Three-dimensional Volume Reconstructions Using Focused Ion Beam Serial Sectioning

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Introduction

Traditionally, focused ion beam (FIB) microscopy systems have been used as instruments to repair integrated circuits, isolate defects or prepare materials for characterization with other techniques. Recently however, FIB microscopy has been used extensively as a standalone characterization technique. Typically, FIB microscopy can be used to probe site specific areas of a sample through secondary electron and ion imaging, energy dispersive x-ray analysis (EDX), or secondary ion mass spectroscopy (SIMS). These analyses will often combine two-dimensional elemental mapping or sputter depth profiles with imaging to investigate spatial variations of chemical and imaging signals. Inherently, these investigations are confined to two dimensions but often, complex materials problems are more easily understood if chemical and geometric information can be collected. Ideally, to generate geometric and chemical relationships, one would like to disassemble a material atom by atom, sort atoms by species and position, and then display this information graphically for analysis. One way to do this might be through a continuous sputter process, but continuous sputter processes yield relatively poor spatial resolution and chemical sensitivity for most materials due to differential sputtering and re-deposition. Difficulties due to differential sputtering and re-deposition can be overcome by discretely sampling a feature of interest as a function of depth and then interpolating geometric and chemical information between data samples. This combination of discrete sampling and interpolation allows for the reconstruction of sample volumes that can then be used to determine chemical, geometric and microstructural relationships.

In this article, a methodology that has been used to successfully produce quantitative three-dimensional volume reconstructions using FIB serial sectioning and linear interpolation is discussed. In addition, specific interpolative reconstruction algorithms are discussed as well as their applicability to different types of feature geometry.

Experimental

One of the most important aspects of quantitative FIB tomography is data collection. In this section, a generic data collection method is described for collecting image data that will be used to reconstruct three-dimensional material volumes. The same data collection scheme can be used to collect chemical information using EDX, SIMS or Auger elemental mappings and then combined with image data to produce three-dimensional chemical maps.

A typical data collection algorithm used for focused ion beam tomography is as follows. Secondary electron images are collected as a function of depth into a material of interest. Each image is divided into pixels, where pixel size is determined by the size of the probe used to collect the image. At each pixel, secondary electron or ion image signals are collected and stored. A feature of interest is then sputtered down to a specified depth with the beam parallel to the surface of interest, and another set of images is collected. To a first approximation, each image collected is considered a slice through a feature at a specific depth. In contrast to traditional imaging techniques, each image slice has a thickness that is determined by the amount of material removed by the beam when collecting secondary electron images. In addition, alignment marks are cut into the periphery of the first slice so that subsequent slices can be aligned with the first slice. These alignment markings are re-cut at several depths to avoid slice misalignment. Image data are then iteratively collected as a function of depth until a feature of interest has been sampled.

There are several aspects of this procedure that require further explanation. First, it is important that a feature of interest be sectioned with the beam parallel to the data collection surface because this minimizes deviations from a planar section due to differential sputtering. If material between slices is removed using normal incidence sputtering, surface topography caused by differential sputtering will increase in magnitude and severely degrade depth resolution.

Second, it is important that slice alignment markers are cut prior to data collection and that these markers remain sharp and undistorted in each slice. Typically, at least three square alignment marks are cut into the periphery of each slice so that both rotational and translational drift can be corrected.

Third, care must be taken to ensure that accurate slice depth can be measured. The most straightforward method for measuring slice depth is to measure sputtered depth edge-on using secondary electron images. In particular, the depth from the original surface is measured with the beam parallel to the sputtered surface. An implicit assumption in this method is that the image plane is flat and not inclined along the beam. An alternative method for determining slice depth is to measure the final sputtered depth using scanning probe microscopy. The total depth is then divided by the number of slices to estimate the depth of each slice.

