A Model for Step Height, Edge Slope and Linewidth Measurements Using AFM

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Abstract. Nano-scale linewidth measurements are performed in semiconductor manufacturing and in the data storage industry and will become increasingly important in micro-mechanical engineering. With the development of manufacturing technology in recent years, the sizes of linewidths are steadily shrinking and are in the range of hundreds of nanometers. As a result, it is difficult to achieve accurate measurement results for nanometer scale linewidth, primarily because of the interaction volume of electrons in materials for an SEM probe or the tip size of an AFM probe. However, another source of methods divergence is the mathematical model of the line itself. In order to reduce the methods divergences caused by different measurement methods and instruments for an accurate determination of nanometer scale linewidth parameters, a metrological model and algorithm are proposed for linewidth measurements with AFM. The line profile is divided into 5 parts with 19 sections and 20 key derived points. Each section is fitted by a least squares straight line, so that the profile can be represented by a set of straight lines and 6 special points, or by a 20×2 matrix of fitted points and a 6×2 matrix of starter points. According to the algorithm, \( W_T \) and \( W_{TF} \), \( W_M \) and \( W_{MF} \), \( W_B \) and \( W_{BF} \) represent the widths at the top, the middle and the bottom of the line profile before and after the least squares fitting, respectively. \( A_L \) and \( A_R \) represent the left and right sidewall angles, and \( H \) represents the step height of the line profile. Based on this algorithm, software has been developed using MATLAB for the calculation of width and height parameters of the line profile. A NIST nanometer scale linewidth artifact developed at NIST’s Electronics and Electrical Engineering Laboratory (EEEL) was measured using a commercial AFM with nanotube tips. The measured linewidth profiles are analyzed using our model, algorithm and software. The model developed in this paper is straightforward to understand, and provides a common set of parameters to evaluate the nano-scale line feature.

INTRODUCTION

Motivation

Development in the manufacturing of modern integrated circuits requires advances in measurement technologies of nano-scale linewidths on semiconductor chips [1]. Linewidths are steadily shrinking and are in the scale of hundreds of nanometers. This trend places tighter tolerances on the variability of the manufacturing processes and increasing demand upon the accuracy of linewidth measurements. Based on the 2001 ITRS-International Technology Roadmap for Semiconductors [2], the smallest linewidth (1/2 of pitch) on Microprocessors (MPUs) is now 130 nm, wafer critical dimension (CD) metrology tool precision is 2.6 nm (3 standard deviations) and maximum measurement bias is 13 nm. It is anticipated that these specifications will be reduced to 80 nm, 1.6 nm and 8 nm, respectively, by 2005, 45 nm, 0.9 nm and 4.5 nm by 2010. This presents a great challenge in the nano-scale linewidth measurement field.

The data storage industry also requires nano-scale linewidth metrology technologies, because it produces devices that write and sense surface features at the sub-micrometer scale, and makes information media products with surface features on the same scale. Currently the most important data storage technologies are magnetic disk storage and optical disk storage. Both of them need to measure linewidth and other surface features at the sub-micrometer level [1, 3]. With the increasing capacity of data storage, the size of surface features is reduced continuously. Moreover, if
the data storage industry moves beyond binary to variable-depth or variable-width encoding, the tolerance band for preserving data integrity will tighten considerably [3].

It is anticipated that many kinds of micro-mechanisms will be developed in the next decade. This capability will depend on the continuous development of material science, manufacturing technology, measurement technology and other related technologies. Nanometrology has been described as the science of measuring the dimensions of objects or object features to uncertainties of 1 nm or less [4]. Just as length metrology plays a key role in mechanical engineering, so nanometrology will play an important role in micro-mechanical engineering. Gears with diameters of only several microns have been fabricated already. So the dimensional measurement uncertainty of the geometry of features, such as tooth pitch and tooth width of such gears will be at the several nanometer level. Furthermore, there are different functional requirements for micro-mechanics, semiconductor manufacture and data storage. Micro-mechanical engineering is concerned with traceable dimensional measurements, because of the requirement of manufacture and assemblage, while the semiconductor manufacture is concerned with insulation and conduction properties, and the data storage industry is mainly concerned with data integrity.

