Improved critical dimension inspection for the semiconductor industry

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Critical dimension inspection based on a library of simulated through-focus diffraction patterns and a mechanical-free defocusing process could improve high-throughput quality control.

The modern semiconductor industry requires simple and effective methods to inspect objects with critical dimensions (CD) of several dozen nanometers. Conventional measurement techniques, such as scanning probe microscopy, provide sub-nanometer imaging resolution but cannot be used in a mass production facility for in-line quality control inspection due to low throughput and the destructive nature of the inspection. The currently used scanning electron microscope-based (SEM) technology is limited to surface CD measurements, and it cannot be applied to side wall angle, undercut, or simultaneous compositional measurements for fin-based, field effect transistor topologies such as 3D FinFETs. Several optical methods with comparative simplicity and high performance have been developed, but these approaches are restricted by the kinds of objects they can inspect. The recently proposed through-focus scanning optical microscopy (TSOM) method offers optical inspection of a wide class of objects with sub-nanometer accuracy based on precise scattered light intensity distribution analysis in the near-focus region using a CCD camera.

TSOM technology that does not use a simulation library is limited by the CCD light detector’s noise threshold and mechanical instabilities affecting sample position during measurements. The effects of mechanical instabilities significantly increase in the case of in-line inspection with high throughput.

In our research, we demonstrated improved CD inspection based on a simulation library by accounting for optical system aberration in simulation models. We propose a way to eliminate the effects of mechanical instabilities of sample position by using axial chromatic aberration as a form of mechanical-free...
Table 1. Sample recognition results. SEM: Scanning electron microscope.

<table>
<thead>
<tr>
<th>SEM measured CD in nm, (±2nm accuracy)</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recognized object width in nm, no aberrations considered</td>
<td>31</td>
<td>39</td>
<td>48</td>
<td>64</td>
<td>79</td>
<td>88</td>
<td>106</td>
<td>126</td>
<td>127</td>
<td>148</td>
<td>151</td>
<td>160</td>
</tr>
<tr>
<td>Recognized object width in nm, aberrations considered</td>
<td>37</td>
<td>48</td>
<td>60</td>
<td>74</td>
<td>82</td>
<td>88</td>
<td>96</td>
<td>105</td>
<td>106</td>
<td>127</td>
<td>137</td>
<td>145</td>
</tr>
</tbody>
</table>

defocusing. The wavelength of the scattered light is scanned over a narrow spectral range of 440–470nm, providing a ±15μm defocusing range.

We simulated our library of TDPs using the finite-difference time-domain method to calculate the spatial distribution of the light field scattered by the objects under inspection. It allowed defocused image construction both with and without accounting for aberrations.10

Figure 2 shows experimental and simulation data for the following parameters: numerical aperture of illumination NA_{ill} = 0.05, collecting numerical aperture NA_{coll} = 0.75, central wavelength \( \lambda = 660\)nm, \( \Delta \lambda = 20\)nm, and the silicon line on the silicon substrate sample having a refractive index of \( \eta = 3.9\). The CD value is 90nm.

The difference between the experimental and simulated normalized TDPs was caused by aberrations in the optical system: see Figure 2(a) and (c). In order to account for the axial chromatic aberration, we determined its value experimentally and introduced the corresponding corrections into the mathematical model. For the phase aberrations, we empirically introduced an additional phase shift to each spatial Fourier component until the best match between experimental and simulated data for an object with 40nm CD value was found. The defined phase shift was subsequently used for the simulation of light scattering from other objects (50–150nm CD values). The normalized TDP for a 40nm CD value object, simulated with consideration of the optical system’s aberrations, is shown in Figure 2(b) and leads to a better match between the experimental and simulation results.

Figure 3. Normalized TDPs for a silicon line test object with a CD of 40nm, measured using: (a) a mechanical-free defocusing approach, and (b) a mechanical scanning defocusing approach.

We simulated two libraries of normalized TDPs for CD value of silicon lines in the range of 40–150nm with 1nm steps. One library included aberration corrections, and the other did not. The CD value of the inspected test object was defined as the CD value of the simulated TDP providing the best match to the experimental one. These results are summarized in Table 1. Green cells in the table correspond to CD value recognition within a ±5nm range for the CD value measured by SEM, while the CD values in the red cells are outside of the ±5nm range.

In order to minimize the acoustic noise, we used mechanical-free defocusing from chromatic aberration inherent to the optical system. We positioned test objects to the best approximate focus and illuminated them by a tunable light source. Wavelength changes due to chromatic aberration resulted in defocusing of the sample image. We measured the corresponding calibration curves for the focus offset and the illumination intensity dependence on the wavelength, and we used these for TSOM data reconstruction.

We measured typical normalized TDPs for the silicon line test object with a 40nm width using mechanical-free defocusing and using direct mechanical scanning defocusing: see Figure 3(a) and (b). Qualitative correspondence between TDPs measured using mechanical and mechanical-free defocusing demonstrate the equivalence of both approaches. The narrow range of wavelength tuning (~10nm) provides the required defocusing range to allow use of laser diodes with a temperature dependent illumination wavelength.

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We showed that the elimination of mechanical defocusing in TSOM measurement improves precision for high throughput in-line quality control optical CD inspection. We are currently working on integrating the calibration system into the device, particularly for direct measurement of the aberrations.

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References