The Dual-Beam—Its Birth, Progress, and Future

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Introduction

At the Pittcon 2014 conference, Dr. Lynwood Swanson, founder of FEI and one of the seminal minds behind the development of dual-beam technology, received the Heritage Award in recognition of his contributions to advanced electron and ion microscopy. FEI introduced the first commercial DualBeam™ instrument in 1993. In the twenty years since, dual-beam technology has become a central technique for imaging, analysis, and prototype fabrication at the nanometer scale. This article takes a look back at how the instrumentation has evolved and a look ahead at where it may be going.

Dual-Beam

Dual-beam instruments combine a focused ion beam (FIB) [1] and a scanning electron microscope (SEM) in a single instrument. The FIB sputters material from the sample surface and is most often used to make precise cross-sectional cuts that reveal subsurface structure for examination. When used with appropriate gas precursors, FIB may also be used to deposit material on the sample surface. The SEM provides high-resolution, non-destructive imaging of the surface revealed by the FIB. A word about terminology: "dual-beam" refers generically to any FIB/SEM instrument, and DualBeam" is the trade name of FEI's line of dual-beam products.

An important characteristic of the dual-beam, and one that likely played an important role in the instrument's initial acceptance, was the configuration of the electron and ion columns (Figure 1) such that the SEM could be used to navigate to a feature of interest with the sample horizontal, and the sample could then be tilted normal to the FIB to mill the cross section without the feature moving out of the field of view. In the tilted milling position, the SEM has a clear view of the milled surface, allowing the operator to monitor the progress of the milling operation and stop milling when the desired structure was revealed. This configuration created a simple and fast solution for locating, cross-sectioning, and imaging a targeted feature [2].

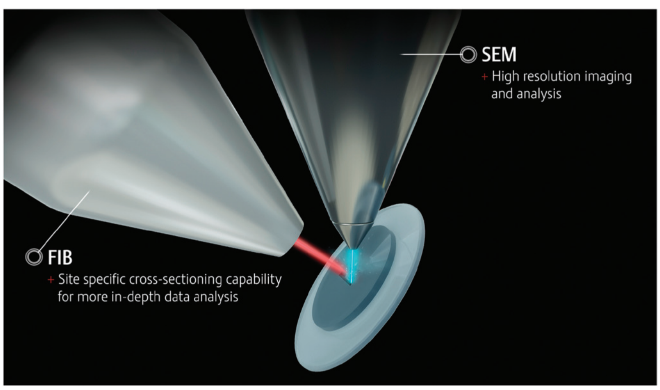

Figure 1: In a dual-beam system the electron and ion beams intersect at a coincident point near the sample surface, allowing immediate, high-resolution SEM imaging of the FIB-milled surface.

Semiconductor Manufacturer Needs

Semiconductor manufacturers, who were at the time struggling with the challenges of fabricating devices with "sub-micron" dimensions, were among the first major adopters of the new dual-beam technology. With each technology node change, feature sizes continued to move beyond the resolving power of light microscopes; and manufacturers readily adopted SEMs for process control and defect review.

With ion beam milling technology, manufacturers had a tool that could look below the surface at a defect location to diagnose the root cause. Software for navigating to defect sites based on coordinates derived from inspection or electrical testing, often combined with CAD data from the circuit layout, further enhanced the value and acceptance of dual-beam technology in defect and failure analysis. Device and instrument manufacturers collaborated to develop a large body of knowledge and expertise that allowed them to quickly and efficiently locate and investigate site-specific features anywhere on the surface of a wafer. Another microelectronics application that drove development of both dual-beam and single-beam FIB technology was the ability to rewire completed circuits to test modifications before committing to the huge investment of time and money required to create new masks and fabricate new silicon devices.

TEM Sample Preparation

Today, as we develop manufacturing processes for semiconductor devices with minimum dimensions of twenty nanometers and less, a new set of forces is driving dual-beam development. Critical features of these devices, now too small to be adequately resolved by SEM, must be imaged in a transmission electron microscope (TEM). Although TEMs, which nowadays can resolve individual atoms, have been available longer than SEMs (the first electron microscope was a TEM), their widespread use has historically been constrained by the difficulty of preparing the extremely thin samples required to allow electron transmission. The required thinness has been pushed even further by the decreasing dimensions of semiconductor devices—ideally the sample should be thinner than the feature it sections. Manual methods of preparing samples this thin are notoriously difficult, time-consuming, and unreliable. The problem is compounded when the section must be site- and orientation-specific, perhaps containing a specific gate or memory cell.