**Current Nano-Scale Linewidth Measurement Methods**

Scanning electron microscopy (SEM) is widely used in linewidth measurements. SEM measurement is sensitive to the material's electrical conductivity and is difficult to perform on an electrical insulator. Using SEM to measure a line on a Si sample, Villarrubia et al. obtained an average linewidth of 447 nm with an expanded uncertainty (k = 2) of ±5 nm [5].

Unlike SEM, atomic force microscopy (AFM) is not sensitive to electrical conductivity and in principle can perform consistent dimensional measurements at the nanometer level on both insulating and conductive samples. Villarrubia et al. measured the same linewidth sample using the NIST calibrated atomic force microscope (C-AFM), which can perform traceable measurements in both x and y directions [6]. The results yielded a linewidth of 449 nm with an expanded uncertainty of ±13 nm.

The electrical critical dimension (ECD) measurement of the width of features is inherently different from SEM and AFM [7]. Instead of imaging a region of a feature and determining the width from one or more cross-section scans of the images, the ECD is a measure of the average cross-sectional width of a conductive feature. The cross-bridge resistor test structure was used by Villarrubia, et al. to measure the linewidth of the same Si sample mentioned above. The measured linewidth was 438 nm with an expanded uncertainty of ±34 nm [5]. For the ECD method, the average linewidth is functionally determined by measuring the conducting feature.

Besides the methods mentioned above, an interference microscope [8], and a scanning transmission microscope [9] have also been used to measure linewidth.

**Problems in Nano-scale Linewidth Measurements**

Although many papers on nanometer scale linewidth measurements have been published, a generally accepted definition of the linewidth has not yet been developed. We take the geometrical definition of linewidth to be the perpendicular distance from sidewall A to the sidewall B, as shown in Fig.1. Because of the interaction volume of electrons in materials for an SEM probe, or the tip size of an AFM probe, it is difficult to achieve accurate measurement results for nanometer scale linewidth even for an ideal line profile, as shown in Fig.1. Furthermore, there is no manufacturing technology that can be used to make a “clear corner” between the bottom and sidewall of a step. Hence a typical profile measured with AFM is as shown in Fig. 2.
Given the imperfections of fabricated measured lines and the expected increase in the effects as line features become finer, a second source of methods divergence is the need for a common mathematical definition of linewidth. Algorithmic differences constitute a source of significant divergence even for the parameters derived in macroscopic coordinate metrology [10, 11]. In addition the algorithms are key points of discussion in setting the measurement protocols for international comparisons in nanometrology. Problems in defining a nanometer scale linewidth measurement are listed below.

The linewidth is the perpendicular distance from which point on sidewall A to which point on the sidewall B?

How does the line height affect the measurement results of linewidth?

Which is the most suitable parameter for the functionality?

To address the issue of definition, this paper proposes a model for calculating nanometer scale line parameters based on AFM measurements. The model may also be suitable for other scanning probe microscopes (SPM) and SEMs.

A MODEL FOR NANOMETER SCALE LINEWIDTH

A model for nanometer scale linewidth should not only be able to represent the geometrical features of lines, but also to reflect functional requirements. Also the data volume of the model should be as small as possible. The model discussed below enables one to obtain the parameters of step height, edge slope, and linewidth from line profiles, assuming first that a line profile has been obtained for which probe width effects are negligible or have been removed.

We divide the profile into several straight-line segments and fit each section with the least square 1st degree polynomial function. Therefore this composite and sectional model is the mathematical representation of original profile. Specifically the profile, as shown in Fig.3, is divided into 5 parts with 19 sections and 20 key derived points. The development of the representation also requires 6 key original points, which are B, M_L, C, D, M_R and E on the profile, as shown in Fig.2.

