An understanding of the fundamental differences among high-performance imaging and analysis techniques has become essential as diminishing device sizes have dramatically increased the need for sub-nanometer spatial resolution.

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Several advanced techniques, including Extreme High Resolution scanning electron microscopy (XHR SEM), transmission electron microscopy, and scanning transmission electron microscopy (S/TEM), can all deliver sub-nanometer resolution, but differ widely in other aspects of the information they provide. A thorough understanding of these differences permits selection of the technique or combination of techniques that best meets the analytical needs of the problem at hand.

The following discussion considers the latest advances in each of the major tools in the context of its principal capability: SEM systems for surface imaging, focused ion beam (FIB) and FIB/SEM Dual-Beam systems for sub-surface imaging, and S/TEM systems for atomic scale imaging and analysis.

Semiconductor analysis

Two different but related trends are driving the need for high-resolution imaging in semiconductor failure analysis. The first, and most obvious, has been the relentless reduction in device size to satisfy seemingly insatiable consumer demand for more computing power and lower prices. When device dimensions were measured in hundreds of nanometers, a conventional SEM’s ability to resolve features down to a few nanometers was more than adequate.

Now, with 22-nm devices in development, those same few nanometers constitute a significant fraction of the critical dimension.

The second trend has been a steady shift in the causes of defects, from random defects caused by contamination originating in the environment or processing equipment; to systemic defects that result from variability in the process itself.

In spite of the fact that smaller devices are vulnerable to smaller particles, and that there are many more smaller particles than larger particles present in the environment, device and equipment manufacturers have become very good at reducing contamination as a source of defects.

At the same time, process variability, which does not scale with decreasing device size (and may well have increased with the migration from 200 mm to 300 mm wafers), accounts for an increasing share of defects as process windows have shrunk with decreasing device size. Process variability is typically manifested as dimensional variability in critical structures, thus multiplying the need for precise image-based metrology to support tighter process control. It is not enough to simply see a 10-nm “killer” defect on a 22-nm line; the width and thickness of that line may need to be controlled within less than one nanometer.

Scanning electron microscopy

SEM scans a finely focused beam of electrons over the surface of a bulk sample and constructs an image in which the brightness at any point represents the intensity of some signal measured when the corresponding point in the sample is illuminated by the scanning beam. SEM is generally regarded as a surface imaging technique. It has broad acceptance based on its speed, flexibility, simplicity, and minimal sample preparation.

Surface imaging is certainly the most common form of imaging in semiconductor process control.
SEMs that offer sub-nanometer resolution over the entire range of beam energies. XHR SEM is a new category of SEMs that offers sub-nanometer resolution over the entire range of beam energies. Most analyses begin when a defect is detected, usually with visible or UV inspection tools. For many years SEM has played a primary role in defect review and dimensional control (CD-SEM) in the manufacturing process, as well as failure analysis of packaged parts and field returns. Unlike light, which is transmitted by some materials, electrons are readily scattered by any material, and therefore SEM is generally considered to be a surface imaging technique.

As is often the case, the practical definition of “surface” depends on the application. High-energy-beam electrons do penetrate the sample to a depth determined by their energy and the sample composition. As they penetrate, they scatter and spread throughout a region known as the interaction volume, the volume from which the various images originate. Ultimately, SEM resolution is limited by the size of the interaction volume.

The size of the volume can be reduced by reducing the beam energy. However, conventional SEMs cannot focus the low-energy electrons into a sufficiently small beam, and therefore beam diameter then becomes the limiting consideration.

Low beam energy offers other advantages in semiconductor applications. It reduces the risk of damaging delicate circuit elements and it can reduce or eliminate charging artifacts that interfere with imaging and measurement. Most important, it increases the specificity of the image to critical surface phenomena.

**Extreme high-resolution SEM**

XHR SEM is a new category of SEMs that offers sub-nanometer resolution over the entire range of beam energies, from 1 keV to 30 keV. It preserves the traditional SEM’s ease of use, sample handling flexibility, and minimal sample preparation requirements. In addition to filling the front line imaging role of a conventional SEM, they provide the capability to investigate complex three-dimensional surfaces with sub-nanometer resolution, a capability that will become increasingly important as new gate structures such as FinFETs are more widely used. Equally important, they can deliver surface-specific images that are not available from any other imaging technique available today.

Characteristic X-rays generated by electron beams offer a means of determining the elemental composition of the sample. X-ray images (maps) are generally noisy and have poor spatial resolution; however, they can still provide vital information in failure analysis applications, such as identifying the source of a contaminating particle. XHR SEM’s ability to deliver sub-nanometer imaging resolution over the full range of accelerating voltages, including the higher voltages most useful for X-ray analysis, makes it an ideal analytical platform.

**Focused ion beam**

FIB is similar to SEM except that the scanning beam is composed of ions, typically gallium, that have much greater mass than electrons. As a result, FIB can make precisely controlled cuts in the sample. DualBeam systems combine an electron and an ion column configured to allow high-resolution SEM imaging of the surface cut by the FIB. The need to see structures and defects below the surface has grown steadily in importance as design and process innovations have increased the three-dimensional complexity of integrated circuits: multiple interconnect layers; re-entrant, dual damascene processes; copper barrier, seed and fill; sidewall spacers; complicated gate stacks; and more.

