CAMECA
SCIENCE & METROLOGY SOLUTIONS

AMETEK
MATERIALS ANALYSIS DIVISION

A WHITE PAPER FROM CAMECA



Next-Generation SIMS Instruments Enable Fast, Accurate Analysis for High-Volume Semiconductor Manufacturing

Introduction

High-volume manufacturing of semiconductors requires transformation in one critical area: metrology for compositional analysis. A new generation of HVM metrology solutions must enable significant tool improvement for factory startups, ramping-in of pilot lines, and increases in manufacturing yield.

Compositional metrology can reduce both the cost of manufacturing and the time to market for new products through accurate characterization of process films. However, an increasing diversity of chip types spreads limited metrology resources over a wide range of challenging applications for each microanalytical instrument. This, in turn, places demands on throughput and automation in order to measure rapidly and under varying analytical conditions. Measurements on test structures place added requirements on metrology, due to continuous shrinkage of test pads areas. Finally, existing measurement capabilities are challenged by the swift pace of feature size reduction, alongside the introduction of new materials and structures.

This paper reviews current microanalytical solutions using Secondary Ion Mass Spectrometry (SIMS), and shows how the above challenges are addressed in the latest generation of SIMS technology. Recent developments allow SIMS to achieve its full potential — as an in-fab characterization instrument for high-volume semiconductor manufacturing.

Current SIMS Solutions

SIMS characterization has conventionally been performed by instruments located outside the fab or at contract laboratories.

Compared to other characterization techniques, SIMS provides a unique combination of extremely high sensitivity for elements from hydrogen (H) onwards, with detection limits down to parts per billion (ppb) levels for many elements; high lateral resolution imaging (down to 50 nm); and a very low background that allows high dynamic range (more than 7 decades).

For semiconductor analysis, two major SIMS technologies have become established: dynamic (magnetic or quadrupole) SIMS and time-of-flight SIMS.

Dynamic SIMS

Dynamic SIMS utilizes a high-dose ion bombardment that erodes successive layers of the sample, providing information about its elemental and isotopic composition over depths that can range from nanometers (nm) to tens of micrometers (µm). To enhance the ionization yield, dynamic SIMS sources use reactive primary ions — mostly oxygen (O) or cesium (Cs) — with an energy range between 100 electron volts (eV) and a few tens of kilo electron volts (keV). This bombardment breaks molecular bonds on the surface, so it provides mostly isotopic and elemental information. Elemental detection limits can reach ppb for several elements. To achieve such sensitivity, a high data rate is mandatory, achieved with continuous sputtering (DC mode). The mass analysis is typically performed with a magnetic sector or quadrupole mass spectrometer.

Traditionally, dynamic SIMS has been a leading technique for in-depth dopant profiling in semiconductor fabrication. It's also used for trace element, contamination, and compositional microanalysis — a variety that makes it an effective tool for critical fab process characterization.

Established solutions

A range of SIMS solutions from top manufacturers address the needs of a broad array of semiconductor applications.

Currently, a top-of-line dynamic SIMS magnetic sector instrument, such as the CAMECA IMS 7f-Auto, is the solution of choice for in-depth dopant profiling, easily accessing high impact energies for analyzing deep within materials at high throughput.

This instrument is capable of achieving detection limits as low as sub-ppb for some elements. With a small sample chamber and ultra-high vacuum, it is often used for detecting atmospheric species, such as hydrogen (H), oxygen (O), nitrogen (N), carbon (C), etc. In addition, an automated storage chamber allows unattended analysis on multiple sample holders, increasing sample throughput.

