Review Of CD Measurement And Scatterometry

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Abstract. Scanning Electronic Microscopes (SEM) are widely used either for cross-section measurement (process development) or for top-down CD measurement (production). ITRS roadmap for CD and overlay metrology points out some difficult challenges for next technology nodes. Up to now, we remained confident respectively in SEM capability and in bright field microscopy for next node requirements. Today, the limit of 0.1 micron is crossed and new requirements are stated for new 300 mm fabs. Demands arise for tighter precision, complex profile metrology and fully non-destructive control for in-line and integrated tools. Scatterometry is an alternative solution for CD and overlay metrology, recently introduced in fabs. We propose to review the capability of scatterometry actually demonstrated in fab and potential extensions targeting 65nm technology node. The use of optical CD tools in a production environment has also been assessed for various applications. Finally, an overview of capability extension will be given.

INTRODUCTION

Process control in lithography and etch area needs mainly length measurements: Critical Dimension (CD) and overlay (OVL). Process development relies also on line cross-section information. ITRS requirements for metrology points out some difficult challenges for next technology nodes. Specifications for CD and overlay are especially challenging for development of 65 nm technology. CD metrology precision at gate level is 0.5 nm (3\sigma), or even tighter for the lithography CD budget. The requirement for overlay metrology precision is 2.3 nm (3\sigma) and overlay is actually red-flagged in ITRS roadmap.

Actual panel of metrology techniques is not restricted to usual Scanning Electron Microscopes (SEM) for CD and bright field optical microscope for OVL. Scatterometry has been proven by most suppliers to be a capable solution for 90 and 65 nm node. Other techniques are candidates for CD metrology: CD-AFM or electronic holography. But among alternative solutions to CD-SEM, scatterometry is now considered as a preferred solution for the industry.

METROLOGY AND PROCESS CONTROL

Needs for process control

In order to enable advanced modules tests and qualifications, early development of fabrication processes is needed. For that purpose, lithography and etch tools are operated at their performance limits. Metrology tools have to show aggressive performances, so as to allow robust process control. This is important for a reliable process development. Strong effort for enhanced metrology goes along with advanced patterning effort.

Scanning Electronic Microscopes (SEM) are widely used in microelectronics industry, either for cross-section measurement or for top-down CD measurement. Up to now, the industry remains confident in SEM capability. But today, R&D teams pattern lines with width down to 50 nm or sometime even smaller. E-beam metrology is closer to its limit...
than ever. We will see below that CD measurement 
dispersion is no more acceptable for technology 
development. Some material interaction issues have 
also been faced with 193 nm resist patterns. On top of 
that, demands arise for more complex geometrical 
metrology and fully non-destructive control for in-line 
and integrated tools (especially in the frame of a plant 
for 300 mm wafers production). CD-SEM 
manufacturers are working hard to propose enhanced 
capabilities, for example imaging using a tilted column 
for profile or 3D view reconstruction and low voltage 
operation.

Production equipments are proposed with 
Automatic Process Control (APC) loops. Etch and 
lithography can take advantages of a metrology 
module that can provide information to select/tune a 
recipe or to check for process failures. APC and 
integrated metrology can save cycle-time and should 
globally lead to cost reductions. Scatterometry is today 
the only CD-metrology solution suitable for metrology 
integration. Scatterometry tools show high throughput 
and performances are compatible with lithography 
requirements. Footprint and total volume of modules 
are small enough to allow integration in any kinds of 
equipments. Integrating CD-SEM in litho or etch 
equipments seems to be unrealistic today.

**Context of optical CD metrology**

Optical solutions are now considered to 
complement the standard CD-SEM metrology. 
Scatterometry stand-alone tools are available on the 
market since a few years, but 2002 appears as the year 
when scatterometry has been introduced in fabs. The 
use of scatterometers for CD measurement has been 
proven for IC manufacturing on several sites.

Scatterometry technique allows also the 
measurement of a complete line profile. This technique 
is able to provide the same kind of information as a 
cross-section SEM. One single measurement can also 
provide height of the line (or depth of the trench) and 
sidewall angle. This case is covered by a basic 
trapezoid modeling of the line cross-section. With a 
more complex model for the profile, we can add 
several geometrical parameters. Such a model can 
provide information on very tiny structures as top 
corner rounding of STI or notch of gates. 
Scatterometry tool is utilizable for more than CD 
measurement: it is a multi-parameter tool.

