Detecting profile excursions using spectroscopic ellipsometry

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OVERVIEW This work evaluates the capability of a spectroscopic ellipsometry-based profile technology as a new metrology tool to monitor polysilicon gate processes at 130nm and 90nm nodes. This study proves that this method can consistently flag different profile excursions of polysilicon gate (e.g., small notching, footing, or undercut).

A common issue for etching processes is the existence of a small notch or foot at the bottom of a polysilicon gate. There are many causes of poly gate profile excursions; a change in the grain size of polysilicon, etching condition, energy and dose of ion implantation could lead to different profiles. Even in a single chip, n-doped poly and p-doped poly generally show different profiles. With decreasing device size, it becomes even more important to control the profile of the polysilicon gate because a small notch or foot could have a major impact on the length of the polysilicon gate, and the performance of the device would then be affected significantly, especially for cutting-edge devices. Tighter control of gate profile leads to tighter distribution of transistor speeds, resulting in optimized and more consistent performance.

Monitoring gate profile

The capability of monitoring gate profile is critical for advanced process; currently, in-line CD-SEM is the traditional tool used for monitoring. Because of the intrinsic limitations of a normally incident electron beam, CD-SEM is not capable of detecting a small notch or undercut profile, which means CDs measured using the method may not reflect the real gate length. Cross-sectional SEM (XSEM) and cross-sectional TEM (XTEM) are destructive and not suitable for in-line monitoring. Atomic force microscopy (AFM) can provide an accurate 2D profile in some cases, but it cannot flag a small notch, and its throughput is not suitable for a high-volume manufacturing fab. Electrical test of transistor performance provides accurate gate lengths, but it takes days, or even weeks, to accomplish. None of the traditional technologies provide a good solution for in-line monitoring of polysilicon gate profile.

Spectroscopic ellipsometry-based technology has long been used in thin-film measurement. For the past several years, the same technology equipped with software featuring library-matching capability also has been used to provide fast, accurate, and precise 2D profile information [1–3]. This metrology technology is commonly referred to as SpectraCD (SCD). This technology can provide the cross-sectional profile of periodical features, such as 2D line gratings, or dense contacts.

In this study, SCD was tested to see whether it could flag profile excursions of etched polysilicon gate. Two traditional profile excursions are shown in Fig. 1 (see p. O2), a small notch and a small foot. There are three issues included in this study: 1) the capability of the new process as a metrology tool; 2) its capability to detect profile excursion of polysilicon gate; and 3) correlation of results with electrical test.
Figure 1. Two traditional abnormal profiles of etched polysilicon: a) a small notch and b) a small footing.

Figure 2. Schematic of a polysilicon ADI model.

Figure 3. Schematic of a gate etch model.

Figure 4. Dynamic precision (pooled 3σ) of 130nm n-poly AEI wafer with a 960nm pitch.
**Measurement models**

Schematic presentations of the models used for polysilicon after-develop inspect (ADI) and after-clean inspect (ACI) are shown in Figs. 2 and 3 (see p. O2). For a poly ADI process, the structures of interest are resist lines/spaces that sit on top of an antireflective coating layer, on top of n-doped or undoped polysilicon, gate oxide, and bulk silicon. The resist lines in the grating structure were modeled as single trapezoids in the library. For a poly after-etch inspect (AEI) process, the structures of interest are etched polysilicon lines/spaces sitting on top of gate oxide and bulk silicon. The etched polysilicon lines in the grating structure were modeled with an additional degree of freedom for detecting notching or footing.

**Results**

**Dynamic precision.** Dynamic precision results were obtained by measuring the same wafers 10 times with loading and unloading. For both ADI and AEI, the wafers were patterned with normal (best focus and best exposure energy) conditions. A total of five fields were measured per wafer. For the 130nm process-node wafers, one field included two sites: n-poly and p-poly. For the 90nm process-node wafers, only one site was measured. From these raw data, a pooled 3σ was calculated as the dynamic precision.

