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Statistical Analysis of Multilayer Structures in Electron Microscopy Using Image Processing

Image processing can be used to generate high density critical dimension measurements that allow us to extract the full profile of the interfacial roughness in a multilayer stack.

Introduction

Electron microscopy images play a critical role in semiconductor device characterization, allowing engineers to visually inspect devices and measure critical dimensions relevant to their performance. This process of measuring critical dimensions can be repetitive and time consuming when done manually. Although this is less of an issue when only a few measurements are needed, these issues can become prohibitive when it is necessary to examine the full profile of a specific dimension across the entire image or when measurements need to be made across many images. In these cases, automatic image processing is required to extract the critical dimension information. In this Application Note, we demonstrate our capability to generate a large number of measurements in a single image to determine the roughness of interfaces in a multilayer stack and the roughness correlation across layers.

Discussion

Figures 1a, b show high-angle annular dark field (HAADF) scanning transmission electron microscope (STEM) images of a Mo-Si multilayer stack. In HAADF STEM images, the intensity is roughly proportional to Z^2, so the bright layers are Mo and the dark layers are Si. For the purposes of this illustration, we will focus on the top/bottom interfaces of the 40th silicon layer, shown in Figure 1c. The most important step in measuring the roughness of the interface is first accurately measuring its position across the entire image. To accomplish this, we start by choosing an intensity threshold to build a mask that roughly selects the Si layer, as shown in Figure 1d, and then extract the pixel positions on its perimeter. This serves as an initial guess for the interface position on both the top and bottom of the 40th Si layer.

Next, we apply a Sobel filter to the image that will highlight the position of the interfaces with high

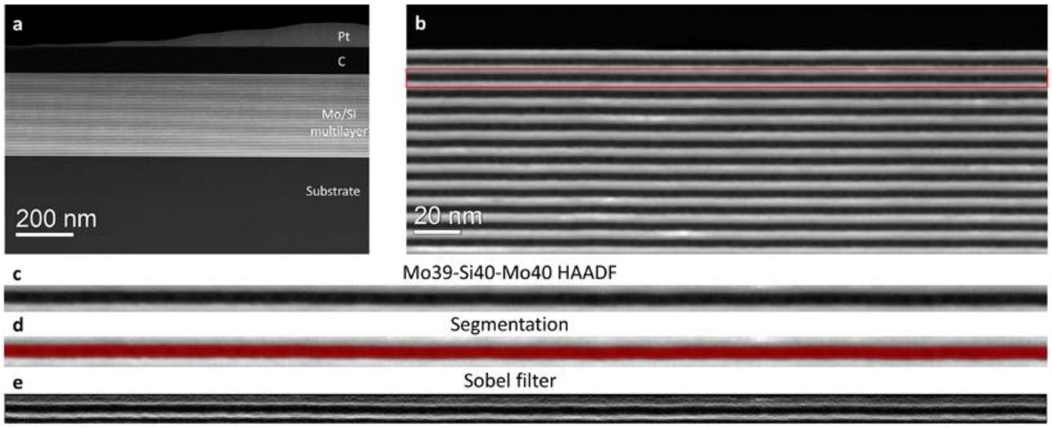


Figure 1: ***a*** *HAADF STEM image of a Mo/Si multilayer stack.* ***b, c*** *Higher magnification views of the top layers from* ***a****. The highlighted layer in* ***b*** *is the Si layer chosen for analysis and shown in a cropped view in* ***c. d*** *The segmentation of the Si layer in red is based on an intensity threshold.* ***e*** *The resulting image after a Sobel filter is applied.*

