Local Electrode Atom Probes for 3-D Metrology

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ABSTRACT

Imago Scientific Instruments is developing its Local Electrode Atom Probe (LEAP®) microscope for use in semiconductor, data storage, and other nanotechnology industries to provide 3-D atomic-scale metrology. The LEAP microscope achieves true 3-D atomic-scale analysis by using a high electric field to remove individual atoms from material surfaces and a position-sensitive detector to record information that reveals the atoms' position and identity.

The LEAP microscope represents a new class of tool for atomic-scale characterization whose analytical capabilities surpass those of currently employed metrology tools. The LEAP microscope's atom-by-atom analysis achieves higher spatial resolution and greater sensitivity than TEM, and provides lateral spatial resolution that is not available by SIMS.

Specific industry needs that may be addressed by the LEAP microscope are quantitative analysis of dopant distributions in ultra-shallow junctions, purity/interface structures of ultra-thin dielectrics, and multilayer thin film structure in read/write head and storage media technology.

This paper presents results of LEAP analysis of buried interfaces in electronic materials to show the unique nature of the analytical information provided by the technique and the potential benefit to industry of developing a metrology tool based on LEAP technology.

Keywords: atom probe, characterization, metrology, nanoscale analysis, 3-D imaging

1 THE LEAP MICROSCOPE

Imago's LEAP microscope is an innovative version of a 3-Dimensional Atom Probe (3DAP) microscope. Briefly, 3DAPs analyze materials in the following manner:

- A needle-shaped specimen with a prepared tip (100 nm radius at the apex) is placed into a vacuum chamber.
- A voltage is applied between the specimen and a detector, resulting in an electric field that pulls on the atomic nuclei on the specimen tip. At a high enough field, atoms lose one or more electrons and field evaporate from the tip as positive ions. The voltage is applied in pulses to allow for a known time of departure, and carefully controlled such that atoms are removed one at a time.
- After leaving the specimen, the atom is accelerated by the divergent field toward a position-sensitive detector that records the location and time of impact of the atom. The time of impact is determined by the accelerating voltage and atom mass.
- This approach achieves very high spatial resolution (better than 0.5 nm) and high magnification (10^6X) by projection.
- As the analysis progresses, the entire surface layer of atoms on the specimen is removed, exposing the underlying layer. This process is continued over thousands of atomic layers.

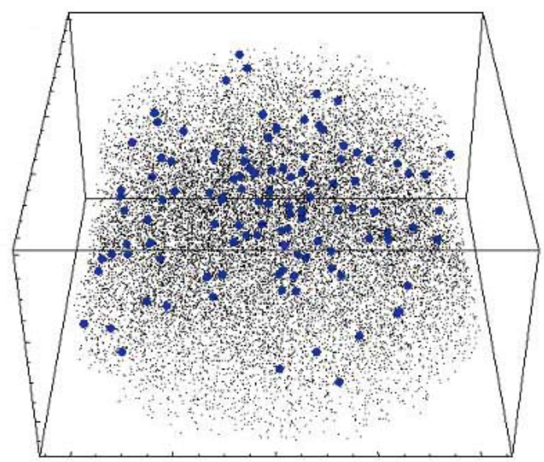

Figure 1. Results of 3DAP analysis of boron-doped silicon. Dots represent individual atoms; Si is shown in gray, boron in blue.

The three-dimensional picture of the atomic structure and composition of the specimen can be re-created, as shown in Figure 1, from the record of position and time of impact of the atoms pulled off the specimen as follows:

Atomic structure: By employing simple geometry, the original position of the atom on the specimen tip can be computed from the position at which the atom collides with the detector, since the top surface of the apex of the specimen maps directly onto the flat surface of the detector. This positional information reveals the 3-D atomic *structure* of the specimen.

Atomic composition: The identity of atoms can be determined from the time of flight from the specimen tip to the detector, equal to the difference in time between the voltage pulse that causes the atom to leave the specimen and time of impact of the specimen atom on the detector.