**Figure 4** (see p. O2) shows the dynamic precision for a 130nm n-poly AEI wafer. The grating pitch is 960nm. Dynamic precisions on top CD, middle CD, bottom CD, and profile height are all in the range of 0.1–0.3nm. The sidewall-angle measurement precision is <0.1°. Other dynamic precision results from these wafers are listed in Tables 1 and 2 (see p. O4). The dynamic precisions for CD and profile height are all <0.5nm, and the precision for the sidewall angle is <0.2°. CD precision requirements for the isolated line measurement recommended by the ITRS are 1.1nm and 0.6nm for 130nm and 90nm processes, respectively; the new metrology technique can therefore meet the ITRS precision requirements for these nodes.

**CD correlation.** For this technique to be a candidate for advanced process metrology, it is important to confirm that CDs measured by it can correlate well with those measured by an in-line monitor tool. The in-line monitor tools in most of the fabs are CD-SEMs. In this section, we present CD correlation results between CD-SEM and the SCD technique.

For both poly ADI and AEI layers, the wafers were patterned with a normal profile. Best focus was used for the whole wafer of the ADI layer, but exposure energy decreases gradually from column 1 through column 7. The result is different CD values for measurements made on different columns (see Fig. 5 on p. O4). In each grating, five different sites were measured on the CD-SEM. CD correlation results for the 130nm n-poly ADI wafer are shown in **Fig. 6a** (see p. O6). Three different pitches were measured: 320, 540, and 960nm. In the CD range of interest, R² values are all >0.99, which means CD correlations are very linear for all three pitches. For the 130nm AEI wafer, two different pitches were measured: 320 and 960nm (see **Fig. 6b** on p. O6). Again, CD correlation between the two methods is very linear. Additionally, linear CD correlation for both poly ADI and AEI means that SCD results compare well to the CD baseline obtained from CD-SEMs in the manufacturing line.

The SCD technique also reports sidewall angle, obtained from the CD correlation wafers; CD-SEM cannot easily measure this attribute. **Figure 7** (see p. O6) shows the sidewall angle trend for the 130nm poly ADI wafer. There are three kinds of gratings with different pitches. As described before, exposure energy decreases gradually from column 1 through column 7, and the whole wafer was prepared at best focus. Different gratings show different tendencies (Fig. 7).

The sidewall angles of dense gratings under different exposure energies are very consistent, but those of iso gratings change gradually. **Figure 8a** (see p. O7) shows the CD-SEM image of iso gratings with the largest exposure energy; **Fig. 8b** shows the one with smallest exposure energy. The profile of Fig. 8a looks tapered in comparison with that of Fig. 8b. The trend from the SCD method matches that of the CD-SEM images. The sidewall angle can be used as a factor of profile quality for in-line process monitoring. This result further demonstrates that both CD and sidewall angle measured with the new technique agree well with the results from the more established CD-SEM metrology.
Figure 5. Exposure condition of ADI wafers for CD correlation. Best focus was used for the whole wafer. Exposure energy decreased gradually from column 1 to column 7.

### Table 1. Dynamic precision of 130nm polysilicon gate (pooled 3σ; nm or degree)

<table>
<thead>
<tr>
<th>Type</th>
<th>Pitch</th>
<th>Top CD</th>
<th>Middle CD</th>
<th>Bottom CD</th>
<th>Sidewall angle</th>
<th>Height</th>
</tr>
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<tr>
<td>ADI</td>
<td>n-poly</td>
<td>320</td>
<td>0.14</td>
<td>0.17</td>
<td>0.32</td>
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<td></td>
<td>n-poly</td>
<td>540</td>
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<td>0.21</td>
<td>0.05</td>
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<tr>
<td></td>
<td>n-poly</td>
<td>960</td>
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<td>0.21</td>
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<td>0.06</td>
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<td>AEI</td>
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<tr>
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<td>p-poly</td>
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<td>0.25</td>
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<tr>
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<tr>
<td></td>
<td>p-poly</td>
<td>960</td>
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<td>0.11</td>
<td>0.22</td>
<td>0.04</td>
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</table>