Volume Reconstruction

Once image data have been collected as a function of depth into a sample, they can be processed further to reconstruct the sampled volume. There are several methods available to reconstruct volumes, but this article will focus on two methods, linear intensity interpolation and shape based interpolation.[1-2] In linear interpolation schemes, collected data are concatenated as a function of depth to produce a set of discretely sampled data. Volume elements (voxels) between slices are then interpolated using linear interpolation algorithms. Linear interpolation schemes are accurate for objects that can be generated by extrusion operations such as columnar grains and vias in multilevel interconnect structures. Figure 1 shows an example of an array of inter-level vias reconstructed from secondary electron image data using linear intensity interpolation.

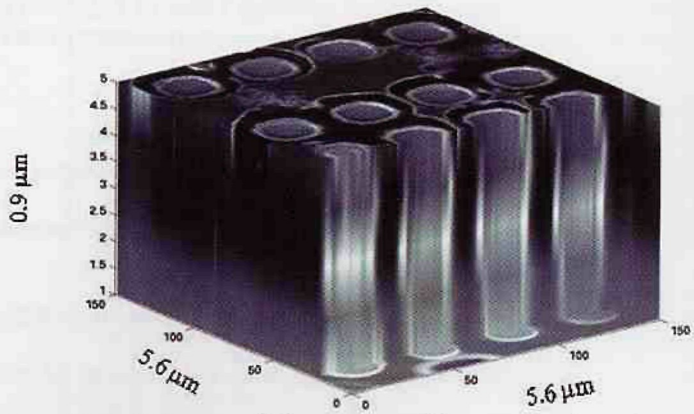

Figure 1: An array of vias reconstructed from a series of secondary electron images collected as a function of depth. Linear intensity interpolation was used to calculate pixel values in volumes between slices.

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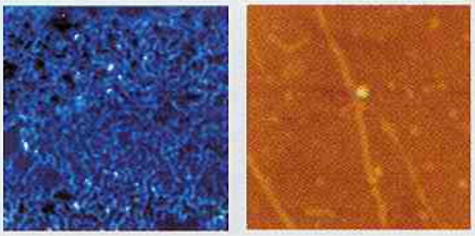

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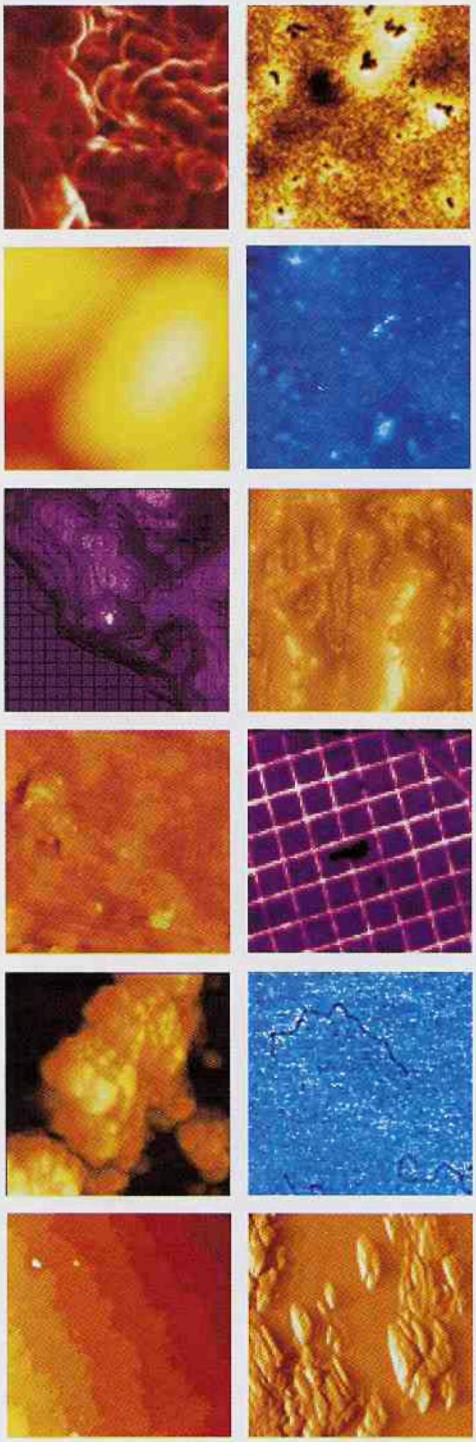