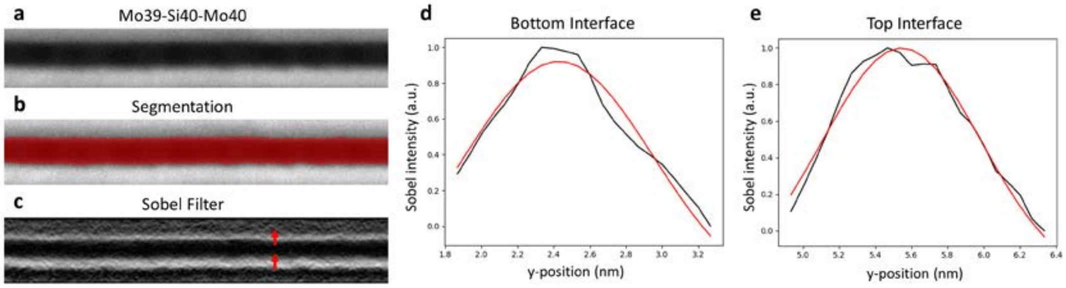


*Figure 2: **a-c** Zoomed in views of the left edge of the Mo39-Si40-Mo40 stack. **d, e** Vertical line profiles used for locating the interface from positions marked in **c**. The Sobel intensity is shown in black and the gaussian fit is shown in red.*

intensity. The Sobel filter effectively performs a numerical derivative over the image, revealing regions where the intensity is changing fastest. Since intensity in HAADF images can be correlated to chemical composition, it is reasonable to define the position of the interface based on the peak intensity in the Sobel filtered image. The image after applying the Sobel filter is shown in Figure 1e. To locate the peak, we extract a vertical line profile for each column of pixels covering either the top or bottom interface and then use gaussian fitting to determine the peak position. The exact position of the line profile and the initial parameters for the gaussian fitting are determined by the initial guess for the peak position. This process is depicted in Figure 2. Another equivalent option for finding the interface position is to directly fit the HAADF intensity with a sigmoid function; the exact fitting process should be chosen depending on the interface morphology.

After the interface is located, the interface roughness can be determined. A plot of the roughness for the top and bottom interfaces is shown in Figure 3. The roughness is defined as the difference between the y-position and the mean y-position of the interface across the entire image. The high density of measurements helps to reveal features that might be missed if only a limited number of manual measurements were made, such as the wide dip across the center of this region. We can also calculate the mean roughness (R_{mean}) and the root-mean-square roughness (R_{rms}) to distill the full profile into statistical quantities. We can also estimate the mean width of the interface (R_{width}) by averaging the standard deviation of each gaussian fit from the previous step. These statistical measures of the interface properties are summarized in Table 1.

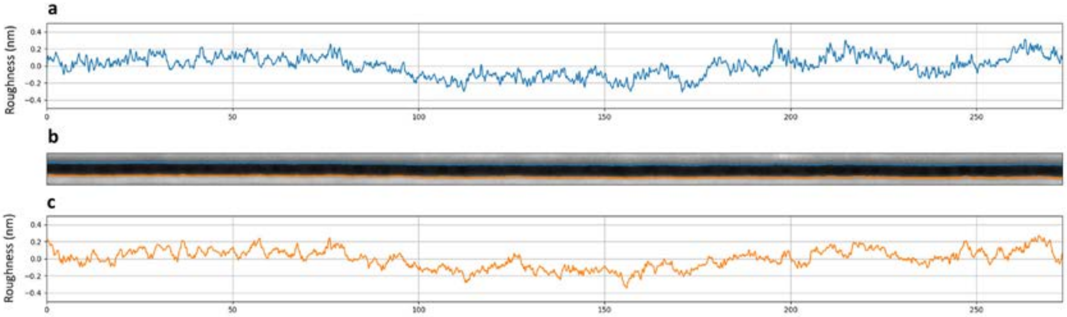


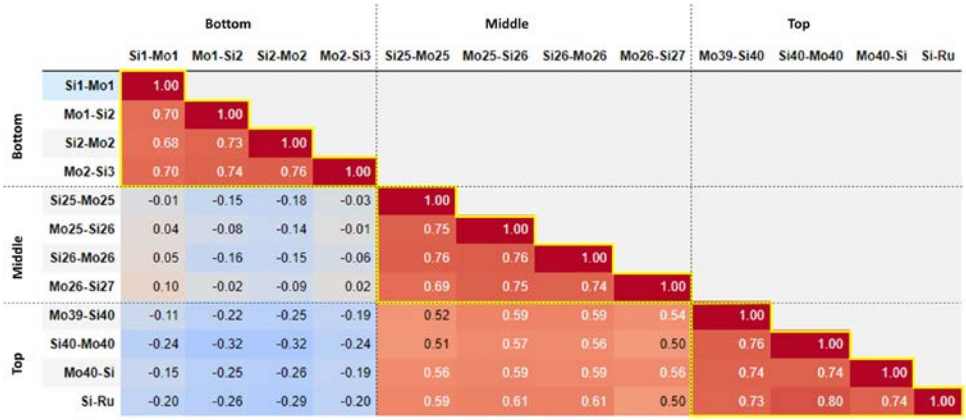
*Figure 3: **a** The roughness of the top Si40-Mo40 interface shown in blue. **b** The cropped region shown in Fig. 1c with the top and bottom interface positions overlaid as determined by gaussian fitting. **c** The roughness of the bottom Mo39-Si40 interface shown in orange.*