### Table 2. Dynamic precision of 90 nm polysilicon gate (pooled 3σ; nm or degree)

<table>
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<th>Type</th>
<th>Pitch</th>
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<th>Middle CD</th>
<th>Bottom CD</th>
<th>Sidewall angle</th>
<th>Height</th>
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<tbody>
<tr>
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<td>u-poly</td>
<td>340</td>
<td>0.14</td>
<td>0.08</td>
<td>0.24</td>
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<tr>
<td>AEI</td>
<td>u-poly</td>
<td>340</td>
<td>0.38</td>
<td>0.05</td>
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</table>
**Capability to flag the profile excursion of poly AEI**

Two kinds of poly AEI wafers were prepared — one with a normal etch profile and the other with an abnormal etch profile. In each wafer there are both n-poly and p-poly sites. XSEM images were used to verify which sites had abnormal or normal profiles. The difference between middle CD and bottom CD, represented as Δ, was also used as a numerical factor to distinguish normal and abnormal profiles. An average of measurements from four fields is reported as Δ.

**Figure 9** (see p. O7) shows the comparison of XSEM and SCD results on normal and abnormal profiles. The pitch of the gratings is 960nm. The four images shown in the center are XSEM images. The upper two images were acquired from the n-poly and p-poly sites of a normal-profile wafer. The profiles are very steep. The lower two images are from an abnormal-profile wafer. By comparing the normal and abnormal profiles of n-poly sites, an apparent footing is observed on the abnormal n-poly. The Δ value of the normal n-poly (8.0nm) is also quite different from that of abnormal n-poly (30.9nm). P-poly sites show very similar results to n-poly sites. On the other hand, the four profiles shown at the left and right in Fig. 9 are from SCD, and these results for normal and abnormal wafers are from the same library. Similarly to the arrangement of XSEM images, the upper two SCD profiles are from a normal-profile wafer and the lower two profiles are from an abnormal-profile wafer. Both normal-profile and abnormal-profile cases using SCD agree very well with the XSEM. The Δ values from the SCD method show a visible difference between normal and abnormal profiles. Based on Fig. 9, it was confirmed that the method can flag profile excursion for iso etch poly processes.

Generally, the profiles of iso and dense etched poly are different. In order to confirm the capability to detect profile excursion of dense etched poly, the same test described above was repeated. The pitch of the dense gratings was 320nm. **Figure 10** (see p. O7) shows the comparison results. The results of dense gratings are different from those of iso gratings in that the difference in profile between normal and abnormal conditions is relatively smaller. The Δ values quantify the tendency. The Δ values of n-poly are 12nm and 17.8nm for normal and abnormal profiles, respectively (the corresponding Δ values for iso gratings were 8.0nm and 30.9nm, respectively). The difference for p-poly is even smaller. All these characteristics observed from XSEM images are confirmed with results using SCD; the technique can also monitor the characteristics of dense etched poly.

Other profile excursions were also evaluated. Another set of wafers with different abnormal profiles was prepared using a 130nm process, again with both n-poly and p-poly sites on the wafer. SCD data show different characteristics for n-poly and p-poly (see **Table 3** on p. O6). The sidewall angles of n-poly are consistently >90° (i.e., an undercut structure). The sidewall angles of p-poly are consistently close to 90°, but there are small notches detected. The parameter dCD1 (Table 3) is a factor that represents a small notch or footing at the bottom of the etched poly. A positive dCD1 indicates a foot; conversely, a negative dCD1 indicates a notch. For example, a dCD1 of –10nm represents a small notch of 10nm in width, at the bottom of the etched poly. The corresponding XSEM images are shown in **Fig. 11** (see p. O8); both n-poly and p-poly XSEM images match well with the profile information obtained by the new method.

