ChipMill

Large-scale ion beam delayering of microelectronic devices yielding nanometer flatness

FISCHIONE INSTRUMENTS

MODEL **1064** ChipMill

A fully integrated solution for millimeter-scale delayering of both logic and memory semiconductor devices. The ChipMill integrates signals from multiple detectors via an artificial intelligence feedback control algorithm to adjust milling parameters in real time. The result is the precise removal of device layers and a highly planar surface.

- Nanometer flatness of the prepared area
- Milling area up to 10 x 10 mm
- Automated sample height detection
- User-friendly interface for the setup of milling parameters and display of images and analytical data
- On-device touchscreen for managing sample insertion and removal
- End-pointing by time, chip structure, or chemical composition
- Components:
  - Ion source
  - Optical camera
  - Electron beam column
  - Secondary electron detector (SED)
  - Backscattered electron (BSE) detector
  - Energy dispersive X-ray spectrometer (EDS)
  - Secondary ion mass spectrometer (SIMS)

ION MILLING AND FISCHIONE INSTRUMENTS

For more than three decades, Fischione Instruments has been a world leader in ion milling for electron microscopy applications. The company's initial ion milling systems were dedicated to transmission electron microscopy (TEM) specimen preparation. Through the years, Fischione Instruments has gained significant expertise in ion source technology to effectively mill and polish samples without causing damage.

Within the same time frame, significant advances in electron optics have occurred. Scanning electron microscopy (SEM) performance is greatly enhanced, particularly high-resolution imaging at low accelerating voltages. This advancement has increased the importance of sample surface characteristics; mechanical preparation artifacts are no longer acceptable.

As the market for ion milling for SEM developed, Fischione Instruments extended its product line of suitable tools. Currently, Fischione Instruments' ion milling systems serve a multitude of applications, including cross-section sample preparation and polishing to support the structural and chemical analysis of various materials for multiple imaging and analytical techniques, such as electron backscatter diffraction (EBSD).

The Model 1064 ChipMill is a natural extension of the Fischione Instruments' product line.

The sample preparation breakthrough of the century

The Model 1064 ChipMill is a fully integrated solution for large-scale delayering – up to a 10 x 10 mm milling area – of both memory and logic semiconductor devices. Compared to all other methods, the ChipMill produces the flattest surface over the largest area. The ChipMill's artifical intelligence automatically adjusts milling parameters to yield nanometer flatness within the prepared area.

The ChipMill reduces time and costs associated with research and development, manufacturing, quality assurance, and failure analysis by yielding unsurpassed results. As the demand for semiconductor devices grows, device sizes decrease, and architecture becomes more complex, the ability to perform controlled delayering during all phases of the product life cycle is essential.

ChipMill components

The ChipMill contains an ion source to mill the sample, an optical camera to monitor milling progress, a scanning electron microscope (SEM) column working in conjunction with a secondary electron detector (SED) and a backscattered electron (BSE) detector for sample imaging. The electron beam also generates X-rays that are analyzed by the energy dispersive X-ray spectrometer (EDS) detector. A secondary ion mass spectrometer (SIMS) yields surface information.

> The ChipMill produces the flattest surface over the largest area

Detector technology

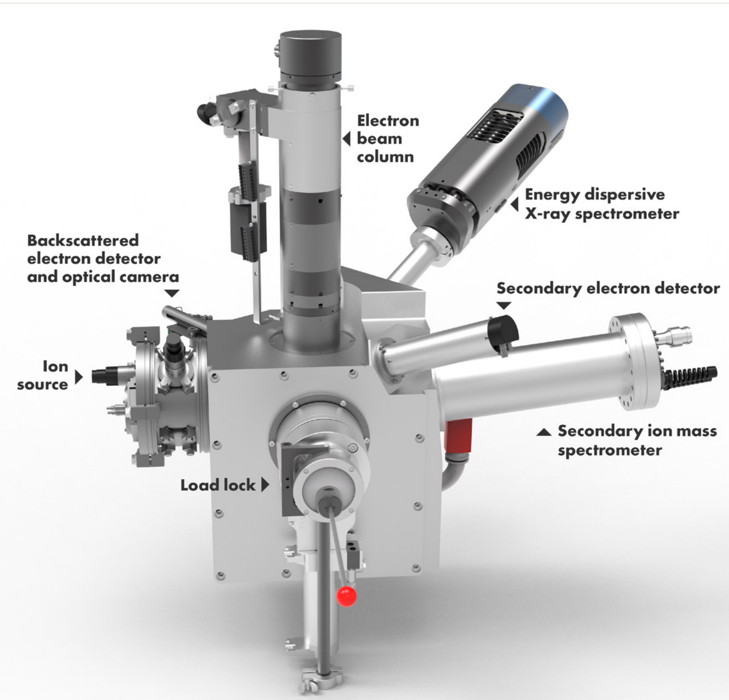
When the sample surface is excited by the electron beam, corresponding secondary electrons are collected by the SED. Electron images are displayed on one of the ChipMill's monitors.