On top of profiling capability, some suppliers have 
shown feasibility of scatterometry-based overlay. 
Suppliers propose today an upgrade of standard bright 
field microscopy, with enhanced targets and enhanced 
software. This solution should fulfill 90 nm technology 
node requirements, but here again a new concept 
should be proposed for 65 nm node. This tool has to be 
compliant with metrology performance requirements 
and with integration in lithography equipment.

But scatterometry is not able to provide any images 
of the measured target. It is actually impossible to 
analyze an image to get information on 3D patterns 
(epecially on holes) and also on defects or process 
failures. Holes measurement capacity is in the roadmap 
of several suppliers and we can guess that this will 
appear on the market in a reasonable time frame.

**HARDWARE AND SOFTWARE FOR 
SCATTEROMETRY TOOLS**

**Hardware and software**

The scatterometry technique is based on optical 
hardware, which are validated and already used in 
fabs. These tools are basically spectroscopic 
ellipsometers, polarized or non-polarized 
reflectometers. Depending on hardware techniques, the 
tool is designed for stand-alone, for integration or for 
both. In the demonstration presented hereafter, 
spectroscopic ellipsometry is implemented in stand-
alone tools; reflectometry is implemented in integrated 
module only or in integrated module and equivalent 
stand-alone tools. A lot of suppliers propose this kind 
of optical tools for film thickness measurements. So it 
seems that development of hardware was not 
necessary in a first step. Suppliers skilled in optical 
tools can easily adapt their hardware for CD 
capability. One supplier has proposed a dedicated tool 
with an angle-varied method with a fixed wavelength 
(symmetrical goniometry). Incidence angle variations 
provide similar effects as wavelength variations. We 
will focus here on usual spectroscopic tools and no 
goniometric results will be reported.

The development effort is mainly put on the 
software: scatterometry needs a powerful analysis of 
the optical signals in order to extract geometrical 
characteristics on the patterned wafer. A much more 
complicated software tool than for film thickness 
extraction analyzes the recorded spectra. One cannot 
find a solution to inverse the famous problem of light 
scattering; so direct simulation tools have to be used. 
The most famous method actually widely used by 
scatterometry suppliers is Rigorous Coupled Wave
Analysis (RCWA). But even today, this requires a huge computer power. Recent advances in computer performance and in numerical methods allow simulation of the light scattering phenomenon. But for realistic stacks, computation remains very time-consuming. Two solutions are available to solve this problem: library pre-computation and scan, and direct regression with error minimization.

In the library approach, each line profile that could potentially be obtained through the technology process on the wafer is simulated. The associated optical signals are stored in a library. The library can be optimized so as to be scanned with a full set of parameters, as efficiently as possible. In any configuration, the duration of the analysis should be roughly the same. The optimization reduces convergence errors and enhances the accuracy of the measurement. From our experience, a specialist will spend three days to obtain an efficient library for a basic application.

As an alternative to library approach, real-time extraction of the parameters is also available. The computer starts with a first set of parameters. Loop after loop, it tries to minimize the error signal and to converge to one best solution. Suppliers claim the solution is unique. In that case, there is no need for a long computation time. But the time needed for data acquisition and analysis may be short or long, depending on the model used and of the complexity of the sample geometry. The need for quick measurement and high throughput does affect the accuracy of the measurement.

In both cases, a model describing line cross-section is used, so as to limit the calculation time. The model fixes the number and types of geometrical characteristics. Some parameters are fixed to accelerate computation time, other are variables. So we can assume that library analysis is more reliable for production control and direct analysis is more efficient for research and process development. Users regard both library and direct solutions as valuable and they appear complementary.

The error resulting in library scanning or in loop minimizing is reported to the user as a statistical parameter (Goodness Of Fit (GOF), or final mean square error). This is a very important figure to consider; this value quantifies the level of confidence the user has in the reported values. If something not considered in the model happens, typically a defect or a process failure, the GOF value drops significantly. As an example, if a parameter is varying on the wafer, but fixed in the model, the GOF will show that the reported values are not appropriate. If a simple trapezoid model is used for a resist lines array, an unexpected variation of BARC thickness across the wafer can be indicated by a GOF variation.