The 5 parts are as follows:

1. Left bottom part extends from O to B' and is divided into three sections by four points O-A_1-A_2-B'.

2. Left sidewall part extends from B' to C' and is divided into four sections by five points B'-B_1-M_L'-B_2-C'.

3. Top part extends from C' to D' and is divided into five sections by six points C'-C_1-C_2-D_1-D_2-D'.

4. Right sidewall part extends from D' to E' and is divided into four sections by five points D'-E_1-M_R'-E_2-E'.

5. Right bottom part extends from E' to End and is divided into three sections by four points E'-F_1-F_2-End.

Using a variation of the algorithm developed and used at NIST’s Surface Metrology Laboratory for measuring the single step height [12], the vertical and horizontal positions of point A_1, A_2, C_1, C_2, D_1, D_2, F_1, and F_2 are obtained. Fig. 4 shows the relations of these points. An evaluation length is centered around the step and equal to approximately twice the step width (W). Four profile sections (A_1A_2, C_1C_2, D_1D_2 and F_1F_2) with length 2W/5 are used to evaluate the step height. These sections are positioned a distance W/20 from the step transitions to minimize any bias caused by rounded corners of the step. The left step height d_1 is the perpendicular distance between the extrapolated portions A_1A_2 and C_1C_2 at the center of the left sidewall. Similarly, the right step height, d_2 is the perpendicular distance between the extrapolated portions F_1F_2 and D_1D_2 at the center of the right sidewall. The step height H is defined as the average of d_1 and d_2.

FIGURE 3. The model of nano-scale linewidth profile

FIGURE 4. NIST Algorithm of Step Height
Next, B₁, M_L', and B₂ on the left sidewall are chosen such that their vertical distances to the left bottom surface are $d_1 \times 20\%$, $d_1 \times 50\%$ and $d_1 \times 80\%$, respectively. Similarly, E₁, M_R', and E₂ on the right sidewall are chosen such that their distances to the right bottom surface are $d_2 \times 20\%$, $d_2 \times 50\%$ and $d_2 \times 80\%$, respectively.

The six sections $\overline{A_1A_2}$, $\overline{B_1B_2}$, $\overline{C_1C_2}$, $\overline{D_1D_2}$, $\overline{E_1E_2}$, and $\overline{F_1F_2}$ are then fitted by least squares straight lines, and yield $B'$, the intersection of the extrapolated portions $\overline{A_1A_2}$ and $\overline{B_1B_2}$; $C'$, the intersection of the extrapolated portions $\overline{B_1B_2}$ and $\overline{C_1C_2}$; $D'$, the intersection of the extrapolated portions $\overline{D_1D_2}$ and $\overline{E_1E_2}$; and $E'$, the intersection of the extrapolated portions $\overline{E_1E_2}$ and $\overline{F_1F_2}$. In addition, we obtain $M_L'$ and $M_R'$, the fitted points at the half height of the left sidewall $\overline{B'C'}$ and the right sidewall $\overline{D'E'}$.

The sections, $\overline{O_1A_1}$, $\overline{C_2D_2}$, and $\overline{F_2End}$ are to be ignored. We replace the data of those sections simply by connecting $O$ and $A_1$, $C_2$ and $D_2$ as well as $F_2$ and $End$ with straight lines.

Based on $C'$ and $D'$, $M_L'$ and $M_R'$, $B'$ and $E'$, the linewidth at the top, $W_{TF}$, the linewidth at the middle, $W_{MF}$, and the linewidth at the bottom, $W_{BF}$, can now be calculated.