Backscattered electrons are produced by the elastic scattering of the primary electron beam with atomic nuclei. Because information is generated by the nucleus of the atom, an indication of elemental composition becomes known.

By varying the electron beam accelerating voltage, the electron penetration depth changes.

ChipMill components

Detectors and additional components are attached to the ChipMill chamber. Clockwise from the top: electron beam column; energy-dispersive X-ray spectrometer (EDS); secondary electron detector (SED); secondary ion mass spectrometer (SIMS); load lock; ion source; and backscattered electron detector (BSE) and optical camera.



The ChipMill alters electron beam operating parameters to distinguish between the surface layer and the layer below.

EDS detects X-rays emitted from the sample surface, providing the elemental composition of the delayered device.

A SIMS system identifies the elemental composition of the top device layer.

The role of electron microscopy in semiconductors

Electron microscopy is used to support every phase of the semiconductor life cycle: research and development, manufacturing, quality control, and failure analysis.

During:

- **research and development**, circuit designs are developed and verified;
- **manufacturing**, processes are improved to enhance performance and yield;
- **quality control**, chip reliability is evaluated; and
- **failure analysis**, defects are identified and analyzed.

Chips are comprised of multiple layers, with each layer having a thickness ranging from a few atomic planes to several microns and node sizes of 3 nm or less. The need for precise, controlled delayering has never been more critical in supporting electron microscopy's role of understanding material properties and chemistry at the atomic scale.

ALTERNATIVE DELAYERING TECHNIQUES

Various techniques are used for delayering. Mechanical polishing involves particles of a micron- or sub-micron scale abrasive compound to abrade the surface of the sample. However, these particles create artifacts or scratches that potentially destroy important chip characteristics. Mechanical methods also do not offer the ability to either precisely control the amount of material removed or predict the process end point.

Etching removes material by subjecting the chip to various chemicals, which causes a chemical reaction that removes material from the chip surface. Depending upon the etchant chemistry, different materials within the chip react at different etching rates; therefore, preferential or non-uniform material removal occurs.

Plasma, or reactive ion etching (RIE), is another method to remove material from the chip surface. RIE uses combinations of ionized reactive gases and non-reactive gases. Reactive ions produce both a chemical reaction and a sputtering effect. Non-uniformities in elemental composition, material density, and etch species can adversely impact etching rates and surface uniformity.

Broad ion beam milling is often employed to delayer chips. In this process, the center of the ion beam typically has increased energy density as compared with its periphery, or tail. As a result, the center of the chip is milled faster than the edges. This creates a concave milling spot in the center where the ion beam is the strongest and a shallower depth at the edges where the ion beam density is weaker. This concave surface profile precludes the ability to image and analyze features located within a large area of a single chip layer.

More recent developments in delayering technology are FIB and plasma FIB (PFIB) technologies; whereby, the ion beam is intensely focused. The drawbacks of these methods are a slow milling rate, a relatively small milled area, and in some cases, the implantation of chemically reactive elements, such as gallium.

Additional techniques enabled by precise delayering are electrical probing to test individual circuits; metrology to measure feature sizes to ensure compliance with design specifications; post-mortem, single-defect failure analysis to remove material until the fault location is revealed; and reverse engineering to delayer a chip in a serial manner for the subsequent analysis of individual layers.

Delayering workflow

Depackaging

Prior to ChipMilling℠, standard depackaging techniques apply. These methods typically employ mechanical or chemical processes that are better suited to removing significant amounts of material as compared to the precise thinning afforded by an ion beam.

ChipMilling

Once the depackaged chip is mounted onto a standard SEM stub, it is transferred through the ChipMill's load lock and positioned on the sample stage within the vacuum chamber.

Following the initial set-up procedure, the chip is ion milled until the predefined end point is achieved. In many cases, the end point is an individual metal layer. After ChipMilling, the chip can be transferred to any one of several analytical devices.

Preparing TEM specimens

The ChipMilled sample can be placed into a focused ion beam (FIB) system for the site-specific extraction of transmission electron microscopy (TEM) lamellae.

Following post-FIB polishing in either a Fischione Instruments' Model 1040 NanoMill® TEM specimen preparation system or Model 1080 PicoMill® TEM specimen preparation system, the specimen's atomic-level structural and chemical information can be ascertained via aberration-corrected TEM imaging and analysis.