### Measuring target on silicon

Scatterometry uses a dedicated target printed or patterned on the wafer. An array of straight and parallel lines, so a grating, constitutes the target. The grating effect is to enhance the diffraction efficiency of the incident light. Light is scattered in several directions, apart from the specular reflection. Energy is withdrawn from the specular reflection, corresponding to 0th order. So in case of a spectroscopic tool, the recorded spectra are affected by the grating: pitch (Bragg condition provides resonant diffraction), but also shape of the grating lines (CD, height, sidewall angle...) As the diffraction efficiency depends on the geometrical characteristics of the grating, we should be able to retrieve geometrical information from the recorded 0th order spectra.

This target should be representative of the lines designed in the circuit. So the design is coherent with design rules and is adapted to each technology nodes and layers. Dense or semi-isolated lines, horizontal and vertical lines can be used. As scatterometry is based on finite grating scattering in a given spectral range, there is an upper limit for pitch: sensitivity diminishes for a low number of lines in the grating and for long pitch. The size of the square target is today limited by the spot size, that is fixed by the hardware and that depends on alignment tolerance of the tool. At the end, the requested area in the scribe lines is more important for scatterometry than for CD-SEM: 50 by 50 microns. For example a design for CD-SEM includes horizontal, vertical, dense and isolated lines in one pattern. Scatterometry will require four targets, on for each type of line.

Target size is considered as an issue for scatterometry metrology integration and deployment. If CD scatterometry is used as the standard tool for process control, the required area in the scribe line for process control will become huge. Solutions for targets integration has to be worked out: targets stacking, horizontal and vertical lines on the same target...
EVALUATION OF PERFORMANCE AND USE IN FAB ENVIRONMENT

We have evaluated the capability of different scatterometry tools/setup (different suppliers). Wafers have been printed targeting 90 nm and 65 nm nodes for demonstration by wide panel of suppliers and then for on-site evaluation of one selected tool.

Scatterometry solutions demonstration

Two sets of test wafers have been realized for demonstration. Targeted application was lithography after resist development. Some wafers have been written using e-beam direct write tool (both gaussian beam and shaped beam). Other wafers have been printed with a 193 nm standard process, using 90 nm gate design rules (described in next paragraph). Thanks to e-beam lithography, we succeed in evaluating targets with linewidth as small as 60 nm after lithography. Four grating designs were selected for the demonstrations, shown in Table 1.

<table>
<thead>
<tr>
<th>Density</th>
<th>CD</th>
<th>Pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>dense</td>
<td>150 nm</td>
<td>300 nm</td>
</tr>
<tr>
<td>semi-dense</td>
<td>100 nm</td>
<td>240 nm</td>
</tr>
<tr>
<td>semi-isolated</td>
<td>70 nm</td>
<td>280 nm</td>
</tr>
<tr>
<td>quasi-isolated</td>
<td>60 nm</td>
<td>360 nm</td>
</tr>
</tbody>
</table>

Wafers have been shipped to different suppliers and demonstrations have been carried out in a two-step timing. We first required blind measurement on the gratings; we have disclosed only design description. Then we provide SEM cross-section results to suppliers. SEM cross-section reveal resist consumption and top corner rounding effect. Then suppliers refined their model if needed and results were updated. Optical constants were not disclosed and each supplier has to measure and use its own n&k dispersion values. At the end we also compare optical data. Some suppliers simulate impact of n&k variations on CD and profile values.

For each selected design, we ask for data on linewidth, height and sidewall angle. Some suppliers also fit the pitch of the grating but most of them use the design pitch as a fixed constant. Some suppliers consider a constant height among the different designs. Note that a given scatterometry hardware, for example ellipsometry, is implemented by several suppliers. So the results disclosed here does not report to one identified supplier. Some suppliers dedicate their tool to integrated metrology purpose. In that case, it is difficult to obtain values for dynamic reproducibility (with load/unload sequence).