Over the last decade, researchers and engineers have developed automated dual-beam routines that can navigate to the targeted feature on a full wafer, cut a thick section

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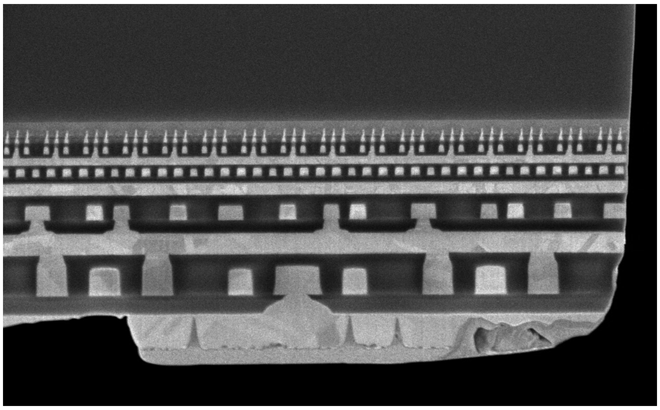

Figure 2: Thin TEM sample from an integrated circuit prepared by DualBeam. Width of specimen in field of view = 8.2 μm.

containing the target from the wafer, transfer the thick section to a TEM grid, and thin the section to the required final thickness, including a final polishing step at low beam energy to remove surface damage created earlier in the process (Figure 2) [3]. In addition to extensive developments in automation, perfecting this capability required sophisticated improvements in the electron and ion columns. The SEM must provide the highest possible resolution and contrast just to see the features of interest. The FIB must deliver the optimal combination of beam current and beam diameter over a wide range of conditions: high current for fast material removal, small beam diameter for precise control, and excellent performance at very low beam energies to limit damage during the final polishing step.

As demand for TEM analysis has grown rapidly, so has market pressure to reduce the cost and improve the throughput of TEM sample preparation. The latest dual-beam instruments can be located very close to the manufacturing equipment that builds and tests semiconductor devices. This proximity to the production line means that dual-beam tools can provide the fastest, most accurate data possible to the engineers who must make critical process decisions to increase and maintain factory yield. These tools have reduced the capital expense of TEM sample prep by 70% and made the process seven times faster. Multiple, site-specific samples now can be taken from whole wafers with their provenance tracked automatically. This provides more data faster—and with better traceability—than manually cleaving the wafer into hard-to-track pieces. Automated dual-beam TEM sample preparation will be a key enabler of the industry's continuing efforts to put more computing power in less space as it seeks to extend the record of progress first described by Gordon Moore in his eponymous Law nearly fifty years ago.

3D Visualization and Analysis

While microelectronics remains one of the most important areas of application for dual-beam systems, the technology has spread to applications in other fields. One common theme in many of these applications was the need for three-dimensional (3D) information at the sub-micrometer level. Materials science, the life sciences, and natural resources all offer telling examples.

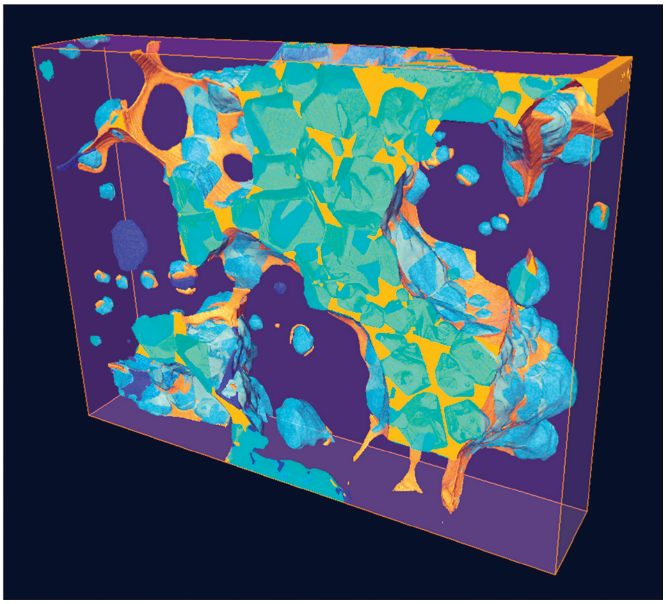

Figure 3: Zinc oxide material fractions determined by reconstruction of serial slice data to yield 3D volume fractions for identified materials and voids. Image width = 33 μm. See the video at: http://bit.ly/R8AAjl