Time of flight is proportional to the atom's mass-to-charge ratio, and so can be used to identify the detected specimen atoms. This information reveals the 3-D atomic *composition* of the specimen.

2 ANALYTICAL RESULTS

Three-dimensional data from LEAP analysis provides new information and new insights for scientists and engineers developing and manufacturing devices at the nanoscale. An important area of application of 3-D analysis is in the study of interfaces.

Interfaces comprise a major structural component of today's electronic materials, most of which are fabricated as layered structures on planar substrates. The most critical layers are typically on the order of a few nanometers thick. In such thin layers, interfaces become a potentially dominant component of the device. It is therefore critical in device fabrication that both the structure and composition of buried interfaces be well understood. The LEAP microscope excels at such buried interface problems.

2.1 Multilayer Thin Film Stacks

Read sensors in current hard drives are made of multilayer thin film structures that utilize the gigantic magnetoresistance (GMR) effect. Thin metal films on the order of 1 to 3 nm thick are layered in the read sensor to create this effect. Two of the most important layers of a typical structure are made of cobalt or cobalt alloys and pure copper or other non-magnetic spacer elements. The signal magnitude from this type of sensor needs to be maximized in practice and is achieved by controlling two critical parameters: layer thicknesses and interface roughness.

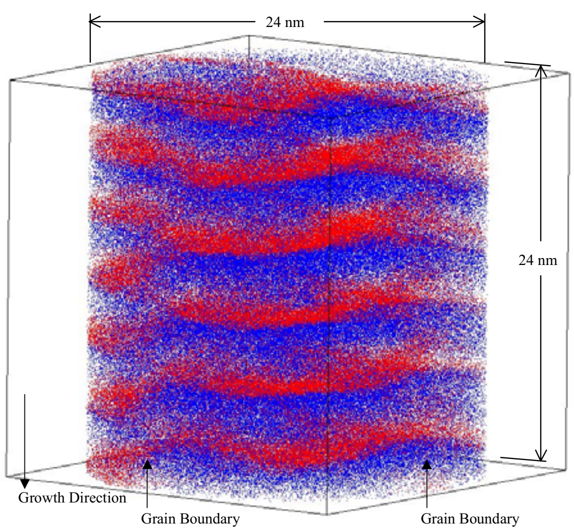

Figure 2. LEAP microscope image of a cobalt-10%iron/copper multilayer test structure. This image shows a 400,000-atom subset of data from a data set that contains information from a total of five-million-atoms. Cobalt and iron atoms are both represented by blue dots, and copper atoms by red dots.

A test structure was fabricated that contains many repeats of these two layers. Figure 2 presents a subset of LEAP microscope analysis results of the multilayer test structure. Six repeats of the layer structure are visible. The figure includes data from 400,000 atoms and only shows the key elements: cobalt, iron, and copper. Low levels of impurities were identified, but are not included here. Cobalt and iron are both shown as blue atoms, and copper is shown as red in the figure.

These materials are known to grow with columnar grains parallel to the growth direction. The location of two suspected grain boundaries is marked in Figure 2. This section of the dataset was chosen to illustrate the presence of the grain boundaries. This dataset provides evidence that that copper diffusion occurs along grain boundaries in these multilayer stacks.

The compositional variations in the structure may be evaluated by an alternate presentation of the analytical data. Evaluation of composition variations at a specific location in the structure is shown in Figure 3. It shows a transverse projection through a thin subvolume of Figure 2. The close-packed planes of the structure ({111} FCC CoFe and {111} FCC Cu) are visible in the image. They serve as an internal length calibration standard. The length scaling in the transverse directions is obtained by assuming uniform atom density in all directions.

