Advances in Scanning Electron Microscopy for Semiconductor Metrology

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INTRODUCTION

With the continuous path towards smaller and smaller dimensions, the semiconductor industry is facing new metrological solutions to guarantee adequate process control and respect specification limits [1]. Metrological SEM, or CD-SEM, is the most common technique available today to perform this task with the appropriate degree of precision and accuracy required by the smallest structures printed on silicon wafers, as agreed for the current and future generations of integrated devices, summarised in Table 1 [2].

A typical leading edge CD-SEM tool features a LaB$_6$ thermal-enhanced field-emission gun, superior electromagnetic column and lens, a high-gain through-the-lens detector for secondary electrons (mandatory for an accurate reconstruction of profiles and topography) and a (wafer) holder which can be biased with respect to the objective lens in order to improve the efficiency of electron collection.

Even the most advanced tools, however, are not completely compliant to all the characteristics required today (for the 90 nm node) by the final user. In fact, the huge improvements brought to the CD-SEM by leading edge suppliers in the last few years in order to overcome some well-known problems [3], typically linked to the insufficient visibility of the bottom of the inspected features (e.g. trenches and holes in the half µm range), can not overcome other phenomena, which became more and more important recently, after the introduction of new materials and the presence of smaller line widths.

A detailed review of the characteristics an ideal tool should comply with in order to keep the pace with integrated-circuit technology, along with suitable solutions to improve metrological outputs is reported elsewhere, along with rough specifications and procedures for related evaluation [4]. In this article we focus on the possible hardware and software solutions which are being studied to get closer to user specifications.

REQUIREMENTS AND DEFINITIONS

The main definitions and user requirements are summarised below to complete the overall picture and to clarify the logic of our reasoning.

Any metrology tool has to be benchmarked with respect to four key elements, provided that a suitable tool is available on the market: ultimate resolution, precision, interaction with sample and universality [5]. Throughout CD metrology, ultimate resolution plays a double role, the former being the usual Rayleigh criterion for optical images, the latter (and somewhat more important) dealing with the measuring power, i.e. the minimum detectable difference in CD between two similar structures.

Precision yields a unique figure for the metrological quality of the tool, combining the ideas of short-term repeatability, long-term reproducibility and tool-to-tool matching [6]. Of course, any kind of measurement requires an interaction between the probing system and the sample: the impact of this interaction on the target should be completely negligible, for any geometrical modification in circuit structure may change the functionality of electronic devices, eventually leading to an electrical failure. Finally, the tool should offer its user all the information beyond CD required to process correctly an integrated circuit, like pattern profiles, sidewall angles and line edge roughness (LER). It is valuable here to point out that all advanced CD-SEM tools have neither stage-tilting nor stage-rotating capabilities, for these two movements would impair their metrological quality.

Figure 1: Ultimate CD-SEM optical resolution.

Figure 2: Shrinkage of 193 nm photore sist.
CURRENT STATUS

It is now possible to assess the status of leading-edge SEM-based CD metrology by carrying out an analysis based on the factors described in the previous section.

Resolution

With respect to this key property, as shown in Fig. 1, CD-SEMs in general behave properly, even if some improvements are required to cope with advanced applications, like accurate edge detection and LER evaluation. In particular, a measuring power of the order of 0.1 nm is gained by magnifications as high as 500,000X and very small pixel sizes the contrast between the pattern and the foreground is ensured by the highly accurate E x B effect used to drive secondary electrons towards the detector.

Precision

Up to a very few years ago, precision was almost the only merit figure in CD metrology. Though the situation has changed, precision is still key to comprehensive tool characterization. Today the behaviour of SEM tools as a viable solution for a wealthy CD metrology is marginal. In fact, the definition of precision includes also the contribution to uncertainty due to measuring the same structure with different tools (in principle of different models): no known cluster of systems is able to perform such ultimate performance: wafers require such ultimate performance, which brings about a further local feature-dimming step and thus a local variation in line width (7).

Universality

SEM-based CD metrology is amongst the richest available on the market, being able to measure directly the most precious parameters, like line width at the bottom of the line, line width at the top of the line, hole diameter, LER (Fig 3), pitch, distance between two lines in the same field of view and corner rounding. Furthermore, it may give the user other key information, like sidewall angle and line height, through indirect approaches. Line-profile reconstruction, the greatest weakness of CD-SEM against a universal utilisation, is an area where improvements are awaited in a very short time. Finally, new process steps are also likely to challenge SEM-based CD metrology, for they may require correct image acquisition from structures with aspect ratios (the ratio between the depth of a trench and its CD at the bottom) as high as 20:1.

EXPECTED DEVELOPMENTS

The challenges reported above are so demanding that SEM technique might be dropped as a potential solution for future CD metrology unless effective breakthroughs are found in time.

Resolution

Whenever the Rayleigh criterion for resolution is considered, two mainstreams are being pursued, the former being represented by a well-tailored field configuration within the objective lens, typically gained by cooling the lens itself or by introducing pure electrostatic components; the latter by a different kind of electron source, brighter and more collimated that obtained through thermally assisted field emission. A promising option is offered by replacing current cathodes with carbon nanotubes, which are advantageous also for other aspects. The main problem here consists in producing sufficiently reliable nanotubes in an industrially reproducible way. Finally, another option is offered by the detection of low-loss energy electrons, which are scattered at a blazing angle from the wafer surface. This solution has two drawbacks: these electrons, whose energies are close to those of backscattered component, do not give information about topography; secondly, detectors can not be placed through-the-lens, hence creating an unreal shadow effect due to the asymmetric detector configuration, which is a major problem for CD-SEM because in general the stage cannot be rotated.