The dCD1 values shown in **Table 3** exhibit the same trend as the XSEM images shown in **Fig. 11**. XTEM images were used to accurately verify the dCD1 values reported by SCD. Six gratings on an etched poly wafer were cut to collect the images. On each grating, five XTEM images were saved from five different etched poly lines. Correlation of the size of any small footing or notch with dCD1, determined from XTEM and the new technique, respectively, is shown in **Fig. 12** (see p. O8). Each data point represents one SCD data point and an average of five XTEM data points. In total, 30 XTEM images were acquired for **Fig. 12**. The R² value shows that the correlation is good, which means dCD1 reported by SCD can be correlated to the notch/foot size extracted from the XTEM images. Based on this result, SCD can be used to monitor a small poly foot or notch, which is hardly achievable by traditional nondestructive metrology tools.
Figure 6. CD correlation between CD-SEM and SpectraCD. a) CD correlation for 130nm n-poly ADI wafer. There are three different pitches measured, including 320, 540, and 960nm. b) CD correlation for 130nm n-poly AEI wafer. Two different pitches were measured — 320 and 960nm. All the gratings measured have normal profiles.

Figure 7. Sidewall angle trends of 130nm poly ADI. There are three kinds of gratings with different pitches. P320, P540, and P960 represent 320, 540, and 960nm pitches, respectively. Exposure dose decreases gradually from column 1 to column 7.

Table 3. SpectraCD data of 130nm etch poly

<table>
<thead>
<tr>
<th>Type</th>
<th>Result type</th>
<th>Wafer number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>n-poly</td>
<td>Sidewall angle</td>
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</tr>
<tr>
<td></td>
<td>dCD1 (nm)</td>
<td>1.7</td>
</tr>
<tr>
<td>p-poly</td>
<td>Sidewall angle</td>
<td>89.8</td>
</tr>
<tr>
<td></td>
<td>dCD1 (nm)</td>
<td>-9.0</td>
</tr>
</tbody>
</table>
Figure 8. CD-SEM images of poly ADI gratings from a) largest exposure energy and b) smallest exposure energy. The pitch of the grating is 960nm.

Figure 9. Comparison of XSEM and SCD for four different conditions: n-poly with normal profile; p-poly with normal profile; n-poly with abnormal profile; and p-poly with abnormal profile. The pitch of the gratings is relatively isolated (960nm).

Figure 10. Comparison of XSEM and SCD for four different conditions: n-poly with normal profile; p-poly with normal profile; n-poly with abnormal profile; and p-poly with abnormal profile. The pitch of the gratings is relatively dense (320nm).
Figure 11. XSEM images of 130nm etch poly.  
a) The n-poly image shows an undercut structure and b) p-poly shows a small notch at the bottom.

Figure 12. Correlation of the size of small footing/notch (dCD1) determined from XTEM and SCD.

Figure 13. Correlation between bottom CD of SCD and \( L_{\text{cap}} \), including n-poly and p-poly sites.
Correlation with electrical data, $L_{cap}$

Bottom CDs reported with the new method were correlated with the electrical gate lengths, $L_{cap}$. $L_{cap}$ represents the gate length determined from the capacitor polysilicon and gate oxide. Instead of a capacitor under a single etched poly line, $L_{cap}$ is a measurement average from tens of etched poly lines. The correlation between bottom CD of the SCD method and $L_{cap}$ is shown in Fig. 13 (see p. O8), including n-poly and p-poly sites. Each data point represents an average from a wafer; altogether, five wafers were measured for this test. The $R^2$ correlation coefficient for n-type devices is very good; more work would be required to understand whether the result for p-type devices could be improved.

Conclusion

In this work, capability in three areas has been presented for 130nm and 90nm poly ADI and AEI processes using the new technique: 1) as an advanced metrology tool; 2) as a way to flag profile excursions of etched poly; and 3) as a means to correlate its measurements with electrical data. SpectraCD measurements show precision and linear CD correlation with CD-SEM. Metrology capability of the new method also shows linear correlation with electrical data ($L_{cap}$) at the 130nm and 90nm process nodes and bottom CD. The method is also able to flag different profile excursions of etched poly, including footing, undercut, and notching. The size of the foot/notch reported by SCD agrees well with the size extracted from XTEM. The relationship makes the technique suitable for in-line monitoring of footing or notching — a capability not easily achievable by traditional nondestructive metrology tools.

Acknowledgment

SpectraCD is a trademark of KLA-Tencor Corp.

References


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