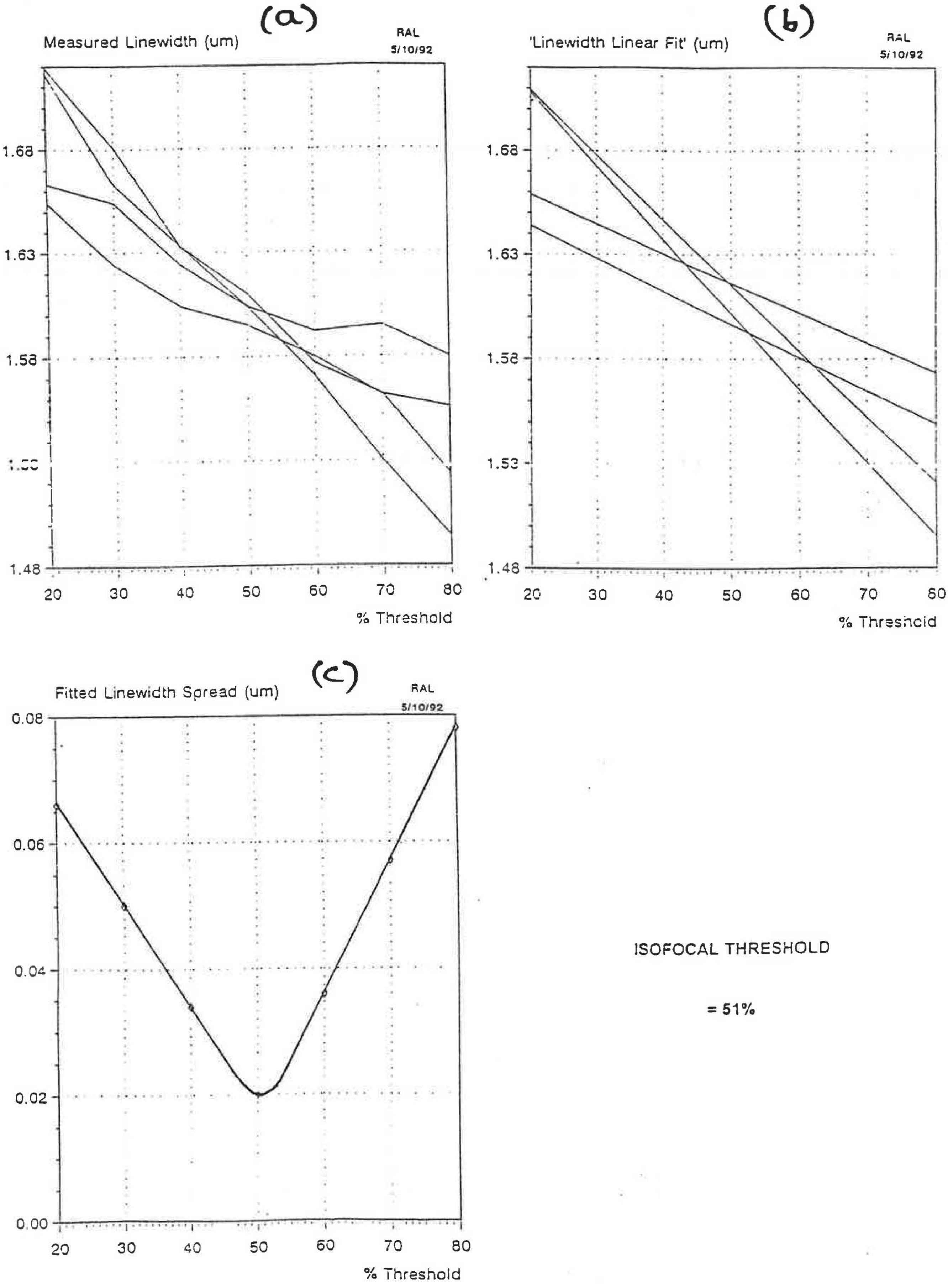


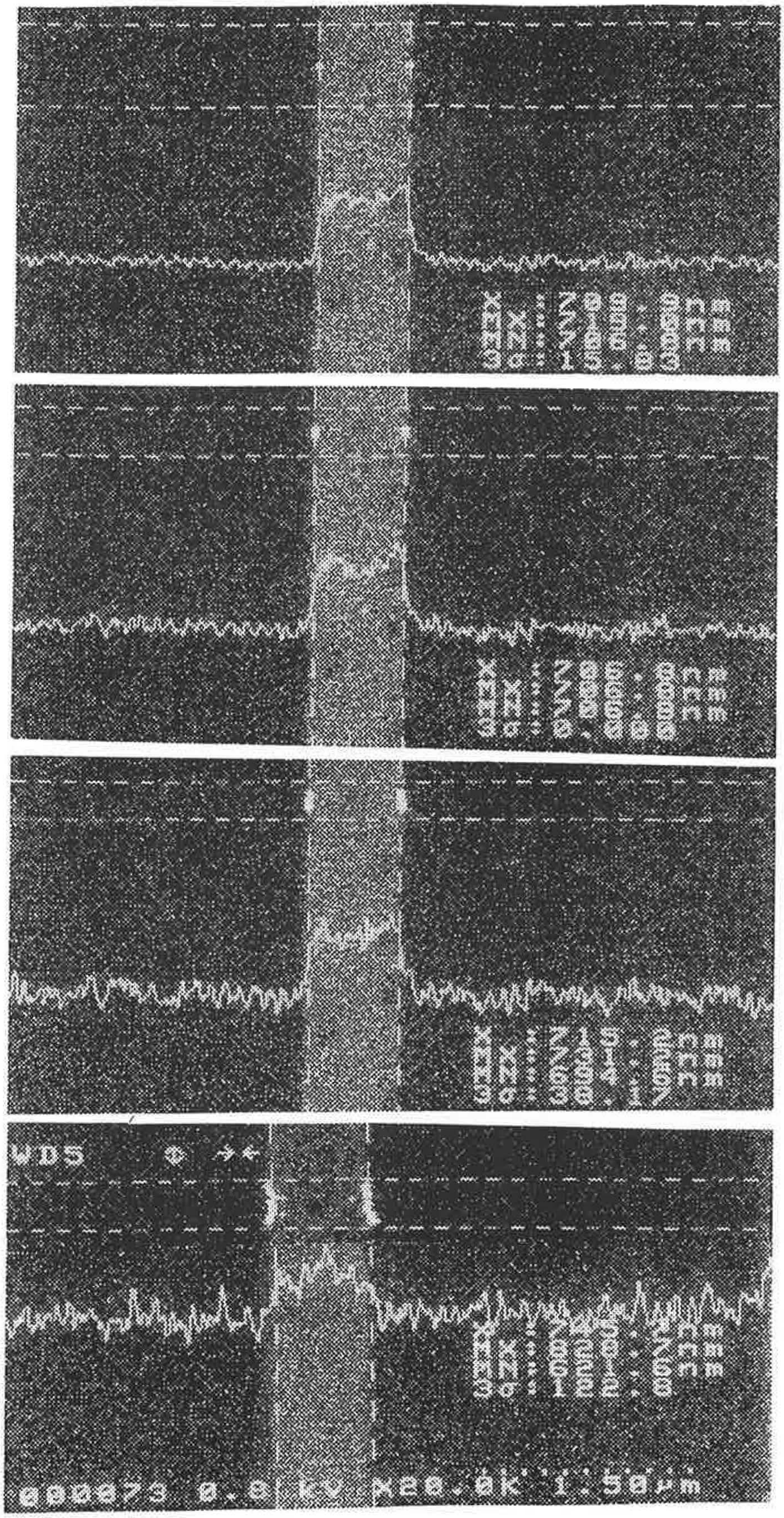
Fig 3. Comparison of profile analysis methods on S4000