The same strategies can be applied also to increase the measuring power, for a better resolution improves the contrast of SEM images, enabling higher magnifications and thus larger pixel sizes at no expense, i.e. with no image degradation.

Precision

The path towards higher and higher precision requires better stability in measuring algorithms and weaker interaction between the primary beam and the structure to be measured (to increase short-term repeatability), greater accuracy in edge detection and in stage movement (to increase long-term reproducibility) and a fine tuning of the main machine parameters within the same cluster.

Table 1: List of key metrological specifications.

<table>
<thead>
<tr>
<th>Technology Node</th>
<th>Year</th>
<th>Precision (3σ, lines, nm)</th>
<th>Precision (3σ, holes, nm)</th>
<th>Precision (3σ, LER, nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>2001</td>
<td>0.1</td>
<td>3.0</td>
<td>0.9</td>
</tr>
<tr>
<td>90</td>
<td>2004</td>
<td>0.6</td>
<td>1.8</td>
<td>0.54</td>
</tr>
<tr>
<td>65</td>
<td>2007</td>
<td>0.41</td>
<td>1.3</td>
<td>0.36</td>
</tr>
<tr>
<td>45</td>
<td>2010</td>
<td>0.29</td>
<td>0.9</td>
<td>0.26</td>
</tr>
<tr>
<td>32</td>
<td>2013</td>
<td>0.21</td>
<td>0.64</td>
<td>0.18</td>
</tr>
<tr>
<td>22</td>
<td>2016</td>
<td>0.15</td>
<td>0.44</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 2: Actual performance of leading-edge CD-SEM.

<table>
<thead>
<tr>
<th>System</th>
<th>Precision (3σ, lines, nm)</th>
<th>Precision (3σ, holes, nm)</th>
<th>Precision (3σ, LER, nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.6</td>
<td>0.9</td>
<td>2.4</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.9</td>
<td>3.1</td>
</tr>
<tr>
<td>C</td>
<td>1.4</td>
<td>1.6</td>
<td>Not Available</td>
</tr>
</tbody>
</table>
of tools through well-balanced procedures and stable secondary calibration samples (to increase tool-to-tool matching, which accounts today for about half the pie of the total precision).

Advances in measuring algorithms are granted by leading-edge tool suppliers at any major revision of the main software of their machines: a deeper knowledge and better models of key mechanisms ruling secondary electron emission close to sharp angles are increasing accuracy in edge detection. The aim here is in essence double: minimising both the apparent beam width (ABW) of the primary beam and its asymmetry. In particular the ABW is a merit figure of the average edge width of a specific insulated line artifact as determined from data acquired during normal operation; the asymmetry is a measure of the magnitude of the difference between the left and right edge widths of a similar insulated line. The accuracy of stage movement is greatly increased by the introduction of interferometric devices instead of linear-encoded mechanisms.

Tight control of main machine parameters, typically linked to electron emission on one hand and to lens column behaviour on the other, is the mainstream to a better tuning of SEM clusters, at least belonging to the same model, thus reducing the tool-to-tool contribution to precision. Procedures for cluster matching and secondary samples are normally produced and certified in-house. Precision for LER measurements has to be increased, but more accurate definition of relevant quantities has to be agreed beforehand.

Interaction with sample

Huge efforts are being made to reduce the physical deformation several materials suffer from under a continuous flow of electrons. These pattern modifications heavily depend at least on electron-landing average energy, and exposure time and dose. The usual average landing energy for CD applications ranges from 700 to 1500 V, whilst the typical electron current ranges from a few pA to hundreds of pA. Exposure time depends on the desired quality of the scan; however for pure metrology purposes this parameter might not be a key factor, since even a poor signal-to-noise ratio is good enough to collect CD data properly.

Several options are being currently introduced: e.g. remote autofocus (i.e. focusing is done not on the same structure you wish to measure, but on a similar one a few μm away), which shortens the time of the interaction in the critical zone to pure measuring operations; lower average landing energies (down to 100 V) to reduce the region of secondary electron emission to a very thin layer and the so called ‘rectangular scan’, where magnification along the axis orthogonal to the scanning direction is at least halved with respect to the magnification along the scanning axis this last trick doubles (or more) the area struck by the scanning primary beam at the high magnification the full SEM scan isto allow the system to find the proper edges for measurements and then to carry out the measurement itself. Instead, it is usually believed that even a small difference in line profile is likely to be unveiled by a minimal variation of line scans, with a better and faster output than the previous tiling option. However, this approach still requires thorough investigation.

CONCLUSIONS

The challenges the world of CD metrology in the semiconductor industry are facing today require novel solutions in almost all technical aspects for CD-SEM to be competitive as a viable solution for the next technology nodes, as defined in roadmap tables. A review of the current status of the art is presented here, along with the main guidelines towards future developments in CD-SEM tool sets. The analysis performed in this article shows that almost all the issues are being correctly addressed in the required timeframe, apart from LER precision (but a definitive LER definition still has to be agreed beforehand) and tool-to-tool matching (but in a first phase, a single tool approach is acceptable). This analysis leads to the conclusion that SEM will be used as the primary technique for CD measurements at least for the next two nodes, even if alternative techniques, like optical scatterometry or AFM, might be used for niche applications.

REFERENCES


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