B, C, D, and E are four points on the original profile that separate the left bottom surface and left sidewall, top surface, right sidewall and right bottom surface. Because it is usually difficult to determine their positions accurately, we choose them as starter points to calculate the linewidth at the top, $W_{TF}$, and linewidth at the bottom, $W_{BF}$, before fitting. $M_L$ and $M_R$ are two starter points at half the vertical height of the left sidewall and right sidewall of the profile before fitting, and the horizontal distance between $M_L$ and $M_R$ is the linewidth at middle, $W_{MB}$, before fitting. The left sidewall angle $A_L$ and right sidewall angle $A_R$ can be calculated as the slopes of the fitted straight line $\overline{B_1B_2}$ and $\overline{E_1E_2}$.

As mentioned above, a line profile can therefore be represented by a set of straight lines $L_i$ and 6 starter points, as shown in Fig. 2 and Fig. 3, or by a 20×2 array of fitted points $M$ and a 6×2 array of starter points $P$.

The subscripts $x$ and $y$ represent the position of the horizontal and vertical coordinate, respectively. For instance, $A_1y$ is the vertical coordinate of $A_1$, and $A_1x$ is the horizontal coordinate of $A_1$.

$$M = \begin{bmatrix} O_x & O_y \\ A_{1x} & A_{1y} \\ A_{2x} & A_{2y} \\ B_1' & B_1y \\ B_2' & B_2y \\ M_{1x} & M_{1y} \\ B_{2x} & B_{2y} \\ C_1' & C_1y \\ C_{1x} & C_{1y} \\ C_{2x} & C_{2y} \\ D_1x & D_1y \\ D_2x & D_2y \\ D_1' & D_1y \\ D_2' & D_2y \\ E_1' & E_1y \\ E_{1x} & E_{1y} \\ E_{2x} & E_{2y} \\ E_{2} & E_{2y} \\ F_1x & F_1y \\ F_{2x} & F_{2y} \\ F_2' & F_2y \\ E_{End} & E_{End} \\ M_{Rx} & M_{Ry} \\ E_1' & E_{1y} \\ E_{1x} & E_{1y} \\ M_{Ry} & M_{Ry} \\ E_{End} & E_{End} \end{bmatrix}$$

$$P = \begin{bmatrix} B_x & B_y \\ M_{1x} & M_{1y} \\ C_x & C_y \\ D_x & D_y \\ M_{Rx} & M_{Ry} \\ E_x & E_y \end{bmatrix}$$

Usually AFM or other SPM instruments image a rectangular area on the sample in measurement. The image of the sample is a combination of many profiles. Assuming that there are $N$ profiles in an image, we use the mean $\mu$ and standard deviation $\sigma$ of parameters derived from the $N$ profiles to statistically evaluate the whole sample image. Then the data with biases from the value greater than a $3\sigma$ limit are taken out and the mean is calculated again. Finally, a 3D model image consisting of $N$ 2D model profiles is obtained. This is done in order to avoid including outlier profiles, arising from surface flaws and particles, in the analysis.

**THE ALGORITHM AND ITS SOFTWARE IMPLEMENTATION**

According to the model and algorithm, the following steps are used to calculate and analyze the linewidth of a sample.

1. Read an image and translate it to an $M \times N$ matrix.
2. Determine the scan size along $x$ and $y$ axes, and the range of the image in $z$.
3. Choose the $i^{th}$ profile for analysis.
4. Use a threshold criterion for the height difference of adjacent points to determine the corner positions of B, C, D, and E.
5. Based on the NIST step height algorithm, calculate $d_1$ and $d_2$, as well as $A_{1x}$, $A_{2x}$, $C_{1x}$, $C_{2x}$, $D_{1x}$,
D_{2x}, F_{1x}, and F_{2x}. These are positions on the x-axis of points of A_{1b}, A_{2b}, C_{1b}, C_{2b}, D_{1b}, D_{2b}, F_{1}, and F_{2} (refer to Fig 4).