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It is clear from Figure 1 that linear intensity interpolation has faithfully reconstructed portions of these vias where there are no irregularities in sidewall profile. There are however, areas where sidewall irregularities are observed and in these areas the reconstruction appears blurry and smeared. These blurry and smeared regions are areas where via sidewalls have become irregular and cannot be accurately reconstructed with linear intensity interpolation methods. In general, linear intensity interpolation methods cannot accurately reconstruct object volumes that have significantly curved interfaces along the data collection axis, and should only be used as rough approximations or to reconstruct volumes that can be generated by extrusion operations along the data collection direction.

In order to overcome geometric limitations imposed by intensity interpolation methods, several other reconstruction algorithms have been developed. Shape-based interpolation is one scheme developed for medical tomographic imaging that uses interfaces present in data sets to reconstruct complex features.[1-2] Shape-based interpolation is more accurate than intensity based reconstruction techniques because the shape of the object, rather than image intensity, is being interpolated, thus inaccuracies and edge blurring often observed in intensity interpolation are avoided.[1-2] Since FIB microscopy images and elemental maps consist primarily of spatially varying intensities, shape-based interpolation can be readily adapted to tomographic reconstructions of geometric and chemical data from FIB microscopy data. Shape-based volume reconstructions can be used to not only establish chemical and geometric relationships, but also to obtain quantitative information such as the sharpness of interfaces, surface area, volume, and volume fraction of features of interest.

In shape-based interpolation, the shortest distance of a voxel to the edges of a feature is calculated as shown in Figure 2. If a voxel is inside the edges of a feature, this distance is entered into a voxel as a positive distance; if a voxel is outside the edges of a feature; its closest distance to feature edges is entered into a voxel as a negative distance. Voxels that fall on the edges of a feature, by definition, have zero distances. The determination of whether a voxel is inside or outside of a feature is done using standard inside-out tests.[3]

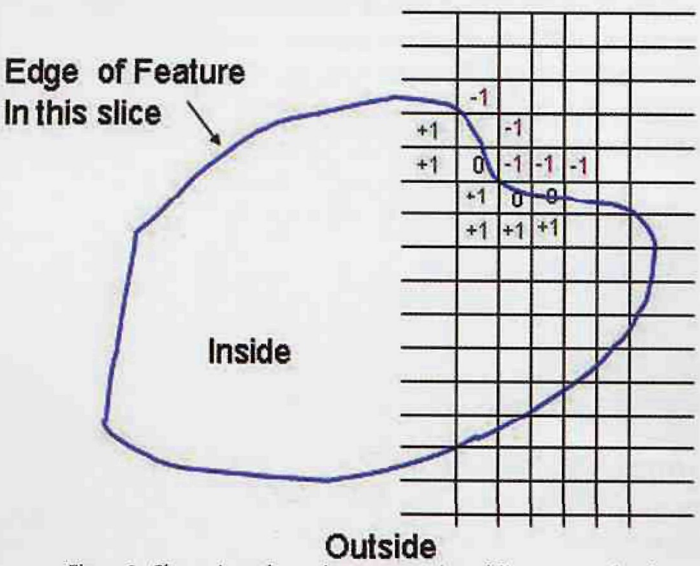

Figure 2: Shown is a schematic representation of distances to edges in a slice used for shape based interpolation. The closest distance to an edge is calculated and stored in a voxel. If a voxel is outside an edge, its value is recorded as the negative, if it is on the edge its value is zero and if it is inside an edge its value is recorded as positive.