Some commercial labs handling wafers for semiconductor customers present

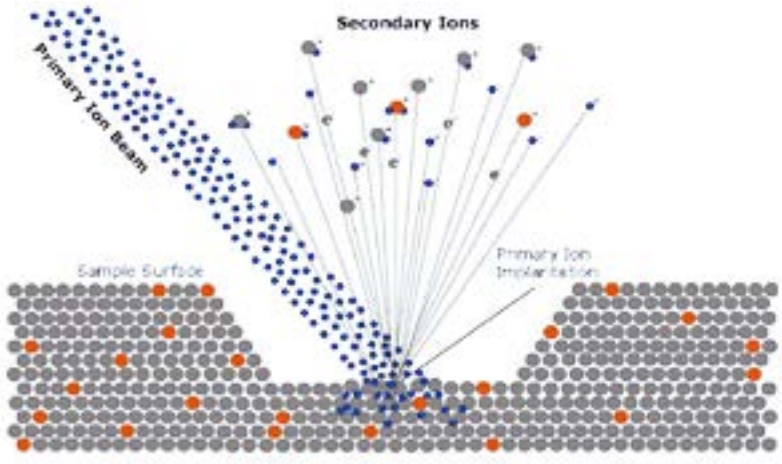


Fig. 1 The SIMS sputtering and ionization process.

the need for analyzing thin films, along with the flexibility to analyze either electropositive or electronegative elements. These needs are met by instruments such as the CAMECA IMS Wf. The IMS Wf handles up to 300 mm wafers and enables ultra-low primary ion impact energy analysis – ideal for ultrathin film applications that need high depth resolution. When requirements are limited to the analysis of small samples, such as test coupons from the fab, the CAMECA SC Ultra offers the same capabilities as the IMS Wf, but on non-wafer samples.

Finally, thin-film multilayer structures demand a technology that can measure many elements simultaneously. Quadrupole mass spectrometer-based instruments offer a proven solution. Moreover, they enable quick and easy analysis at a lower cost compared to magnetic sector spectrometers, (at the expense of mass resolving power).

Hence, labs looking for easy-to-use, fast mass switching for multiple-element detection, as well as good charge compensation for use on insulators in compound semiconductor devices, utilize the CAMECA quadrupole SIMS 4550, as long as there are no demands on mass resolution.

While the above-listed instruments can fulfill the needs of different depth profiling applications, they are not typically the best choice for sub-micron lateral resolution. For this, CAMECA has developed the NanoSIMS 50L — which can provide lateral resolution down to 50 nm and simultaneous detection of up to 7 masses in parallel.

TOF SIMS

A second SIMS technique, time-of-flight (TOF) mass spectrometry, is more optimized for use in static SIMS.

In static SIMS, a low-intensity primary ion beam is applied to a sample, generating atomic and molecular ions from its top monolayers. Static SIMS provides information on that top surface composition, with a focus on molecular characterization. TOF mass spectrometers are well adapted for static SIMS analyses, given their capability for analyzing all masses in quasi-parallel mode, up to a few thousand atomic mass units (amu).

A tool based on TOF SIMS technology can offer certain benefits in some fab applications, enabling high sensitivity to molecules on surfaces. This tool can collect all sample masses at the same time. Users need not know in advance what masses are present in a given material. This is not often a factor in fabrication, but can be useful in failure analysis or in certain development tasks.

However, TOF SIMS instruments labor under some substantial drawbacks. They cannot sputter and analyze simultaneously, resulting in poor duty cycles, which translate into low sample throughput. The need for operating two separate ion sources and columns simultaneously increases the complexity and hence reliability of the instrument, impacting uptime. Sensitivity is limited by the information in each pulse, and so is considerably lower than with dynamic SIMS — in spite of efforts to maximize such information by methods such as bunching. This constraint restricts the TOF instruments' application to films with a limited dynamic range and sufficiently high concentration of the element of interest to allow detection.

Moreover, the counterpart of good surface resolution is poor performance at greater depths, as for thicker films and nonplanar 3D structures. Compared to magnetic sector or even quadrupole SIMS models, any TOF SIMS instrument provides significantly less sensitivity for in-depth analysis.