6) Use Equation (1) to calculate the step height $H$.

$$H = \frac{1}{2}(d_i + d_j)$$  \hspace{1cm} (1)

7) Determine M_{Lx} and M_{Rx} from the half height of $d_i$ and $d_j$, and they are the positions of M_{L} and M_{R} on the x axis.

8) Calculate the linewidth at the top, $W_T$, the linewidth at the middle, $W_M$, and the linewidth at the bottom, $W_B$, by Equation (2):

$$W_T = D_x - C_x$$
$$W_M = M_{Rx} - M_{Lx}$$
$$W_B = E_x - B_x$$  \hspace{1cm} (2)

9) After fitting the profile by a set of least squares straight lines, obtain a new profile, $L_i$, which consists of $A_1$, $B_1$, $C_1$, $D_1$, $E_1$, $F_1$, and can be represented by Equation (3):

$$y = p_{1A}x + p_{0A} \hspace{1cm} A_1 \leq x < A_2$$
$$y = p_{1B}x + p_{0B} \hspace{1cm} B_1 \leq x < B_2$$
$$y = p_{1C}x + p_{0C} \hspace{1cm} C_1 \leq x < C_2$$
$$y = p_{1D}x + p_{0D} \hspace{1cm} D_1 \leq x < D_2$$
$$y = p_{1E}x + p_{0E} \hspace{1cm} E_1 \leq x < E_2$$
$$y = p_{1F}x + p_{0F} \hspace{1cm} F_1 \leq x < F_2$$  \hspace{1cm} (3)

Where the constants $p_{ji}$ ($i=A, B, C, D, E, F$) are the slopes of the sections, and the constants $p_{0i}$ ($i=A, B, C, D, E, F$) are the y-intercepts of the sections.

10) Calculate $B'_x$, $C'_x$, $D'_x$, and $E'_x$ from Equation (4):

$$B'_x = (p_{0A} - p_{0B})/(p_{1B} - p_{1A})$$
$$C'_x = (p_{0B} - p_{0C})/(p_{1C} - p_{1B})$$
$$D'_x = (p_{0C} - p_{0D})/(p_{1D} - p_{1C})$$
$$E'_x = (p_{0D} - p_{0E})/(p_{1E} - p_{1D})$$  \hspace{1cm} (4)

11) Determine $W_{TF}$, $W_{MF}$, and $W_{BF}$ from Equation (5):

$$W_{TF} = D'_x - C'_x$$
$$W_{MF} = \frac{1}{2}(E'_x + D'_x - C'_x - B'_x)$$
$$W_{BF} = E'_x - B'_x$$  \hspace{1cm} (5)

12) Calculate $A_L$ and $A_R$ from Equation (6):

$$A_L = \tan^{-1}\left(\frac{C'_x - B'_x}{C'_x - B'_x}\right)$$
$$A_R = \tan^{-1}\left(\frac{D'_x - E'_x}{E'_x - D'_x}\right)$$  \hspace{1cm} (6)

(13) Calculate $W_T$, $W_{TF}$, $W_M$, $W_{MF}$, $W_B$, $W_{BF}$, $A_L$, $A_R$, and $H$ for N profiles one by one, and calculate the mean and standard deviation of N profiles.

(14) Remove the calculated parameters with biases that exceed the $3\sigma$ limit from the sample means and recalculate again until all outliers are removed.

(15) Finally use the 2D model profiles $L_i$ to construct a 3D model image.

In this study, the program was developed with MATLAB [14] software. The measurement results are provided in numerical values and charts.