ISOFOCAL THRESHOLD

= 51%

Fig 4. Example of isofocal threshold determination for 1.5 μm Cr line



4 X 64
LINES

PITCH 4

8 X 32
LINES

PITCH 8

16 X 16
LINES

PITCH 16

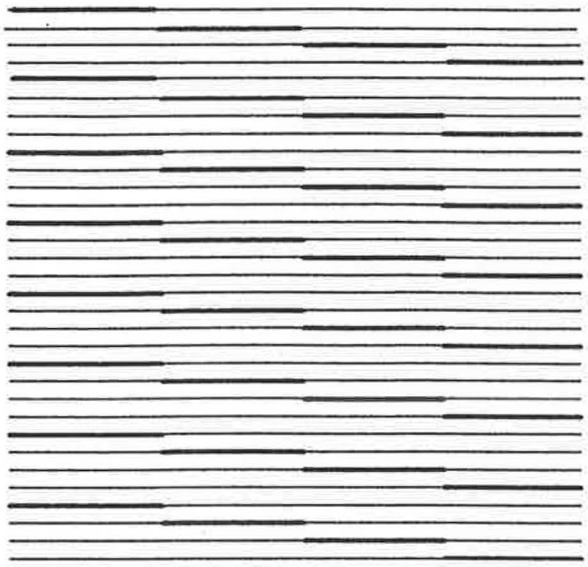
32 X 8
LINES

PITCH 32

Fig 5. Attempts to interleave S4000 measurement blocks

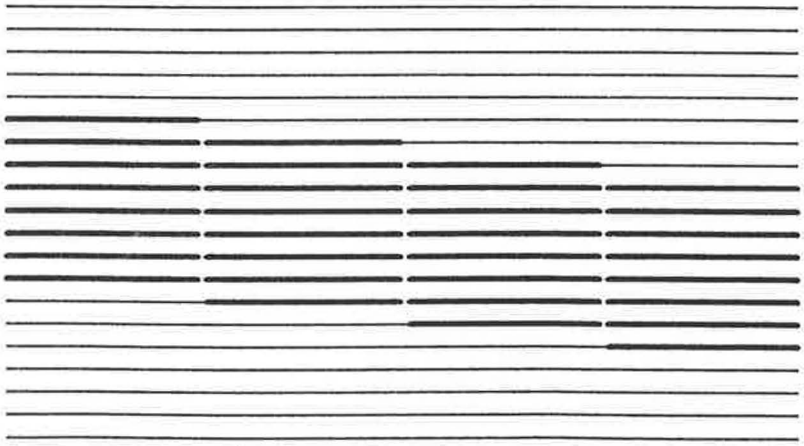
INTERLEAVED SCAN LINE SUMMATION

(B) INTERLEAVED USE - SIGMA GIVES NOISE ONLY



4 BLOCKS OF 8
SCAN LINES AT
PITCH 4

EXPECTED SUMMATION - NO OVERLAP
EACH SCAN LINE USED ONCE ONLY



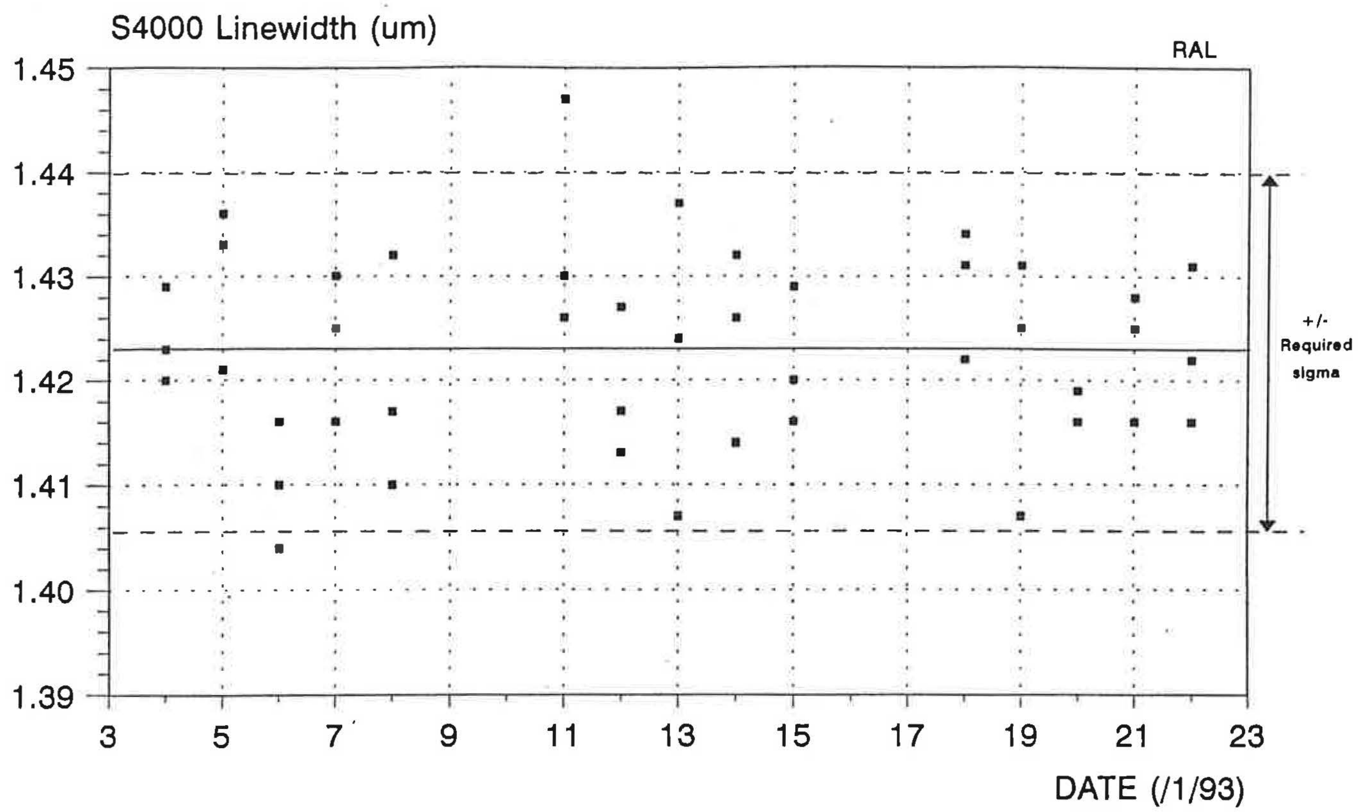
CENTRAL SET OF
SCAN LINES USED
IN EACH BLOCK

ACTUAL SUMMATION - BLOCKS OVERLAP
EACH SCAN LINE SHOULD BE USED ONCE ONLY

PITCH BETWEEN LINES RESET BY SEM SOFTWARE

Fig 6. Expected and actual measurement block "interleaving"

1.5um Qz line (IMEC)



1.5um Cr line (IMEC)