Existing Challenges

Semiconductor fab management has long wished for microanalytical instruments with the degree of automation, throughput, and reliability needed for direct integration into the production line.

To enable fabs' use of such advanced instrumentation as SIMS — by integrating the technology's superior analytical performance with required levels of automation and robustness — instrument designers have had to overcome significant challenges.

Complexity

SIMS instruments are sophisticated. Throughout their history, most have been used as scientific instruments for research, and have been situated in laboratories. They have demanded considerable amounts of time devoted to setup, calibration, and preventive maintenance, typically falling short of the uptime levels associated with other fab equipment.

An expert user

Conventionally intended for use in research labs, SIMS instruments have been designed to be heavily customizable. However, this level of flexibility often brings the corresponding need for an expert who can use the instrument effectively for different applications and instrument conditions. Unfortunately, the time this expert spends on optimizing instrument conditions can take away from throughput, and the user's skill will impact the repeatability of results. Semiconductor fabrication, on the other hand, requires that the instrument be run by a fab operator, who handles multiple characterization instruments — but not at the level of an expert. So designing a SIMS tool for fab use demands an increase in automation of the instrument, particularly for beam alignment, mass resolution change, impact energy switching, etc. Note, however, that such automation should not significantly compromise performance and results obtained relative to those achieved by an expert.

Small pad measurements

Fabs often use test pads on patterned silicon wafers to perform analyses. These pads can be 50 µm x 50 µm or smaller. Successful measurement on ultra-thin films in such small areas requires obtaining a tightly focused beam at extremely low impact energies, down to 150 eV. Moreover, a high-precision stage is required to reliably position the beam in the center of the test pad, so that the primary ion beam raster is completely within the area of the pad. As a consequence, fabs have often limited the use of SIMS to analysis of blanket wafers or coupons.

Repeatability in results

A key challenge for success in process integration is being able to build the least amount of variability into each step of processing a wafer. These process steps in turn rely on metrology of one kind or another to evaluate the quality and reproducibility of their films. As a consequence, getting repeatable results is key to the success of every step, and crucially important for semiconductor manufacturers.

Thus, the basic challenges for any new generation of SIMS semiconductor solutions are: how to move the instrument inline or near-line, incorporating tool automation for wafer handling plus tuning, calibration, analysis, and quantification — while fulfilling the high expectations for repeatability in results; all this without the hand of an expert user to guide each measurement.

Next-Generation SIMS Solutions

Fortunately, fabs looking for answers can now find a whole new generation of SIMS solutions for semiconductors. The best example: the brand-new AKONIS from CAMECA. It leverages the decades of deep technical expertise the company has aquired while setting the benchmark for lab microanalysis using dynamic SIMS technology. In AKONIS, CAMECA has augmented that expertise with the automation and reliability required for use in or close to a semiconductor fabrication line.

This kind of inline SIMS instrument has a host of the key performance features requested by fabs.

High uptime

Transformational changes in SIMS instruments are required to deliver the kind of dependable performance that today's fabs demand. To begin with, advances in technology have been made specifically to maximize uptime.

For example, the makers of AKONIS have implemented a simplified, innovative ion source for greater reliability and serviceability. Updated system electronics offer increased robustness — with a mean time to repair (MTTR) of just two hours! The complexities associated with dual-source, dual-column systems are intentionally eliminated to enhance the uptime of the instrument for fab use. On the secondary side, a modified magnet cooling circuit improves magnetic field stability. These design improvements for stability and reliability mean that only a single measurement is required to have confidence in the results obtained on AKONIS, unlike in conventional SIMS which might need up to 3 measurements to increase statistical confidence in the results due to run-to-run variability. AKONIS is designed for an average uptime of greater than 95% — a high point in semiconductor SIMS instrumentation.

Precise positioning on pattern wafer pads

Performance improvements are also necessary to keep up with the analytical demands of positioning on pattern wafer pads.