**SAMPLE AND MEASUREMENT**

A NIST prototype nanometer scale linewidth sample developed at NIST’s Electronics and Electrical Engineering Laboratory (EEEL) was chosen for experiments [7,13]. This sample is an etched silicon single crystal on an insulating buried oxide [5]. Fig.5 shows the layout of a typical cell. The cell is lithographically patterned on an n-type (Arsenic doped, $6.5\times10^{17}$ atoms/cm$^3$) SIMOX (separation by implantation of oxygen) wafer. The surface is single crystal Si with a 200 nm thick implanted oxide buried approximately 250 nm below the top surface. The top face of the wafer is a (110) plane. Undesired regions were etched down to the oxide, leaving a specimen oriented line along the [1 1 2] direction. Because of the crystal geometry, the etching results in {111} sidewalls on the specimen line. The sideways are thus slow-etch planes for the KOH etchant employed in line fabrication, yielding, in principle, lines with vertical sidewalls and low edge-roughness. The linewidths were designed from 250 nm to 2500 nm, and we chose a test structure with designed linewidth of 1000 nm. The pattern measured is shown in Fig.5.

**FIGURE. 5.** Optical image of the sample showing the specimen lines.
A commercial AFM was used to perform measurements for this research. The instrument is a Digital Instruments, NanoScope IIIa, [14], which is designed for measuring a small sample, and provides images with size up to $512 \times 512$ pixels. All three axes are driven piezo-electrically; the translation range for $x$ and $y$ axes is $120 \, \mu m$; the measurement range of the $z$ axis is $5 \, \mu m$. The system can scan the sample surface in both the trace and retrace directions. All images discussed here were taken with the tapping mode of operation. Because the linewidth of the sample is about $1 \, \mu m$, we choose a scan size of about $3.36 \, \mu m$ to provide the algorithm with enough data points at a suitable spacing resolution of about $6.6 \, nm$.

The nanotube tip, used to image the sample, was fabricated at the NASA Ames Research Center [15]. Fig. 6 shows an SEM image of the nanotube tip.

**ANALYSIS AND DISCUSSION OF MEASUREMENTS**

Figure 2 and Figure 3 shows a set of measurement results of a single profile of the sample, where the 20 key derived points and 6 starter points in the model can be seen. The matrix of fitted points $M$ and the matrix of starter points $P$ are:

\[
M = \begin{bmatrix}
0 & -157.8 \\
387.4 & -145.7 \\
899.6 & -168.3 \\
970.4 & -171.5 \\
971.8 & -151.7 \\
979.2 & -47.9 \\
984.9 & 31.4 \\
988.1 & 75.6 \\
1063.7 & 75.7 \\
1589.0 & 76.6 \\
1615.3 & 76.1 \\
2140.6 & 76.7 \\
2262.2 & 76.9 \\
2265.3 & 61.1 \\
2283.3 & -29.7 \\
2298.1 & -104.5 \\
2304.4 & -136.3 \\
2370.4 & -137.3 \\
2869.4 & -144.8 \\
3361.8 & -143.8
\end{bmatrix}
\]

\[
P = \begin{bmatrix}
965.2 & -159.1 \\
978.4 & -47.6 \\
1004.6 & 63.5 \\
2206.2 & 79.5 \\
2285.0 & -32.2 \\
2311.3 & -140.0
\end{bmatrix}
\]

The units above are nm.

According to the algorithm developed in this paper, we obtain $W_i=1201.6 \, nm$, $W_{TF}=1274.1 \, nm$, $W_M=1306.7 \, nm$, $W_{MF}=1304.1 \, nm$, $W_B=1346.1 \, nm$, $W_{MF}=1334.1 \, nm$, $A_L=94.10^\circ$, $A_R=101.20^\circ$ and $H=230.2 \, nm$.  

The values of $W_T$ and $W_{TF}$, $W_M$, $W_{MF}$, $W_B$ and $W_{MF}$, $A_L$ and $A_R$ and $H$ for an image with 239 profiles are shown in Figs.7-11. Also shown are values for the mean and standard deviation of these quantities after outlier removal as shown in Table 1 later.

**FIGURE 6.** SEM Image of a nanotube tip.

**FIGURE 7.** The $W_T$ and $W_{TF}$ of 239 profiles of an image (The dashed line is $W_{TF}$).

**FIGURE 8.** The $W_M$ and $W_{MF}$ of 239 profiles of an image (The dashed line is $W_{MF}$).
Table 1. The measured results for parameters of the line profile. Units are as shown on the left except for columns 3 and 4.