The composition profile in Figure 4 is derived from Figure 3. Each datum in the profile corresponds to approximately two atomic layers in Figure 3, and there are 120 atoms/datum. Error bars are not shown in the figure but at each datum, they are dominated by the statistical noise associated with this number of atoms per datum. This composition profile shows a feature that has been observed previously [1,2]: the diffuseness of the copper-on-cobalt interface (following the growth direction) is less than the diffuseness of the cobalt-on-copper interface. This can be seen visually in the subvolume image and in the slopes of the composition profile at the interfaces.

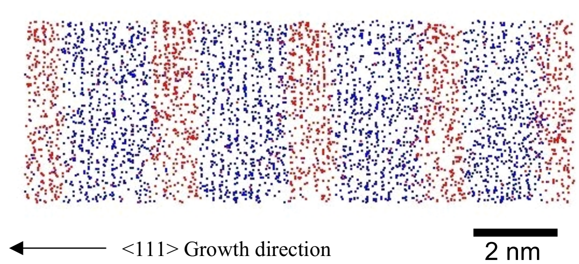

Figure 3. A 2-D projection of a thin 3.2 nm by 3.2 nm square cylinder of the image in Figure 1 that shows the close-packed atomic planes ({111}FCC CoFe or {111}FCC Cu). The layer thicknesses are determined from these image data to be 2.4 nm and 1.4 nm for the CoFe.

The interface diffuseness may be evaluated from this image by measuring the distance over which the

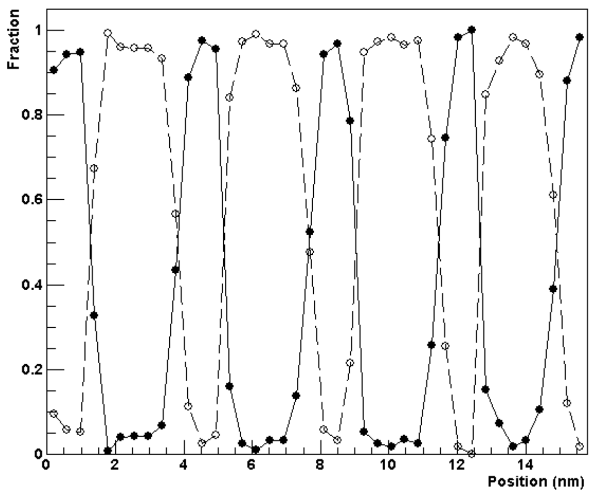

Figure 4. A local composition profile through the subvolume in Figure 2 along the growth direction. The length scale of the profile is calibrated from the spacing of the atomic layers in the image. Filled circles are copper concentration and open circles are cobalt plus iron concentration.

composition changes from 90% to 10% at each interface. This 90-10 interface thickness was determined to be 0.60±0.05 nm for the copper-on-cobalt and 0.90±0.05 nm for the cobalt-on-copper interfaces, in reasonable agreement with previous such measurements [2]. Such observations play a crucial role in the development of these nanoscale devices and have had impact on actual process development in the data storage industry.

2.2 Metal-Oxide-Semiconductor Structure

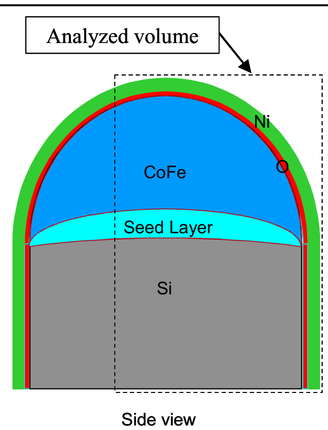

Figure 5. Schematic illustration of the metal-oxide-silicon specimen analyzed in Figure 5.

Specimens of a complex silicon/silicon oxide/metal structure were also prepared for analysis for demonstration purposes. Silicon posts were oxidized in air at room temperature, coated with nickel to form the metal-oxide-silicon structure and then annealed at 175°C in nitrogen. Figure 5 shows a schematic depiction of the specimen.