<table>
<thead>
<tr>
<th>Hardware Techniques</th>
<th>SE*</th>
<th>NI* Reflectometry</th>
<th>Polarized NI* Reflectometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD 60 nm</td>
<td>0.8 nm</td>
<td>NA</td>
<td>3.6 nm</td>
</tr>
<tr>
<td>CD 70 nm</td>
<td>0.9 nm</td>
<td>NA</td>
<td>1.1 nm</td>
</tr>
<tr>
<td>CD 100 nm</td>
<td>0.5 nm</td>
<td>NA</td>
<td>0.6 nm</td>
</tr>
<tr>
<td>CD 150 nm</td>
<td>0.8 nm</td>
<td>NA</td>
<td>2.1 nm</td>
</tr>
</tbody>
</table>

### TABLE 2b. Shift of bottom CD value measured with different scatterometry techniques to CDSEM value.

<table>
<thead>
<tr>
<th>Hardware Techniques</th>
<th>SE*</th>
<th>NI* Reflectometry</th>
<th>Polarized NI* Reflectometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD 60 nm</td>
<td>5 nm</td>
<td>5 nm</td>
<td>9 nm</td>
</tr>
<tr>
<td>CD 70 nm</td>
<td>5 nm</td>
<td>5 nm</td>
<td>7 nm</td>
</tr>
<tr>
<td>CD 100 nm</td>
<td>8 nm</td>
<td>4 nm</td>
<td>10 nm</td>
</tr>
<tr>
<td>CD 150 nm</td>
<td>10 nm</td>
<td>5 nm</td>
<td>6 nm</td>
</tr>
</tbody>
</table>

SE: Spectroscopic Ellipsometry
NI Reflectometry: Normal Incidence Reflectometry

All scatterometry CD data were compared to a measurement done on standard top-down SEM. The targets were measured on the corresponding wafer before sending the samples to the suppliers. Generally, a shift appears between SEM value and scatterometry value. For small CD values, this shift is generally negative. In Tables 2a and 2b, we can see that spectroscopic ellipsometry provides dynamic reproducibility less than 1 nm for every tested CD design. Globally, each three technique seems to provide adequate results for CD metrology. But we shall emphasize that data shown in table 2 are provided after disclosure of line profiles (cross-section SEM picture). Note also that some suppliers have easy access to top-down SEM and can use these to confirm their data. Concerning profiling capability, the different techniques are not equivalent. Measuring small features in a profile, as footing or top corner rounding, implies high resolution (hardware and software). Data on height, sidewall angle and small features are not always coherent among suppliers. Non-polarized reflectometry shows poor capacity. From both series of tests, we have concluded that spectroscopic ellipsometry and polarized reflectometry are very promising hardware solutions. Results from blind test make more differences. After disclosing SEM results, most suppliers can claim good results. That's why we plan to evaluate scatterometry as an independent tool. Process engineer and scatterometry application engineer will systematically guess the model.
**Spectrosopic ellipsometer evaluation**

**Tool installation and protocol setup**

After analysis of demonstration results, a KLA-Tencor ellipsometer has been installed in 200 mm fab (ASET F5x with SpectraCD™ options). We have evaluated scatterometry as an alternative to CD-SEM in the frame of a joint evaluation agreement. We have mainly studied scatterometry using a library approach. Some comparison with direct regression solution, also available from KLA-Tencor, has been achieved. A dedicated parallel computer has been installed for library generation and data analysis.

Various applications have been studied: CD control and profile measurement after lithography and after etch, optimization of targets, sensitivity to defect,... CD control has been assessed for different technology nodes and also for tool follow-up and tool qualification especially in lithography cluster. Systematic correlations with top-down SEM and cross-section SEM were performed. The aim is to confront scatterometry results with data obtained from standard tools used in the fab for production. These are early results for scatterometry and statistical analysis on a lot of wafers, lots and products will be necessary to have a clear view of scatterometry performances for production.

In order to assess scatterometry as an independent tool, libraries were generated without prior information on the patterns, except design and exposure data. In order to create a library, a complete model of stack and resist shape has to be built. A dedicated wafer is printed or patterned for first spectra recording. Geometrical model of line profil, nominal values and variations of parameters are guessed and tuned using a first software direct analysis. Once the model is determined, the library itself is computed by varying each parameter in its range. Then SpectraCD™ software tool determines for each parameters the principal minimum of an error trend curve. After transfer of the library to the tool, Each measurement will find a corresponding result in these interpolated error curves and not in the discrete library. So the step of discrete parameters does not impact the accuracy of the measurement. For some cases, the library generator software is unable to compute a set of trend curves. The solution is to fix some parameters. In that case a variation in the process will not be identified.