<table>
<thead>
<tr>
<th></th>
<th>Mean standard deviation</th>
<th>Number of profiles</th>
<th>Number of outliers</th>
<th>New Mean</th>
<th>New standard deviation</th>
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<tbody>
<tr>
<td>$W_T$ (nm)</td>
<td>1229.0</td>
<td>24.5</td>
<td>239</td>
<td>1</td>
<td>1228.6</td>
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<tr>
<td>$W_{TF}$ (nm)</td>
<td>1281.0</td>
<td>9.9</td>
<td>239</td>
<td>4</td>
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<tr>
<td>$W_M$ (nm)</td>
<td>1306.7</td>
<td>14.4</td>
<td>239</td>
<td>16</td>
<td>1303.6</td>
</tr>
<tr>
<td>$W_{MF}$ (nm)</td>
<td>1303.4</td>
<td>11.4</td>
<td>239</td>
<td>15</td>
<td>1301.1</td>
</tr>
<tr>
<td>$W_B$ (nm)</td>
<td>1339.3</td>
<td>16.2</td>
<td>239</td>
<td>17</td>
<td>1335.7</td>
</tr>
<tr>
<td>$W_{BF}$ (nm)</td>
<td>1325.9</td>
<td>21</td>
<td>239</td>
<td>38</td>
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<td>$A_L$ (°)</td>
<td>94.9</td>
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<td>239</td>
<td>0</td>
<td>94.9</td>
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<tr>
<td>$A_R$ (°)</td>
<td>96.3</td>
<td>4.1</td>
<td>239</td>
<td>10</td>
<td>95.8</td>
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<tr>
<td>$H$ (nm)</td>
<td>226.7</td>
<td>5.3</td>
<td>239</td>
<td>7</td>
<td>226.1</td>
</tr>
</tbody>
</table>

It can be seen that the mean of $W_T$ is smaller than the mean of $W_{TF}$ as shown in Fig. 7. $W_T$ is closer to the real linewidth at the top of the profile; however, it is only determined by the distance between two special points on the profile. On the other hand, $W_{TF}$ may be more representative for the whole profile because of the contribution of more data points used for its evaluation. For most images, the standard deviation of $W_{TF}$ is smaller than that of $W_T$.

As shown in Fig. 8, the difference between $W_M$ and $W_{MF}$ is only 2.5 nm or 0.2 % of the linewidth, and for the same reason mentioned above, the standard deviation of $W_{MF}$ is smaller than that of $W_M$. Multiplying of $W_M$ or $W_{MF}$ by $H$ yields a parameter approximately proportional to the area of the section, and to the line conductance under certain conditions.

As shown in Fig. 9, the mean of $W_B$ is larger than the mean of $W_{BF}$. This may be due either to the difficulty of fabricating a “clear corner” between the bottom surface and the sidewall, or to the rounding effect of the probe tip size. Similarly the standard deviation of $W_{BF}$ is smaller than that of $W_B$. $W_B$ or $W_{BF}$ can, in principle, be used to evaluate the cross-talking current between features, because the larger $W_B$ or $W_{BF}$, the smaller the space of two features, when the pitch is a constant. Hence control of feature isolation in the semiconductor industry could be enabled by measurement of the sizes of $W_B$ and $W_{BF}$.

$A_L$ and $A_R$, shown in Fig. 10, are used to evaluate the shape of sidewalls. Sidewall angles are related to manufacturing technology, the geometric size of tips, and the tip motion direction against the sidewall when performing a measurement. The sample used in this paper has a sidewall angle of 90° in theory. However, because of the properties of instruments, we found that when the tip motion direction is toward the sidewall,
the measurement result of the sidewall angle is closer to 90° than when the tip motion is away from the sidewall. There are two sidewalls in a profile, the tip motion is always towards one sidewall and away from the other, therefore during the operation, we minimized the difference between trace and re-trace by adjusting the set-point parameter on the instrument.