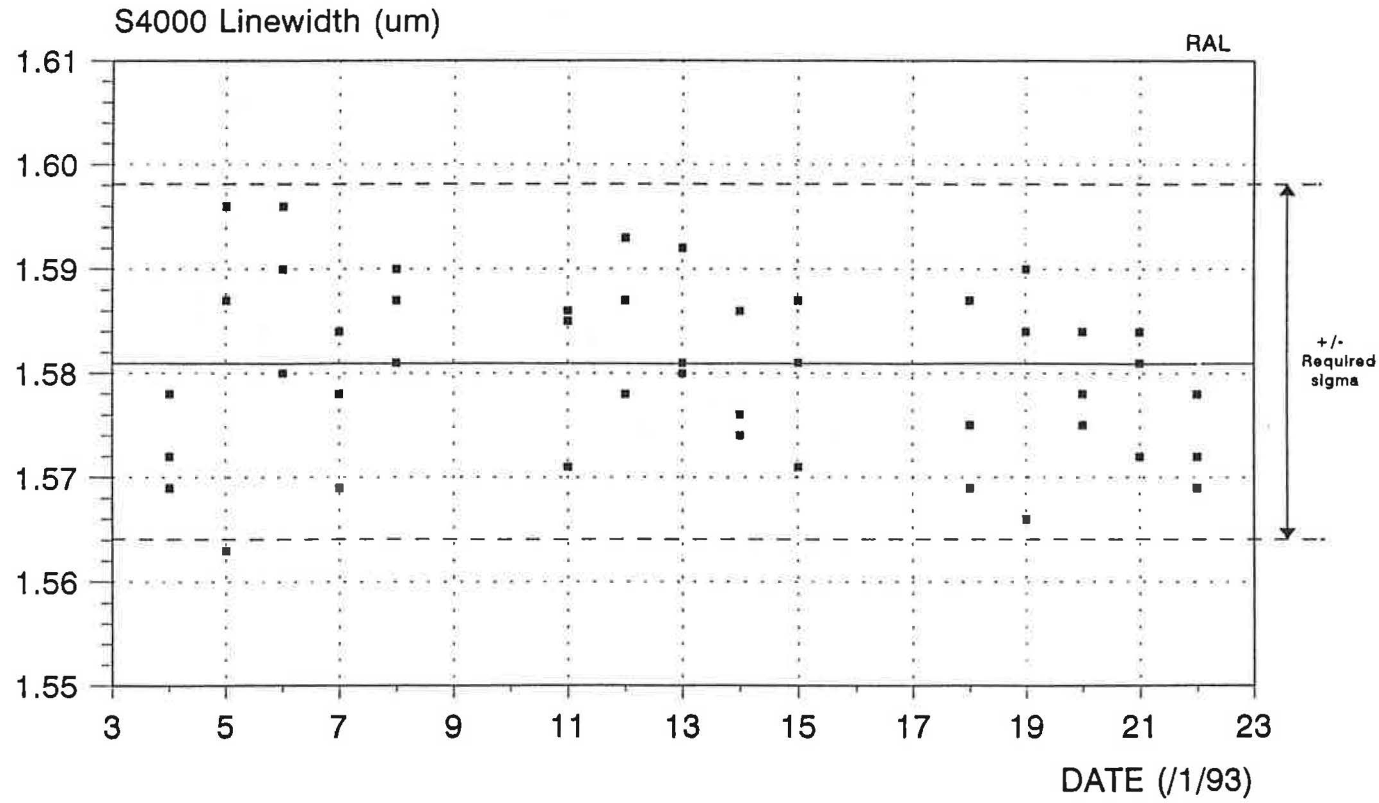
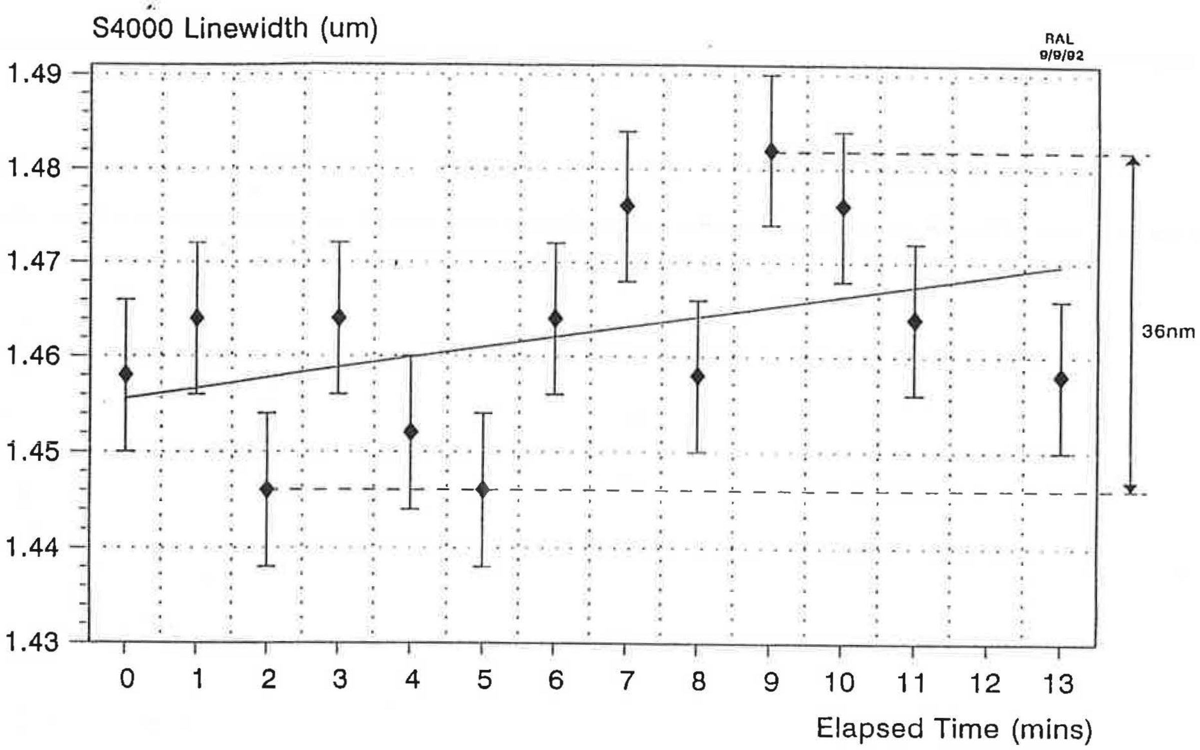


Fig 7. S4000 long term repeatability

EFFECTS OF CONTAMINATION ON 50% THRESHOLD METHOD
1.4um Cr/Qz line (IMEC)



EFFECTS OF CONTAMINATION ON LINEAR APPROX. METHOD
1.6um Cr/Qz line (IMEC)