The everyday macroscopic behavior of materials is controlled by structure at the molecular and atomic level. Although we can certainly extrapolate from 2D observations to model 3D behavior, dual-beam technology provides a means to observe 3D structure-function relationships directly. A simple cross section opens a window into the third dimension, but special reconstruction techniques allow dual-beam instruments to deliver a much more complete view. By repeatedly acquiring an image then milling a thin layer of material from the surface, we can accumulate a sequence of images that represents the 3D structure within the sectioned volume. Combining these images computationally, we can reconstruct a high-resolution model of the volume that the computer can rotate, resection, or otherwise manipulate in a wide variety of ways, allowing materials scientists to view the sample from any angle without reacquiring additional images. Figure 3 shows a 3D rendering of zinc oxide material fractions. The image data may incorporate other simultaneously collected signals, such as characteristic X rays that give specific elemental composition at each point. The conceptual model of the material may be spatially correlated with models generated by other techniques, such as fitting a high-resolution dual-beam model into a larger scale model created with X-ray micro computed tomography (μCT).

Life itself is composed of vastly complex, 3D systems functioning over a range of spatial scales from tissues and cells down to molecules and atoms. Neuroscientists have used slice-and-view reconstructions to follow the paths of neurons through brain tissue. The example shown in Figure 4 is a 3D reconstruction of lung tissue.

Geologists and engineers in the oil and gas industry are very interested in the fine microscopic structure of reservoir rocks. Recently, dual-beam technology has been used to analyze the content and porosity of shales that contain vast untapped stores of petroleum and natural gas. These formations, such as the Marcellus shale that covers a large portion of the eastern United States, are known as unconventional reservoirs because the resources they hold cannot be extracted using conventional methods. The pores that hold the oil or gas are so small and poorly connected that the rocks must be broken up by injecting water, chemicals, and propping agents (sand or other particles to prop open the cracks) at very high pressures in a process known as "fracking,"—hydraulic fracturing. The production technology is expensive, so before they decide to develop a site, the producers must evaluate the content, size, and connectivity of the pores to estimate the amount of oil or gas that can be extracted. As Figure 5 shows, dual-beam technology allows them to visualize the pore network and other components of the shale directly.

Figure 4: 3D reconstruction of rabbit lung tissue. Full width = 1 µm. See the video at: http://bit.ly/1glJO7F

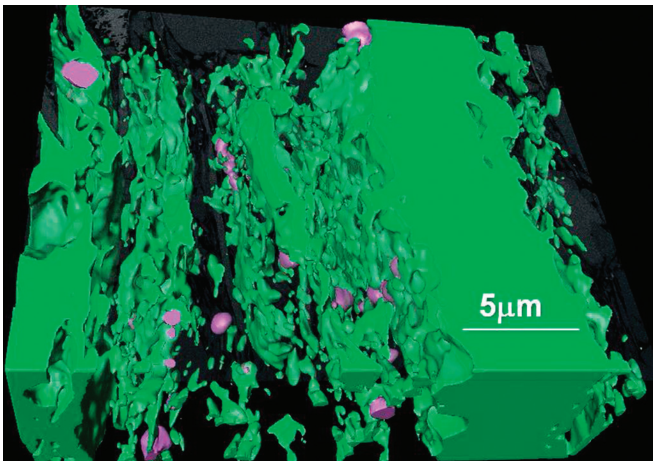

Figure 5: 3D reconstruction of layers of organic matter in a shale sample with limited connection between layers.