The step height $H$ (Fig. 11) is a vertical parameter that is used together with the horizontal parameters to evaluate the geometric shape of a profile. The differences between $W_T$ and $W_{TF}$, $W_M$ and $W_{MF}$, $W_B$ and $W_{BE}$ also reflect information about the shape, size and angle of the tip.

For example, we have obtained a sidewall angle of 90.28° (180° - 89.72°) by taking a smaller scan size and only imaging one edge, as shown in Fig 12.

A 3D model image consisting of N model profiles $L_i$ is shown in Fig. 13. Table 2 presents the results of four measurements at the same area of a sample under different tip motion directions based on the model and algorithm established in this paper, it shows good measurement repeatability among the surface profiles as indicated by the standard deviations.

**FIGURE 12.** A single sidewall profile measured with a scan size of about 450 nm. **FIGURE 13.** A 3D model image.

<table>
<thead>
<tr>
<th>Table 2. The results of four measurements at the same area of a sample under different tip motion directions.</th>
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<td><strong>First measurement</strong></td>
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<tr>
<td><strong>(trace)</strong></td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>$W_T$ (nm)</td>
</tr>
<tr>
<td>$W_{TF}$ (nm)</td>
</tr>
<tr>
<td>$W_M$ (nm)</td>
</tr>
<tr>
<td>$W_{MF}$ (nm)</td>
</tr>
<tr>
<td>$W_B$ (nm)</td>
</tr>
<tr>
<td>$W_{BE}$ (nm)</td>
</tr>
<tr>
<td>$A_L$ (°)</td>
</tr>
<tr>
<td>$A_R$ (°)</td>
</tr>
<tr>
<td>$H$ (nm)</td>
</tr>
</tbody>
</table>
CONCLUSION AND FUTURE WORK

In this paper, a metrological model and algorithm for nanometer scale linewidth measurements are established based on AFM measurements. The software of the algorithm was developed using MATLAB for the calculation of width, slope, and height parameters of the linewidth profile. A NIST nanometer scale linewidth sample developed at NIST’s Electronics and Electrical Engineering Laboratory (EEEL) was measured by a commercial AFM with nanotube tip. The model and algorithm developed in this paper address a data processing need for a common model, procedure, and parameters to minimize one source of methods divergence in nanometer scale metrology.

Parameters of the model may also be related to certain functional properties of semiconductor lines. $W_T$ usually is closer to the real linewidth at top than $W_{TF}$, while $W_{TF}$ may be useful as a stable constructed parameter of upper line topography. $W_M$ and $W_{MF}$ are closely related to the conductance when used together with $H$. This function may become important as semiconductor features become smaller. $W_B$ and $W_{BF}$ could be used to evaluate isolation properties. $A_I$ and $A_R$ are used to evaluate the geometric shape of sidewalls. The parameters $W_{TF}$, $W_{MF}$ and $W_{BF}$ generally have smaller standard deviations than $W_T$, $W_M$ and $W_B$.

Plans for future work include measuring nanometer scale linewidths using different tips while applying the model and algorithm in this paper and analyzing how the results depend on the size and shape of tips. An uncertainty budget is to be developed, and the relations of measurement results with the tip motion direction, scan speed and the contact modes of AFM will be studied. Due to the variation of the mounting angles of nanotubes, measured images usually are only reliable on one side of a line. The other side is distorted because of contact with the oblique nanotube. We are currently studying the feasibility of stitching two images taken in opposite directions to form one image by applying a correlation function to match these images.

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REFERENCES

14. Certain commercial equipment, instrument, or materials are identified in this paper to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the NIST, nor does it imply that the materials or equipment identified are necessarily the best for the purpose.