FIB systems can cut site-specific cross sections through designated features to expose them for imaging and measurement. DualBeam instruments can provide high-resolution SEM imaging of the cross-section surface as it is cut by the FIB. “Slice and view” techniques can reconstruct a detailed three-dimensional model of a structure or defect from a series of images acquired as the cross section advances through the sample.

With its ability to cut precisely located holes, and deposit conducting and insulating materials in tightly controlled patterns, FIB can also serve to rewire a functional integrated circuit. This circuit editing capability allows manufacturers to confirm the validity of proposed changes in the circuit layout without the expense and delay of generating a new mask set and processing new silicon. In the context of sub-nanometer failure analysis, FIB’s most important contribution may be its ability to prepare ultra-thin (less than 100 nm), site-specific samples for TEM and STEM analysis.

**Transmission electron microscopy**

TEM illuminates the sample with a collimated beam of high-energy electrons, and focuses electrons transmitted through a very thin sample into a real image, which it projects onto a fluorescent screen or electronic imaging device. TEM images are two-dimensional projections of the three-dimensional (though very thin) sample. TEM is used primarily for high-resolution imaging and crystallography, though it does offer analytical capability based on characteristic X-ray emission and electron energy loss. Recent breakthroughs in aberration correction have pushed TEM image resolution into the sub-Angstrom range, the scale of atoms themselves.
Equally important, image correctors have greatly simplified image interpretation. Information in the images may now be directly interpreted down to the information limit, eliminating the need for complex image reconstruction procedures and confusion about the instrument’s ultimate resolution (for corrected TEM, image resolution = information limit).

Image correctors also eliminate delocalization, simplifying the interpretation of image information near discontinuities in periodic structures, such as crystalline defects, grain boundaries, and material interfaces.

Advances in sample preparation have greatly improved the ease, speed, and reliability of TEM analysis to the point that it is now practical for routine process control applications, capable of delivering first results in less than two hours, and throughput greater than two samples per hour. Equally important, advances in TEM automation and control systems have eliminated or simplified many of the routine column alignment and instrument tuning procedures.

For relatively large or homogeneous structures, the thin TEM sample can be regarded as a two-dimensional cross section, and its projected image may capture the needed information. However, structures smaller than the sample thickness may contain significant information in the third dimension (the beam direction) that cannot be captured in a single projection. Electron tomography reveals this information by combining multiple images acquired at different viewing angles into a detailed, three-dimensional model with near-nanometer resolution.

TEM can determine the composition of the sample by X-ray or by electron energy loss spectrometry (EELS). This technology analyzes the energy lost by beam electrons that are inelastically scattered by sample atoms.

The amount of energy lost is determined by the electronic structure and environment of the scattering atom, and therefore carries elemental, chemical, and electronic information. In TEM the entire field of view is illuminated simultaneously by the beam, and the spatial resolution of X-ray and EELS analysis is limited by the extent the field of view can be reduced with physical apertures.

Energy-filtered TEM (EFTEM), which forms an image from electrons with a specified energy loss, provides analytical capability with the full spatial resolution of TEM imaging.

**Scanning TEM**

The scanning transmission electron microscope (STEM) scans a finely focused electron beam over a very thin sample and constructs an image from signals measured at each point in the scan pattern. The image construction process is similar to that of the SEM, but the imaged signals and contrast mech-
anisms may be quite different due to the thin sample.

STEM may be carried out in a TEM or dedicated STEM column (with typical beam energies ranging from 100 keV to 300 keV), or in an SEM column (typically at 30 keV). STEM is generally known for its high-resolution analytical capabilities, though in some applications its imaging capabilities rival or exceed TEM.

STEM is known primarily for its ability to provide analytical results with very high spatial resolution. As in an SEM, the signals measured at any instant in time carry information that is specific to the current location of the finely focused beam. Unlike SEM, very thin samples dramatically reduce the size of the interaction volume by eliminating the subsurface spreading that occurs in bulk samples.

Spatial resolution for imaging and analysis typically approaches the diameter of the beam. Aberration-corrected STEMs have demonstrated spatial resolution as good as 0.5 Angstroms.

X-ray spectrometry provides elemental analysis. EELS characterizes composition, chemical bonding and electronic (band gap) states. Monochromators, which reduce the energy spread of the beam, can enhance the spectral resolution of the energy loss analysis. Crystallographic analysis using convergent beam techniques also benefits from STEM’s ability to confine beam interaction within single small crystals and grains.

STEM also provides powerful imaging capabilities. Images formed from elastically scattered electrons exhibit strong material (atomic number) contrast with sharply delineated interfaces. Delocalization, which complicates TEM image interpretation near discontinuities in periodic structures, does not occur in STEM imaging.

A formidable array of tools is available to support failure analysis with high-resolution imaging and analysis. Beyond their shared capability for sub-nanometer spatial resolution, each has specific strengths that are often complementary. Successful, efficient analysis requires an understanding of these differences to select the technique or combination of techniques that best meets the requirements of a particular application.

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