Scatterometry analysis requires the n&k value versus wavelength for each layer of the stack. Accurate measurements and models are needed. Standard models are sometimes unable to fit the data on whole spectral range. Some issues have to be faced during this critical step: optical constants of each new layer have to be determined; each type of implant (N or P) requires a different model; materials constants obtained after process change or upgrade have to be carefully checked. The optical constants of a given material can change during the process, for example after a hard mask deposition or after annealing. So the optical constant could be different if you measure the same pattern at different step of the process. According to these remarks, one can assert that n&k data management is a critical step, and has to be optimized for each different layer and technology. Numerical models for data fitting can be very helpful for scatterometry application.

**Results for some applications**

We will present hereafter a selection of two examples of scatterometry measurement on real device: gate after lithography printing and Shallow Trench Isolation (STI) after etch patterning. It appears that results after etch show better precision performances than after lithography.

The stack for gate includes oxide, poly-silicon and oxide hard mask. According to the process used for gate patterning, layers could show different dispersion curves. Some special behavior could also been understood as refractive index gradient in the layer height. Poly lines are designed at 80 nm and 100 nm on a 600 nm pitch, for a resist thickness in the range 250-330 nm. Measurements have been performed after 193 nm exposure and development. On figure 1, we display the top-CD values obtained from scatterometry and from top-down SEM for each die on one wafer.

![Figure 1: CD dispersion measured on a wafer by scatterometry and top-down SEM average on multiple locations.](image)
SEM measurements have been obtained by averaging values measured on 20 locations on scatterometry target, using standard algorithm. We state that the dynamic is higher for scatterometry. Scatterometry top-CD values are generally lower due to SEM operation close to its resolution limit. The trend in both curves is very similar. We have shown that using a different SEM algorithm (threshold value) allow us to match the SEM and scatterometry values.

On figure 2, scatterometry profile data are superposed to a cross-section SEM picture. Scatterometry find greater CD for 100 nm lines: above 5 nm. But cross-section provides a view on a single point in the 50 by 50 square microns target.

Figure 2: cross-section picture and corresponding trapezoid profil measured by scatterometry (SE).

STI application was studied using the same tool. The stack has standard layers: oxide, silicon nitride and oxide hard mask. CD target is 110 nm, with a dense pitch of 260 nm. Scatterometry gratings were measured using ellipsometry and CD-SEM. The SEM algorithm used here has been especially optimized. The SEM measurement was done on one site only, in the scatterometry grating: we clearly see on figure 3 that the dispersion is much higher for single SEM measurement than for scatterometry. The optimized SEM algorithm allows a better matching between both techniques, but does not reduce the dispersion.

Figure 3: Top-CD measurement with scatterometry and SEM on etch STI scatterometry grating.

The overlap with cross-section SEM picture on figure 4 shows again a good correlation. Scatterometry proves to be valuable for profiling application. The figure also displays the model used for software scatterometry analysis: four trapezoids are stacked to obtain a good representation of STI profiles, in particular for the thin oxide layer. The global shape of the trench is well fitted by scatterometry. The main interest for etch process engineering is the characterization of Top Corner Rounding (TCR) at the top of the silicon trapezoid (second slice from bottom). Such tiny geometrical feature is difficult to quantify but spectroscopic ellipsometry is able to provide this accurate profile information.

Figure 4: cross-section SEM image of STI line profile with scatterometry data.

Scatterometry and CD-SEM measurements follow the same trend on each test wafers we have examined. The shift observed between SEM averaged measurements and scatterometry measurements has been analyzed for etch and litho application. Taking into account the mean value of different results, one can assert that a permanent shift greater than 9 nm is clearly observed for bottom CD. This is coherent with results obtained during demonstrations. For low CD values, this shift appears to be very constant. For higher CD, shift can do up, especially for lithography application. Concerning linearity between both techniques, statistical $R^2$ correlation coefficient is reported in table 3. CD values between 50 nm and 150 nm have been considered (design), after lithography and after etch.