ION BEAM GENERATION

The ChipMill has a cylindrical ion beam with a maximum accelerating voltage of 10 keV. Advanced ion optics allow the beam to maintain its profile over a length of up to 10 cm. Through a momentum transfer/sputtering process, material is ejected from the sample in a precisely controlled manner that yields uniform delayering.

The ion source uses electron impact ionization technology. The source contains a filament cartridge that initiates the flow of electrons, directing them into an ionization chamber. In the ionization chamber, electrons interact with the process gas to create ions. Ions are subsequently extracted and directed through the focusing component of the ion source.

The exit of the ion source contains a beam steering mechanism that deflects the ions in the X and Y directions.

Applying Y-deflection bends the ion beam toward the sample surface, and in combination with the Z-offset of the sample stage, establishes the incident milling angle. Milling at a glancing angle achieves consistent milling.

The X-X raster function scans the ion beam across the sample surface in a variably controlled manner.

To establish planarity within an individual layer, the ion beam must uniformly remove material in a manner that is independent of device geometry and elemental composition. To achieve this objective, an in situ feedback control system employs the output data from the various detectors to adjust ion source operating parameters.

Raster control is automatically varied to correspond with the sample material, area of interest, ion beam energy, and ion beam current. Adjustments to the parameters needed to achieve uniform delayering are automatically controlled to adjust the raster pattern, raster rate, and the effective current density per point. Information obtained from the sample surface is used to modify the beam control parameters. This is the determining factor in achieving optimal surface flatness.

The ChipMilling process

All system components are included within a chamber that is evacuated by an oil-free vacuum system.

A dedicated sample stage featuring X, Y, Z, and rotational movements provides proper sample positioning in relation to various system components. Automated sample height detection places the sample surface at the optimal milling plane.

The ChipMill chamber design allows the ion beam to project across the sample surface at a glancing angle. The milling angle is established by the combination of sample height control and the amount of vertical deflection applied to the ion beam. The milling angle range is 0 to 10°.

While milling, the sample is continuously rotated to minimize non-uniform milling of various elements within the chip that sputter at different rates. Typically, harder materials mill more slowly, while softer materials mill more rapidly. This results in curtaining. Sample rotation normalizes milling and results in a planar surface.

Feedback from the sample surface controls ion beam scanning

During milling, the ion beam scanning pattern is controlled by an advanced algorithm which processes the output of various detectors:

- An optical camera captures interference fringes to determine the material removal pattern.
- Electron beam sample interaction yields secondary electrons that are captured by the Everhart-Thornley SED.
- Backscattered electrons result from the elastic scattering of electrons from the primary beam interaction with the sample surface; the backscattered electrons assist in distinguishing different layers within the device.
- X-rays emitted from the sample during bombardment by the incident electron beam are detected by the EDS system, which yields elemental composition information.
- Ions emitted during the milling process are analyzed by the SIMS, which is a surface-sensitive technique for determining which layer is exposed. It is useful in establishing if a layer is a metal, an oxide, or a nitride.

ChipMill's artificial intelligence process

The ChipMill features an artificial intelligence (AI) process that incorporates a feedback control loop to adjust the ion beam milling parameters in real time. The ChipMill receives and analyzes data from the various detectors to quantify both surface flatness and chemical composition of individual device layers.

Depth profiles are calculated by the ion beam control algorithm, which automatically adjusts the ion beam raster pattern in terms of both dwell time and current density per point while moving across the delayered area. This method of continuous feedback yields a highly planar sample surface.

System programing

The ChipMill is programmable through a standard computer interface. System operating conditions are programmed and viewed on a dedicated monitor. An on-board touchscreen, positioned next to the load lock, facilitates sample exchange.