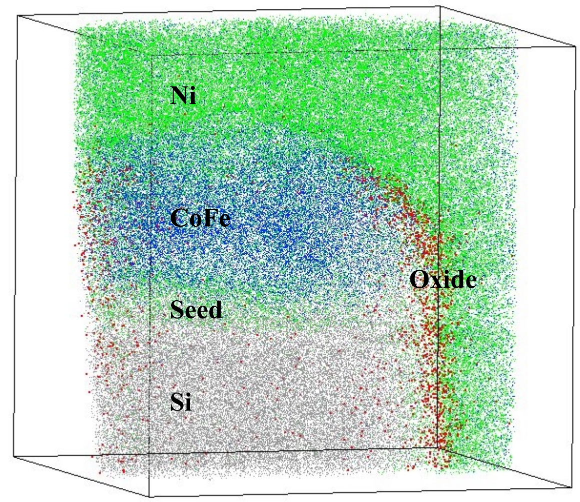

Figure 6. A perspective view of the oxide layer on silicon at a point on the specimen tip below the metal seed layer. Nickel atoms are shown in green, cobalt and iron atoms are blue, silicon is gray, and oxygen is red.

Figure 6 shows a section of the atom probe image of the same specimen. The oxide layer on the silicon is clearly visible in the image. This complex specimen mimics the structure in actual MOS devices and demonstrates that it should be possible to analyze the complex structures encountered in semiconductors using the LEAP microscope.

3 METROLOGY APPLICATIONS

Three LEAP instruments have been built by Imago Scientific Instruments. Imago's LEAP microscopes employ innovative technology that greatly improves analysis speed and simplifies specimen preparation relative to other 3DAPs. These developments for the first time make use of atom probe microscopy for metrology applications a potentially workable proposition. The large throughput of the LEAP microscope makes it realistic to consider applications where information is needed in short timeframes like one hour or less.

In process development, there exists a need for feedback about the effect of a given set of operating parameters on a microstructure so that modifications to the process can be made for the next iteration. Often much iteration is required. In some cases, it can take days to get microstructural feedback which means that the process development can take weeks or months. If the feedback information were available in hours, then the process development cycle could be shortened to days. In fast moving industries like the semiconductor industry, where for example, the implantation regimen for dopants in silicon must be developed for each new generation of chips, shortening the development cycle is extremely valuable.

Another application of the LEAP microscope in manufacturing is tool qualification. The first task in the manufacturing process establishment is tool qualification. A tool like a thin film deposition system or ion implantation device must be qualified when it is first commissioned and again after any maintenance takes it out of production. Whether it is film thickness or implant concentration and distribution, in some industries it can take days to iterate and tune a tool to get it ready for production. With the rapid turnaround of a LEAP microscope, this process might be shortened to hours. If so, major savings in process tool redundancy could be realized.

The extreme short-turnaround application is process monitoring. Where process variability is problematic or where feed forward and feedback are utilized in closed loop process control, the LEAP microscope may be able to provide information in a timely manner. One scenario in the semiconductor industry would use monitor wafers to sample the process at sufficient intervals for control purposes. In this type of application, analysis times would need to be on the order of one hour.

A final example of application is in failure analysis. In failure analysis, the objective is to identify defects as quickly as possible. Today's commonly available analytical tools can usually adequately analyze defects that are larger than one micron. Submicron defects can be *located* by currently available techniques, but not *analyzed* easily with these same techniques. The LEAP microscope may solve this problem. In one scenario, a defect review tool (DRT) can be used to rapidly locate small defects, and then the LEAP microscope may be used to rapidly analyze the defect. The entire process may be completed in less than one hour.

4 SUMMARY

Development of the three-dimensional atom probe microscope for metrology will provide industry with a tool that can contribute to shorter development times for new device designs and faster movement along the manufacturing learning curve. Imago Scientific Instruments has demonstrated the viability of this scenario in principle with its innovative 3-D atom probe, the LEAP microscope, and now is working toward practical implementation of the LEAP microscope as the first true 3-D atomic-scale metrology tool.

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