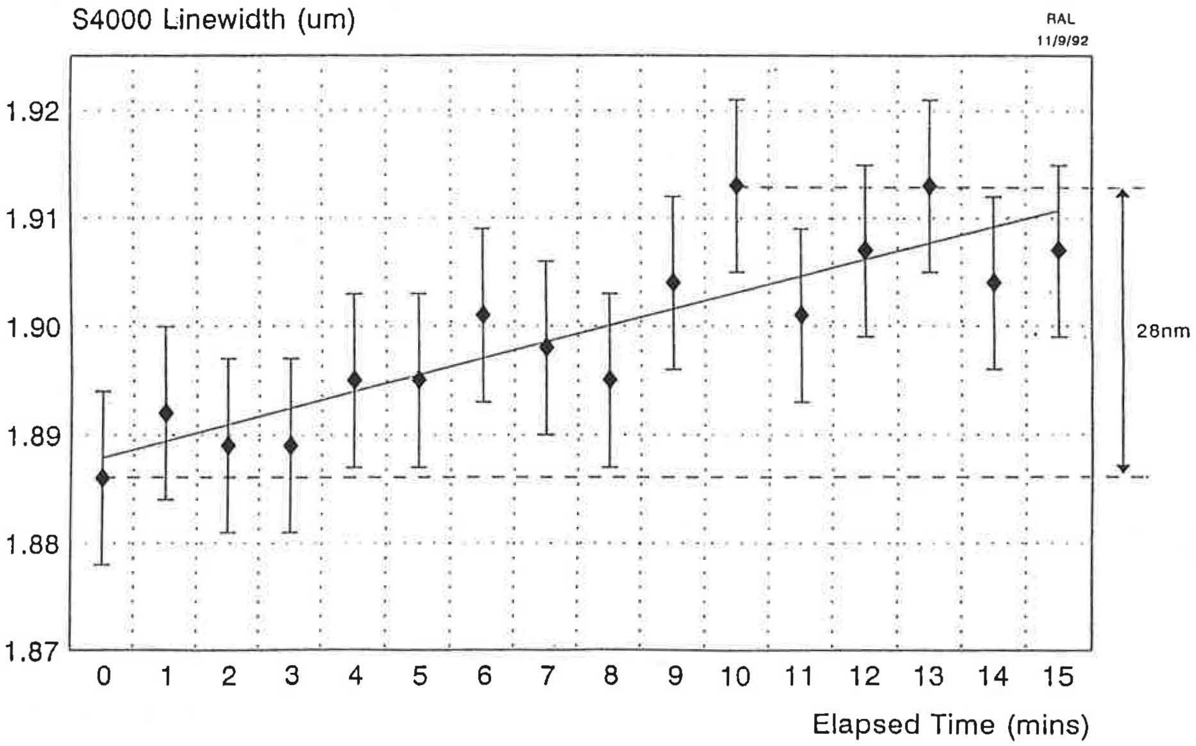
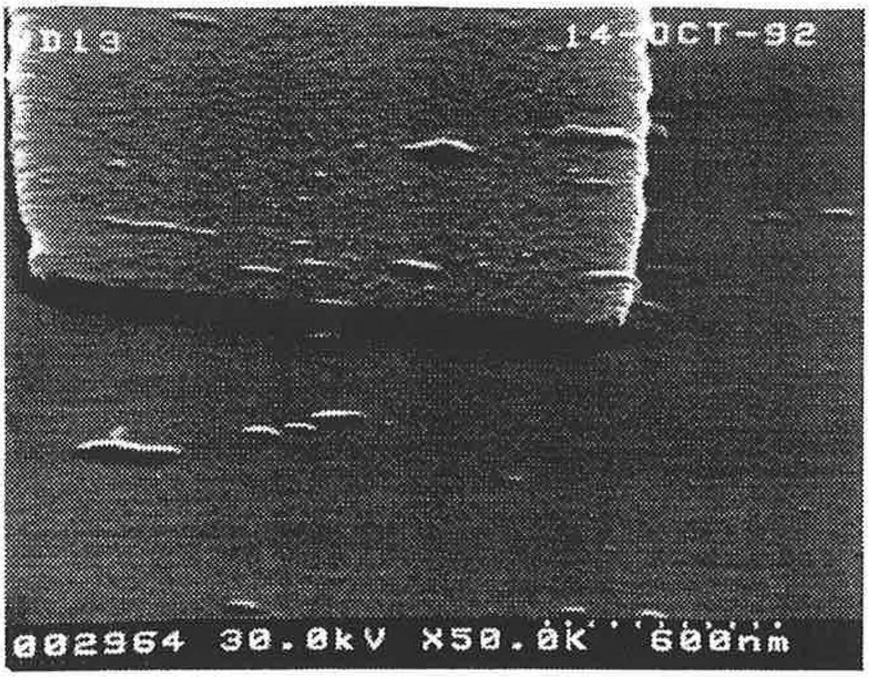
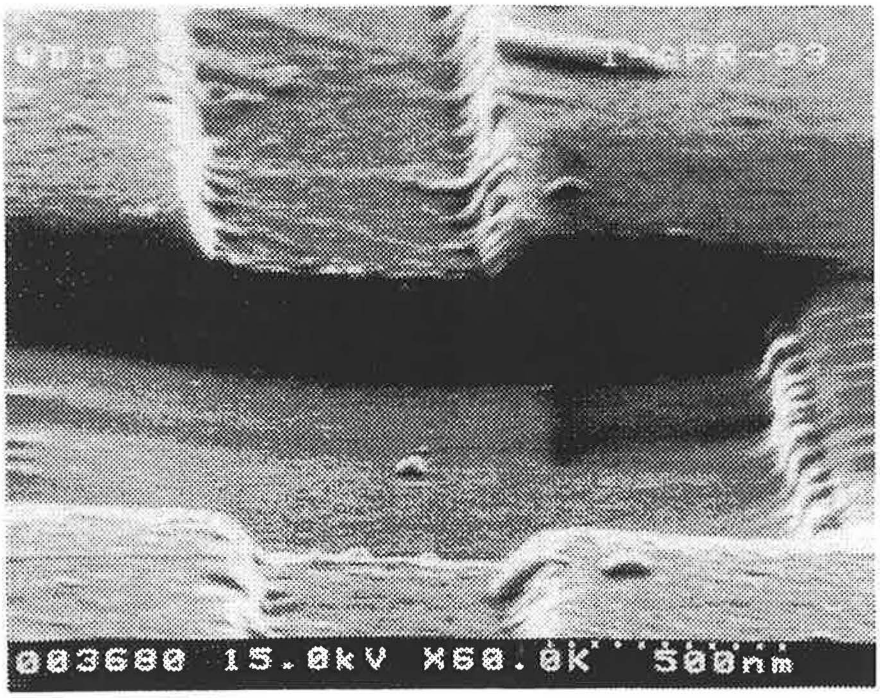