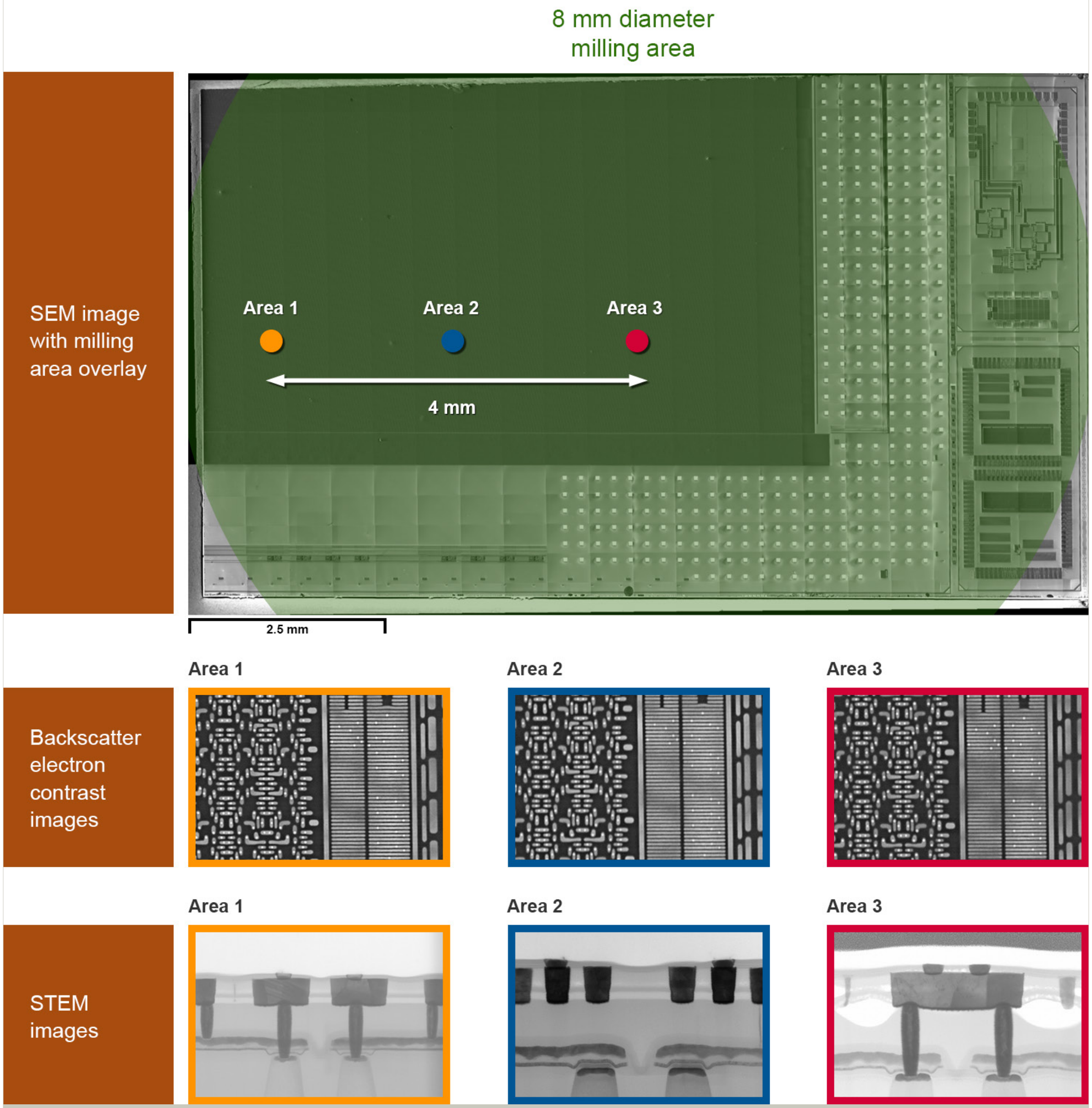
User controls can be placed either adjacent to the ChipMill or in a separate room.

> The ChipMill's pioneering end-pointing technique relies upon the acquisition of images and analytical data to yield precise end-point control

End-pointing

There are various methods of end-point detection, one of which is time-based. However, for time-based end-pointing to be effective, both layer thickness and milling rate need to be very well understood.

The ChipMill's pioneering end-pointing technique relies upon the acquisition of images and analytical data:



Uniformity of device surface after delayering process

Three areas (Area 1, Area 2, and Area 3) of a chip were selected for observation following ChipMilling (top row); the observation areas are spaced 2 mm apart. Backscatter electron contrast images (middle row) of the sample surface for each observation area are shown. Corresponding scanning transmission electron microscopy (STEM) images (bottom row) are also shown. The difference between the three areas of observation across 8 mm is within 50 nm.

- Ion milling exposes hierarchical circuit information from each layer.
- The SEM is operated at a given accelerating voltage to yield information about the surface of the layer being milled.
- The accelerating voltage of the SEM electron beam is increased to yield information relative to the layer below the surface.
- The data is correlated with the chemical composition generated by the EDS and SIMS systems to yield precise end point control.

Maintenance and service

The ChipMill is covered by one of Fischione Instruments' service contract options. To expedite service, the ChipMill has the capability of remote diagnostics. When connected to the Internet, the ChipMill can be accessed by Fischione Instruments Service for rapid troubleshooting and diagnostics support.

To learn more about Fischione Instruments' comprehensive service and preventive maintenance programs, contact service@fischione.com.

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