<table>
<thead>
<tr>
<th>CD</th>
<th>$R^2$ linearity coefficient</th>
<th>Averaged global shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>top CD</td>
<td>0.9828</td>
<td>13.2 nm (2nm 3σ)</td>
</tr>
<tr>
<td>middle CD</td>
<td>0.9983</td>
<td>11.3 nm (2.4 nm 3σ)</td>
</tr>
<tr>
<td>bottom CD</td>
<td>0.9945</td>
<td>9.3 nm (4.2 nm 3σ)</td>
</tr>
</tbody>
</table>

Table 3. Linearity and shift between CD-SEM and scatterometry.
ENHANCEMENT AND EXTENSION TO NEW APPLICATIONS

Scatterometry is a valuable technique, but with some weak points. One goal of our study is enhancement of scatterometry users' aspects (global target size). We attempt to assess the use of light scattering towards advanced applications that are not covered today. We did not find very aggressive performances for profiling application (notched gates are not well characterized). Actual scatterometry tools do not provide holes measurement (diameter, ellipticity, depth) or true isolated features. It has been shown that hole in an array measurement is feasible. Full 3D measurements and overlay are also among the possible applications of scatterometry.

As IC manufacturer, we are able to implement different features in the grating: holes array, 2D patterns containing horizontal and vertical line section, superposed arrays for overlay detection, lines with process induced edge roughness... are some examples. We can record spectra from all these different designs and check directly on acquired results if some tendency or some sensitivity is present.

Especially overlay could be measured using actual scatterometry ellipsometer or reflectometer. By taking spectra from superposed gratings with a programmed shift, the curves show sensitivity. A set of spectra collected by spectroscopic ellipsometry is shown in figure 5.

![Figure 5: measured ellipsometry spectra S1 and S2 with scatterometry targets for overlay measurement.](image)

The impact of overlay shift between both gratings is clearly observed on two resist gratings, printed one on the other using e-beam lithography. Both interdigitated gratings had a 400 nm pitch and 100 nm lines.

Measurements have been recorded for overlay shifts varying from 0 to 50 nm. We did not consider the sign of the shift for this feasibility evaluation. Following protocol has been tested for overlay defect evaluation. Two theoretical spectra are simulated: one with perfect alignment and one with a reference shift (for example 10 nm). For measured spectra and reference spectra, a quadratic error signal is generated (with respect to the spectra of the perfect alignment case). Then both error signals are correlated. Because the error signals show the same trends, the correlation curves present a clear maximum. Reducing the wavelength range can avoid confusion with some secondary maxima. By calculation and simulation, we can show that the maximum value of the correlation curve is linked to the overlay shift value. For this protocol, we need one measured spectrum and two simulated spectra.

But on silicon, things are different. The measurements were impacted by the line profile and the capability of the overlay measurement was limited. We have used RCWA simulation to generate simulated spectra. This implies the definition of a model to approximate the line profile. The measured spectra are affected by the overlay shift and the simulated spectrum is affected by the error due to the approximation. For small overlay shifts, it appears to be impossible to isolate the overlay error from the approximation error. For our case study, an overlay shift below 30 nm was not identified. That means that an accurate profiling of the line is required. The profile information can be extracted from a second measurement on a different target. Instead of simulating spectra on a reference overlay target, we can print this reference target and measure spectra from this target. This will provide a relative evaluation of the overlay shift. Increasing the number of scatterometry target will allow overlay value extraction.

CONCLUSION

We have extensively studied metrology capability of scatterometry in a fab environment, for application to 90 nm and 65 nm nodes. Use in lithography and etch area has shown promising results in term of resolution and precision. Spectroscopic ellipsometry has proven to provide accurate spectra for scatterometry analysis, but others optical hardware will be evaluated. Reflectometry appears to be most appropriate for metrology integration in production equipment. The normal incidence optical path shows better capability for small modules suitable for
integrated metrology application. Direct regression software has also to be evaluated against library solution.

Extension of scatterometry technique towards new applications is foreseen: overlay, two-dimensional patterns and holes measurement will be considered as next application for new optical metrology techniques. We have shown that overlay measurement is feasible using scatterometry implemented on ellipsometry.

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