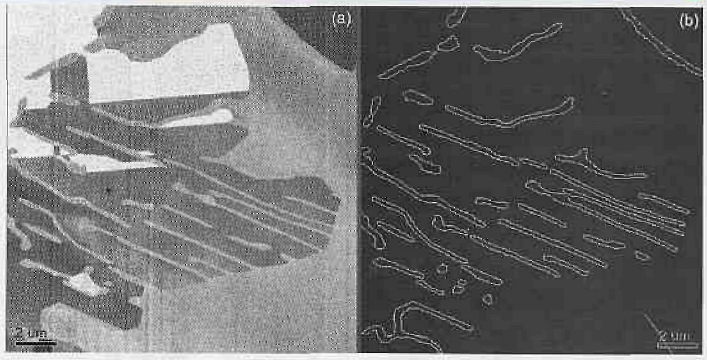

Figure 3: (a) A secondary electron image showing a Cu-In lamellar colony that is to be reconstructed. (b) Shown are edges that will be used for shape based interpolation. These edges were found by using standard image processing edge detection methodsiv.

Once each slice has been processed and edge distances determined, inter-slice distances are found by using bi-linear interpolation. After interpolation has been completed, voxels that have negative edge distances are turned off (set to zero) and the resulting volume is represented by voxels that have zero or positive distances to feature edges.

Putting shape based interpolation to use, image data from each collected slice are processed prior to volume reconstruction. In particular, the edges of features of interest are identified and labeled so that shape-based interpolation routines can properly identify those voxels that are inside and outside of a feature in a particular slice. Edges within image data can be found using one of several standard image processing techniques. Shown in Figure 3 are typical images and corresponding edges from a Cu-In lamellar colony.[4] The image shown in Figure 3a is a secondary electron image and the edges of Cu-In lamellae are shown in white in Figure 3b.

Once edges have been identified in each slice, shape based interpolation routines are used to reconstruct the volume enclosed by the edges in each slice. Figure 4 shows a volume reconstruction for the

Figure 4: A volume reconstruction of a Cu-In lamellar colony reconstructed using secondary electron images and shape base interpolation. The red structures shown in this reconstruction correspond to the lamellae shown in Figure 3.

Cu-In colony shown in Figure 3. This reconstruction was calculated using 17 slices similar to those shown in Figures 3a and 3b.

It is clear from the reconstruction shown in Figure 4 that irregular shapes and curved surfaces can be accurately interpolated using shape based methods. There is a wealth of information available from volume reconstructions like the one seen in Figure 4. This volume can be sliced and viewed from arbitrary directions, using standard graphical software, and then used to determine several stereological parameters. For instance, one-, two- and connectivity relationships can be determined, as well as the volume and areal fractions of features like the lamellae, all of which can be calculated directly rather than inferred from two-dimensional image data. These types of data have direct applications to thermodynamic and kinetic models commonly used in materials science and engineering.

The reconstructions shown in Figures 1 and 4 are good examples of the types of three-dimensional spatial maps attainable using FIB serial sectioning and linear interpolation. These techniques however are not suitable for all samples and several considerations should be kept in mind. First, both linear intensity interpolation and shape based interpolation require that there be sufficient contrast in secondary electron images to identify features. For shape based interpolation this is particularly important, because contrast gradients at feature surfaces are typically used to find edges. If contrast at feature interfaces is not sufficient, significant errors in edge identification are possible and these errors will be propagated into volume reconstructions.

Second, the ultimate resolution of these techniques is determined by the ultimate achievable point to point resolution determined by the contrast transfer functions of either the ion or electron column used to collect images. As such, the ultimate feature size that can be reconstructed is constrained by the point to point resolution of the imaging column.

Finally, a critical eye should be used when examining images and edges from slice data. In particular, investigators should take into account possible sputter artifacts such as redeposited materials, knock-on cascade displacements from sputtering and differential sputtering. If not properly accounted for, all of these effects may introduce unwanted artifacts into feature volume reconstructions.

Conclusions

A method for tomographic imaging using FIB serial sectioning and linear interpolation has been reviewed. Two linear interpolation algorithms were shown to reconstruct features of interest, but shape based interpolative methods are best for features of arbitrary shape. As with any analytical technique, care must be taken during data collection and processing steps in order to avoid introducing artifacts into final volume reconstructions. ■

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