Fig 8. Effects of deliberate contamination on S4000 linewidths

GOLD COATED SAMPLES (80 deg TILT)

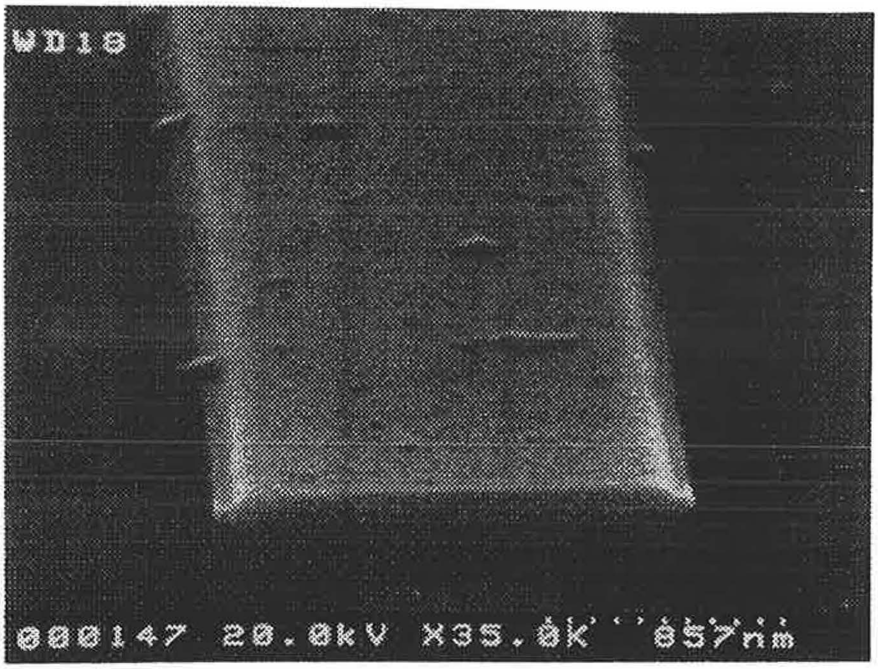


End View of IMEC Chrome Line

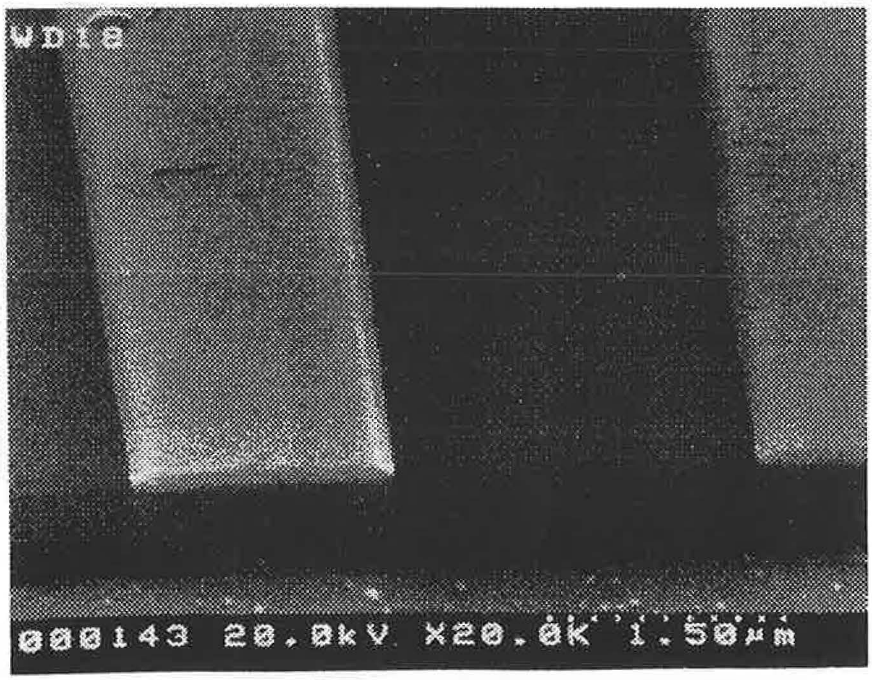


FIB-etched Sample Supplied by NPL

Fig 9. Physical profile imaging in S4000