Interface	R_{mean} (nm)	R_{RMS} (nm)	R_{width} (nm)
Si40-Mo40	0.098	0.119	0.556
Mo39-Si40	0.090	0.109	0.544

Table 1: Interface Statistics

This process can be easily repeated across several layers within one image after identifying all interfaces. Roughness across the entire stack can be obtained and statistical measurements can be plotted to enable meaningful comparison across the entire stack.

In addition, we can examine both short-range and long-range correlations in the roughness profile between different interfaces. To measure this, we extracted roughness profiles for three sets of interfaces near the top, middle, and bottom of the multilayer stack and then we calculated the pair-wise Pearson correlation coefficient which is a measure of linear correlation between two functions. The results are summarized as a correlation matrix in Figure 4. Values close to +/- 1 indicate strong positive/negative correlation and values close to zero indicate no correlation. From the matrix, we can see that there is consistent strong short-range positive correlation between the roughness of adjacent layers. Weaker long-range correlations also exist between different regions of the stack.



		Bottom				Middle				Top			
		Si1-Mo1	Mo1-Si2	Si2-Mo2	Mo2-Si3	Si25-Mo25	Mo25-Si26	Si26-Mo26	Mo26-Si27	Mo39-Si40	Si40-Mo40	Mo40-Si	Si-Ru
Bottom	Si1-Mo1	1.00											
	Mo1-Si2	0.70	1.00										
	Si2-Mo2	0.68	0.73	1.00									
	Mo2-Si3	0.70	0.74	0.76	1.00								
Middle	Si25-Mo25	-0.01	-0.15	-0.18	-0.03	1.00							
	Mo25-Si26	0.04	-0.08	-0.14	-0.01	0.75	1.00						
	Si26-Mo26	0.05	-0.16	-0.15	-0.06	0.76	0.76	1.00					
	Mo26-Si27	0.10	-0.02	-0.09	0.02	0.69	0.75	0.74	1.00				
Top	Mo39-Si40	-0.11	-0.22	-0.25	-0.19	0.52	0.59	0.59	0.54	1.00			
	Si40-Mo40	-0.24	-0.32	-0.32	-0.24	0.51	0.57	0.56	0.50	0.76	1.00		
	Mo40-Si	-0.15	-0.25	-0.26	-0.19	0.56	0.59	0.59	0.56	0.74	0.74	1.00	
	Si-Ru	-0.20	-0.26	-0.29	-0.20	0.59	0.61	0.61	0.50	0.73	0.80	0.74	1.00

Figure 4: The correlation matrix between the roughness profiles of different interfaces within the multilayer stack. Values close to +1 (red) indicate strong positive correlation. Values close to -1 (blue) indicate strong negative correlation. Zero indicates no correlation. Short-range correlations are highlighted in yellow.

Conclusion

In this application note, we have demonstrated how image processing can be used to generate high density critical dimension measurements that allow us to extract the full profile of the interfacial roughness in a multilayer stack. From the roughness profile we can calculate statistical quantities and correlations that can give further insight into the structure's physical properties and performance as a component in semiconductor devices. Eurofins EAG provides our clients with access to state-of-the-art electron microscopy facilities and expertise to deliver the highest quality imaging data. In addition, we also offer customized quantitative image processing solutions to help our clients extract as much information as possible from their data. Look for future Application Notes detailing how conventional image processing can be combined with deep learning computer vision to measure critical dimensions in more complex structures. Contact us today to learn how we can help with your next project.