If 3D is Good, 4D Must be Better

The fourth dimension is time—how do materials change over time as they interact with their environment or are subjected to various external stimuli such as mechanical, electrical, thermal, chemical, magnetic, and many more. Conventional SEMs require high vacuum in the sample chamber to avoid scattering the electron beam. However, specially designed instruments permit gases at low pressures in the sample vicinity. This offers the opportunity to observe interactions between the gas and the sample directly. It also relaxes some of the constraints that previously made observations of dynamic phenomena difficult in conventional SEM, such as the use of a continuous conductive coating to avoid charging artifacts on nonconductive samples. These specially designed systems become essentially a laboratory in a box, combining FIB-based sample preparation and manipulation in high-vacuum mode with high-resolution SEM imaging of sophisticated dynamic experiments in a variety of sample environments.

Nanoprototyping—Building Machines Too Small to See

Over the last decade or so, whole categories of nanotechnology-based products have come into existence. They are so small that we are often unaware of their presence, but they have become an essential component of many of the things we use every day. They include microelectromechanical systems (MEMS), optical components, microfluidic devices, and many more. These tiny devices are often fabricated using batch processes to deposit and remove precisely patterned layers of materials, in a manner similar to semiconductor fabrication processes. This makes them inexpensive to produce in large quantities, but those methods are slow and expensive when used to develop prototypes of new designs. Dual-beam's ability to deposit and remove material with nanometer-scale precision, with exact repeatability over areas measured in mm^2, and immediately see the results provides a better way to create prototypes and test modifications.

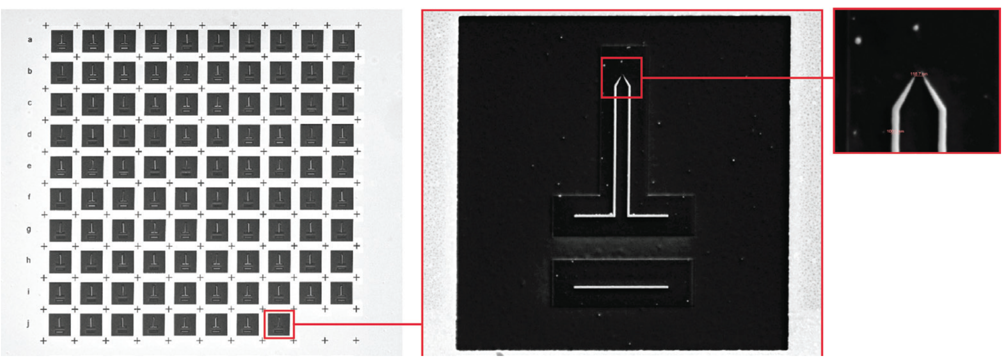

Figure 6: Array of antennas, minimum feature size <50 nm, written over a $200 \times 200\,\mu m^2$ field. Image courtesy of CIC nanoGUNE.

High-resolution patterning engines, specialized deposition and milling protocols, and a range of gas-assisted deposition and etching chemistries combine to deliver a fast, versatile nanoprototyping capability that can significantly reduce the number and length of development cycles for new nanotechnology-based products (Figure 6).

Current and Future Directions

Software for analysis and visualization has become increasingly important as the volume of data generated and dual-beam systems have grown. Data are often generated for a three- or four-dimensional array representing points throughout the analyzed volume over the relevant period of time. Gaining insights from this raw data regarding the behavior and properties of the sample is challenging, to say the least. Important progress has been made in visualization routines that translate the data into intuitive visual models that are easier to interpret and understand.

Another area of software development that holds great promise is automation. As dual-beam instruments evolve from laboratory-based instruments to industrial tools, they must be easily operated by personnel without training or expertise specific to the technique. Equally important, as experiments become longer in duration and the volume of data increases, automation can enable unattended operation that frees up human resources and improves the repeatability and reproducibility of data. Finally, as new applications proliferate, software and hardware development will permit the tight integration of dual-beam imaging and analytical protocols into seamless workflows that enhance productivity and deliver valuable answers when and where they are most needed.

Conclusion

In the twenty years since its commercial introduction, dual-beam technology has become the industry standard for imaging and analysis in numerous scientifically and commercially significant applications. Though the initial impetus for its development came largely from the semiconductor manufacturing industry, it has now become an important technique in disciplines as diverse as the life sciences, materials science, and natural resources development. Although much of its success is certainly based on the fundamental utility of an instrument that can image, analyze, and manipulate the sample at the nanometer scale, substantial credit must also be assigned to the collaborative efforts of suppliers and customers in developing the specific techniques and workflows that deliver value to scientific and commercial users alike.

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