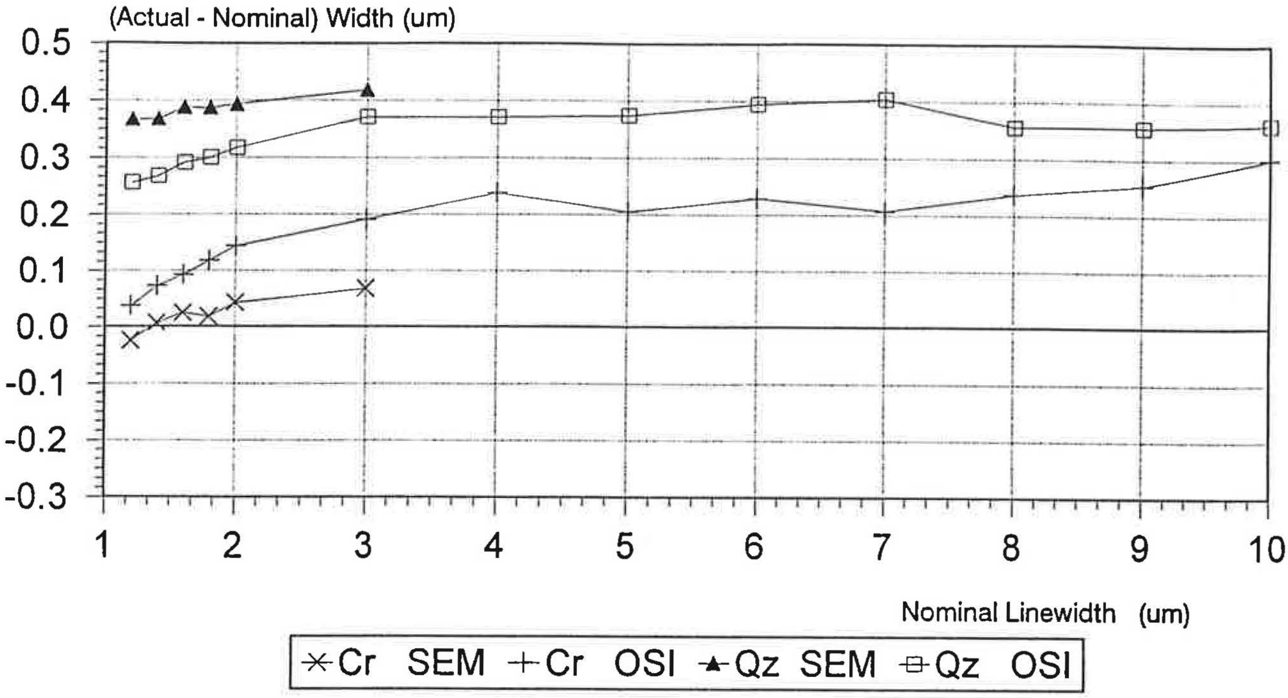
FIB-etched Chrome Line



FIB-etched Chrome & Quartz Lines

Fig 10. Wall angles on FIB-etched Hoya AS2 Cr/Qz masks

Cr and Qz Lines   No Correction



Cr and Qz Lines   45° Wall Angle Corrections

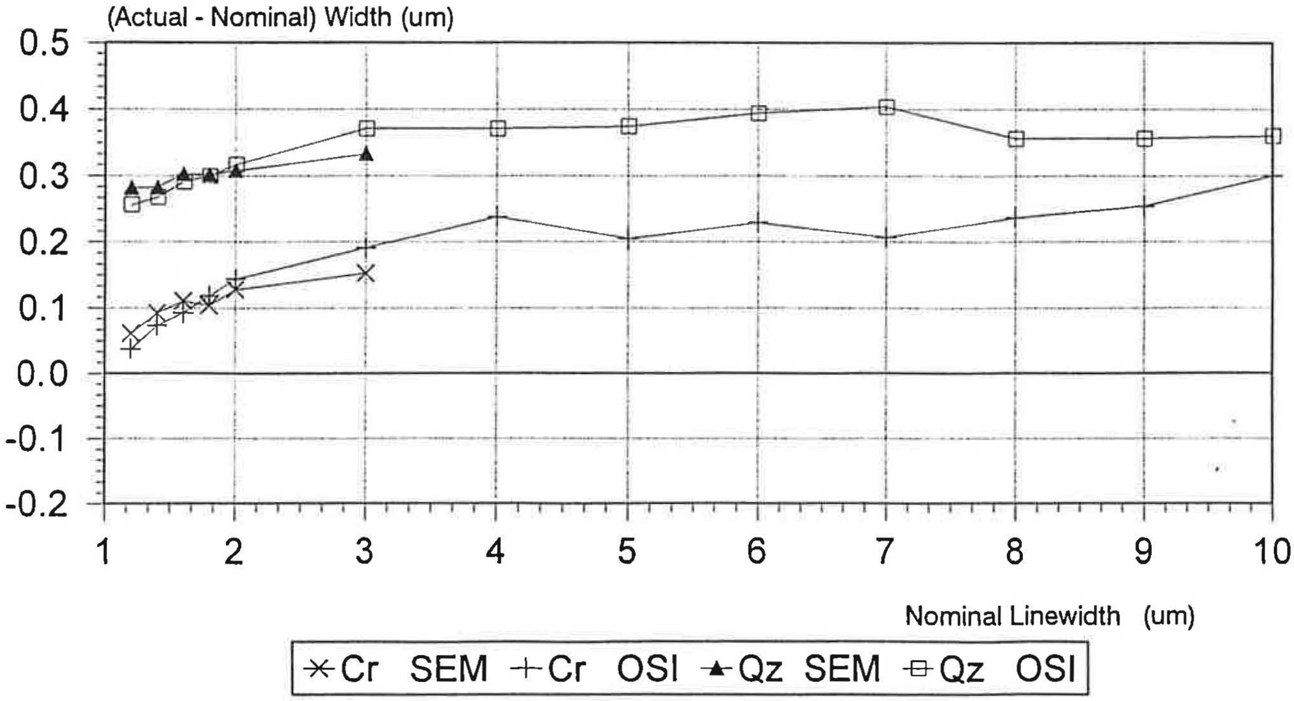
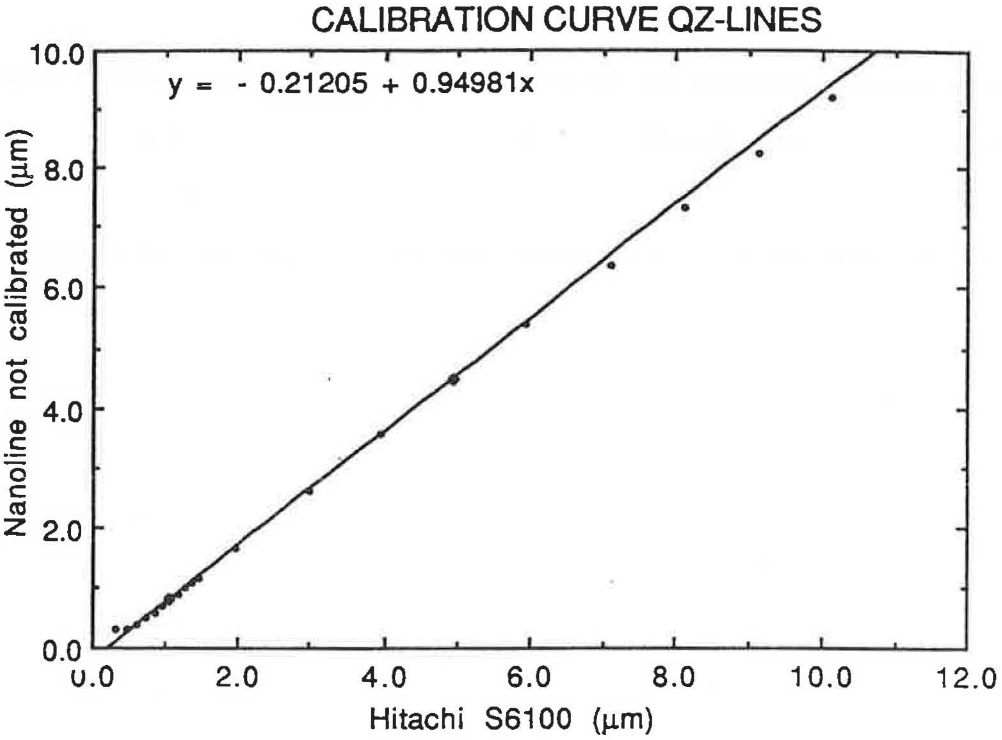


