A Vision-Based Approach to Automated Analysis of Structure Boundaries in SEM Images

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Three-dimensional (3-D) structures are utilized in various devices and performance characteristic of such a device is sensitive to the actual dimensions of the fabricated structure. Therefore, it is often necessary to analyze the dimensional fidelity of a structure with high precision. An AFM may be employed in measuring depth profiles. However, its accuracy depends on the sharpness of a tip and is significantly limited for structures with deep narrow features. Another method is to use a SEM to obtain cross-section images, which is more generally applicable. One problem in this method is that it involves tedious tasks of locating structure boundaries and measuring feature dimensions and may lead to a substantial measurement error, especially if done manually. Hence, it is desired to have an automated systematic procedure for analysis of SEM images.

In this study, a vision-based approach has been developed for detecting the boundary of a structure in a cross-section SEM image and compensating for translational, scaling and rotational distortions, in order to quantify the dimensional difference between the target and fabricated structures. The first implementation of the approach is tuned for sawtooth and staircase structures shown in Fig. 1 and Fig. 4 though it can handle any shape of structure.

In the SEM image, the boundary region tends to appear brighter than other regions. Since the image intensity is higher in those boundary regions, we have applied a peak detection technique to locate boundary points. The intensity value of each image point is compared with those of its horizontal or vertical neighbors depending on its gradient direction, and the point is marked as a peak if it has higher intensity than its two neighbors. Among the peak points detected, only those points corresponding to cross-section boundaries are retained. The target profile (see Fig. 1(b)) is given by a 1-D function, i.e., only one boundary point is allowed for each location on the horizontal image axis. Since a boundary point may not be detected on some horizontal locations, the final output of the peak detection procedure is a set of points $\{(k, y_k)\}$, $k \in \Omega$, where Ω is the set of horizontal positions for each of which a boundary point is detected. In Fig. 2, the output of the peak detection step and the final filtered points corresponding to the cross-section boundary, obtained from the structure in Fig. 1, are provided.

The next step is to match the target profile, $h(x)$, and the detected image point set $\{(k, y_k)\}$. If there is no scale change between $h(x)$ and y_k, they differ by an unknown translation only, i.e., $y_k = h(k+u) + v$, where (u, v) is the unknown translation vector. The translation can be found using the template matching technique: among all possible combinations of (u, v), the one that minimizes the error $E = \sum_k [y_k - h(k+u) - v]^2$ is chosen.

In practice, however, when a sample is placed under the microscope, it is not easy to maintain its orientation so that the cross-section plane is perpendicular to the viewing axis. A small variation of the orientation would result in rotation and foreshortening in SEM image. In order to deal with scale changes and small rotation caused by this non-ideal imaging condition, we introduce two scale parameters and one rotation parameter. Then, the error formula becomes $E = \sum_k [y_k - \alpha h_\theta(\beta k + u) - v]^2$ where α and β are unknown scale factors and $h_\theta(x)$ is the rotated version of $h(x)$, and θ is the rotation angle. The three additional unknown parameters, α, β, and θ are determined using the matching technique in a sequential manner. To find the optimum α, the other two parameters are fixed, and the optimum value is determined using the exhaustive search within the pre-determined range. The other parameters are determined likewise.

The target profiles of the sawtooth and staircase structures, transformed through translation, scaling and rotation, are overlaid with the corresponding SEM images in Fig. 3 and Fig.4, respectively. It can be observed in the figures that the transformed target profiles well match the cross-section boundaries, which demonstrates that the vision-based approach can be further developed into a useful tool for analyzing SEM images.