To enable this capability, a redesigned, ultra-high-resolution sample stage on AKONIS permits precise and repeatable movement for measurements on pads down to 20 µm x 20 µm. The AKONIS positioning instrumentation enables excellent 2 µm accuracy and 1 µm repeatability for greater than 99.7% of all moves. With this level of positioning accuracy, multiple measurements can be made on a wafer after a single global alignment, without requiring local realignment before each measurement of die on wafer.



The all-new AKONIS from CAMECA.

Advanced automation and ease of use

AKONIS implements sophisticated automation routines on the primary ion column. These allow it to run an analysis at the target current setpoint with a tightly focused beam over a broad range of energies — from 150 eV to 7 keV — for applications from ultra-thin films to deep implants.

Moreover, the instrument enables running automated chain analyses, switching between different applications that may require differing instrument conditions — such as mass resolution, analysis current, or impact energy — without any need for human intervention, as illustrated in Fig. 2. This level of automation ensures that a fab operator can run multiple such instruments, each analyzing varying applications — meeting real-world fab analytical demands. In addition, fitted with optical carrier enhancement capability, the instrument is reliably and easily used for charge compensation while analyzing thin insulating films, a growing market in the semiconductor application space.

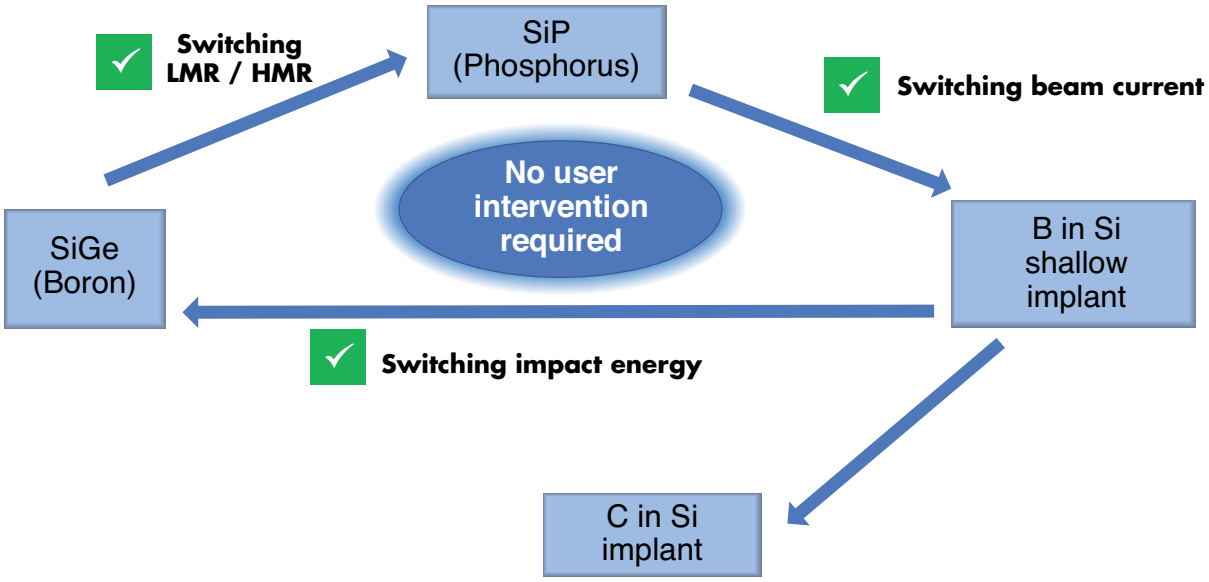


Fig. 2 AKONIS automated operation scenario shows a) switching between low mass resolution (LMR) and high mass resolution (HMR) recipes, then b) switching beam current to raster on a small pad, and finally c) impact energy switching for a deeper implant profiling.