Fig 11. Effects of wall angle correction on SEM measurements



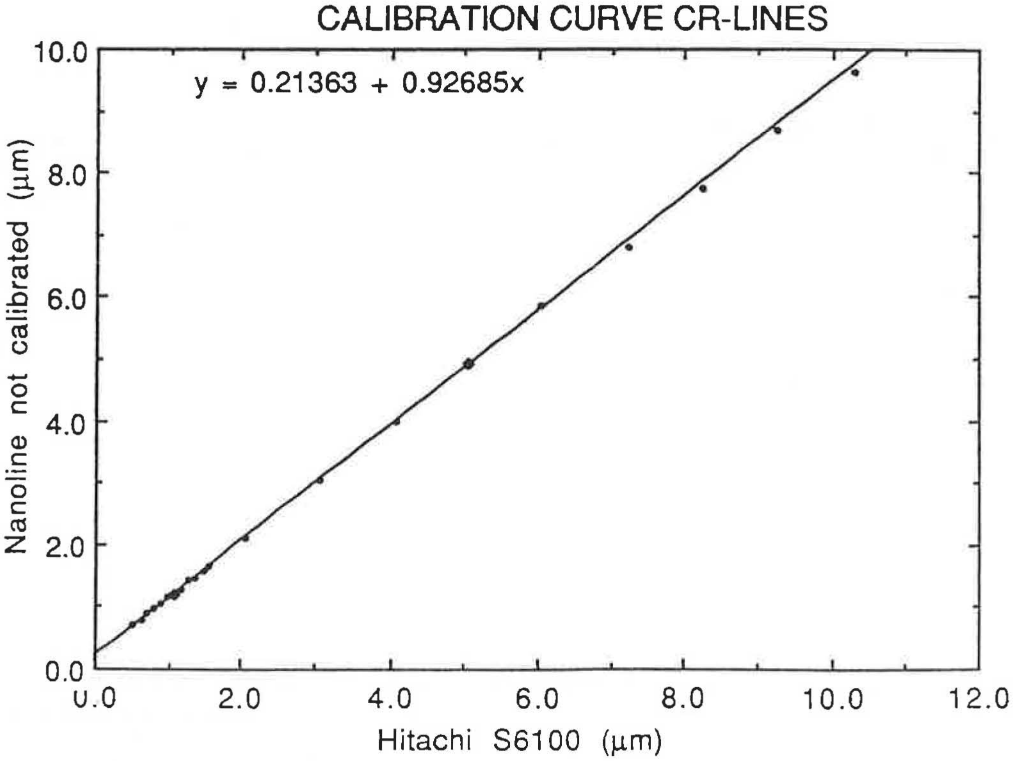


Fig 12. Calibration curves relating Nanometrics Nanoline to S6100 at IMEC. Bold spots show linear part used in calibration.