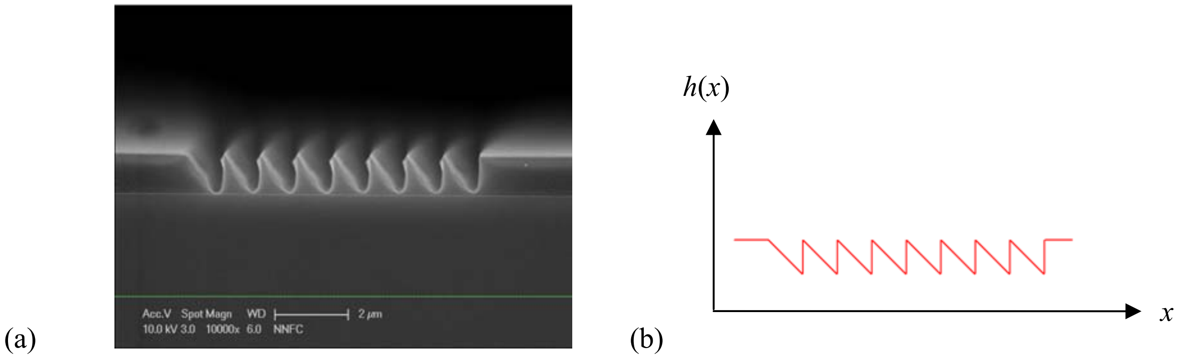

Fig. 1. (a) Cross-section SEM image of the sawtooth structure fabricated in the substrate system of 1000nm PMMA on Si through electron-beam lithographic process. The beam energy was 50 keV and the sample was developed for 30 seconds in the developer of MIBK:IPA=1:1. (b) Cross-section of the target sawtooth structure where both the width and height of each tooth are 1000nm.

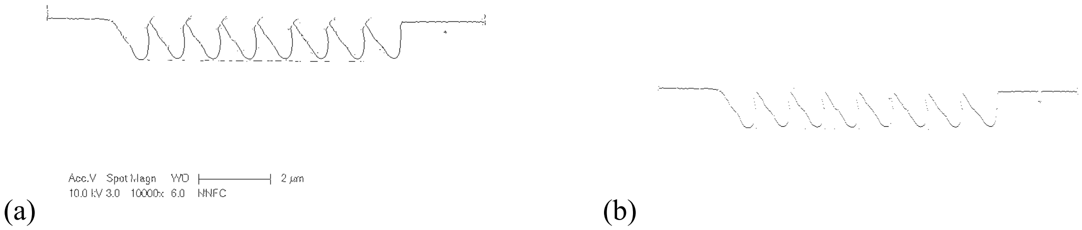

Fig. 2. (a) Detected boundary points for the SEM image in Fig. 1. (b) Filtered boundary points

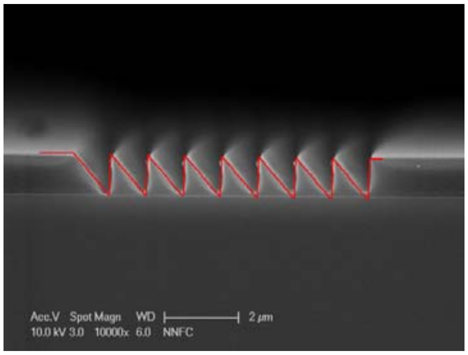

Fig. 3. Transformed target profile superimposed on the original SEM image

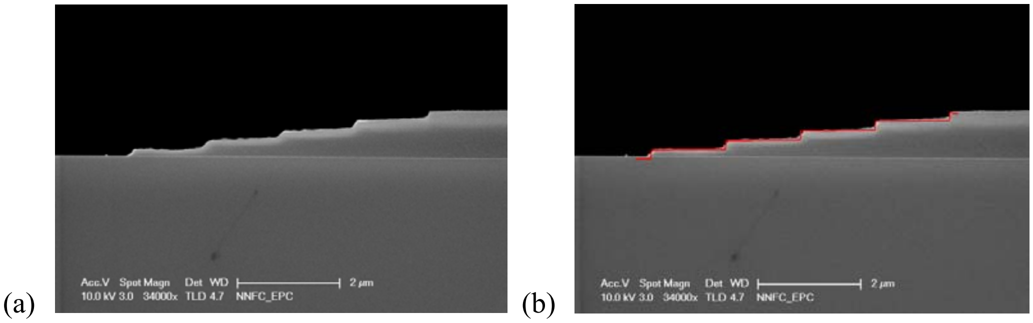

Fig. 4. (a) Cross-section SEM image of staircase structure fabricated by electron-beam lithography (50keV, 1000nm PMMA on Si). (b) Transformed target profile superimposed on the original image.