Other Technical Advances

Statistical process control

The number of steps in device fabrication is increasing nonlinearly with each technology node. So the importance of running each step with maximum repeatability cannot be overemphasized. AKONIS has been designed to respond to this need. It uses a novel ion source, a new ultra-low-energy primary column, and heavy automation of its beam optics to produce a relative standard deviation (RSD) of less than 1% for dose measurement on a broad array of customer applications in fully automated analysis mode. Fig. 3 shows an overlay of 25 B implant profiles, measured on pad craters on 300 mm wafers, in unattended analysis at a throughput-friendly 30 nm/min — all while demonstrating a good detection limit and dynamic range, with a dose repeatability of less than 1%.

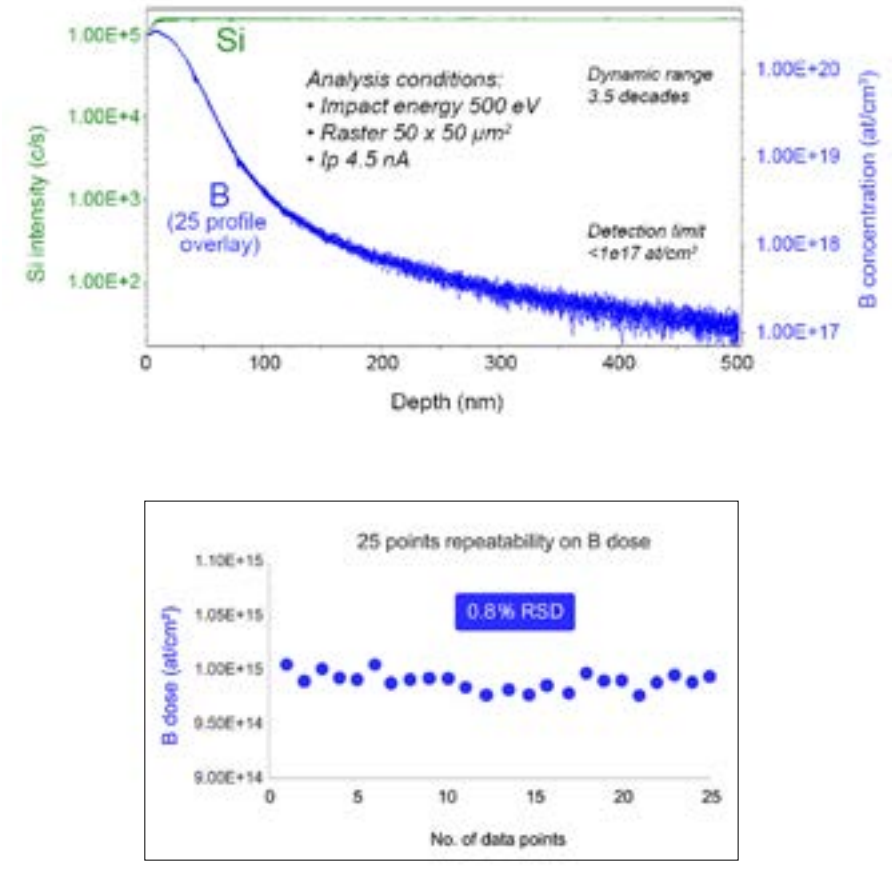


Fig. 3 Top— Overlay of 25 B implant in Si raw profiles, showing high repeatability with a good detection limit and dynamic range for pad analysis. Bottom — Dose repeatability over the 25-point profile of B implant in Si, for statistical process control using test pads on pattern wafers. (RSD = relative standard deviation.)

Conclusion

SIMS instruments have a greater than 60-year record of success in materials analysis. Today, for the first time, we are seeing an inflection in their use case, as users change from expert scientists in laboratories to fab operators. This has notably intensified demands on uptime and automation. SIMS manufacturers such as CAMECA, already the benchmark in dynamic SIMS technology, are driving a significant array of product enhancements — to lead the way in fulfilling customers' expectations of SIMS analysis solutions for high-volume manufacturing of semiconductors.

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