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The Scanning Confocal Electron Microscope (SCEM): a New Tool for Metrology and Semiconductor Device Characterization.

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Current semiconductor devices can have multiple layers in a structure from 2-10 microns thick. Within these layers, important features can range in size from 100's of micrometers to 10's of nanometers. These features are beyond resolution reach of conventional optical and penetration depth of transmission electron microscopy. Recently a new instrument, the Scanning Confocal Electron Microscope (SCEM), has been developed which permits the inspection and direct observation of large field of multilayer thick (>5 μm) semiconductor devices at unprecedented resolutions. The SCEM is an electron-optical implementation of the Scanning Confocal Optical Microscope. The device merges the concept of confocal imaging with the ease of use of the Scanning Electron Microscope, and the penetration ability of the scanning, transmission and x-ray microscopes, while achieving unprecedented resolutions in optically dense materials. In this paper we report on early testing of the SCEM mode in an instrument at AMDs-CeriumLabs.

INTRODUCTION

Metrological measurements of sub-micron, sub-surface features of thick optically dense materials at high resolution have always been a difficult and/or time consuming task in materials research. As is well known in the industry, semiconductor devices are being fabricated as multi-layered, partially metallized structures, which can have from one to five or more layers in a structure that may be 2-10 microns thick. Within the individual layers of this device, important features can range in size from 100's of micrometers to 10's of nanometers [1]. For example, typical modern microprocessors contain in excess of five levels of ~2500-3500Å thick Cu or Al interconnects with diffusion barrier layers on the order of 300Å. Transistors in these devices are fabricated from polycrystalline Si and can range from 1000Å to 2500Å thick, but spacers and Gate-Dielectrics are only on the order of 10's of Angstroms. Often defects on wafers used to produce these devices, either originating from manufacturing malfunctions or contamination, can range from micron in size to few nanometers. This regime of thickness and resolution is beyond reach of conventional optical microscopy, but is critically important to the microelectronics manufacturers in particular, and materials science, and the new emerging nanoscience communities in general.

Because of the inability of conventional metrological methods, which are only applicable to surface feature characterization, the role of characterization of buried structures is therefore, generally relegated to technologically complex and expensive instrumentation having highly penetrating radiation, such as the synchrotron-based Scanning Transmission X-ray Microscope (STXM) [2] or involves the careful preparation of thin cross-section slices for study using the Transmission Electron Microscope (TEM or STEM) [3]. In case of defects, deprocessing procedures relaying on chemical dissolution of layers, reactive-plasma etching, or mechanical polishing are necessary to uncover problems. In such cases, danger exists of changes to the defects themselves from the specimen preparation methods. Recently a new instrument, the Scanning Confocal Electron Microscope (SCEM), has been developed which permits the inspection and direct observation of large field of multilayer thick (>5 μm) semiconductor devices at unprecedented resolutions [4-5]. This ability of imaging through relatively thick specimens makes it a valuable addition to the arsenal of tools used in Failure Analysis (FA) projects. In this paper we report on early testing of this mode in CeriumLabs, an analytical laboratory supporting Flash Memory Device production in Fab-25 of Advanced Micro Devices Inc., as an evaluation of its capabilities. Emphasis in this paper is placed on real-life applications in the field of production defect characterization, wafer level materials FA, and limitations of the SCEM technique rather than the implementation details.

INSTRUMENT

Implementation

The Scanning Confocal Electron Microscope (SCEM) is an electron-optical implementation of the Scanning Confocal Optical Microscope (SCOM) which permits the observation and characterization of sub-surface structures of thick, optically opaque materials. The device merges the concept of confocal imaging with the ease of use of the Scanning Electron Microscope (SEM). The instrument possesses penetration ability of the scanning, transmission and x-ray microscopes and achieves unprecedented resolutions in optically dense materials. It provides both large fields of view as well as a nanometer scale spatial resolution.

The SCEM instrument and principles of its operation were developed using the Advanced Analytical Electron microscope (AAEM) located in the Electron Microscopy Center of Materials Science Division of Argonne National Laboratory (ANL) [6]. The AAEM is essentially an electron-optical bench with ability to feely re-configure electron lenses, alignments and detector systems. The details of SCEM are described elsewhere [4]. Figure 1 shows the ray-path diagram for an electron beam in SCEM mode.

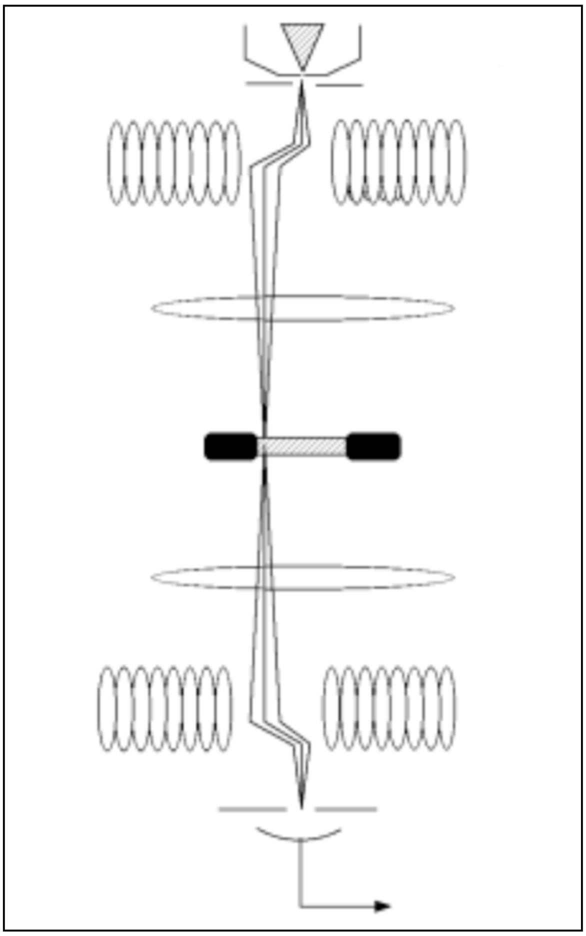

Figure 1 Ray-Path Diagram for SCEM. Described in detail in US Patent 6,548,810

The challenge of the current work was an attempt to implement SCEM "in-the-field" on an existing Scanning-TEM instrument. For this work, we chose Philips CM300SWT–FEG STEM-TEM operated by CeriumLabs to evaluate the feasibility and to test its application to real world devices. The 1997 vintage CM300 is equipped with original Philips STEM unit with off-axis detectors and an additional set of on-axis removable solid-state detectors from Gatan Inc. The instrument also equipped with Free-Lens Control allowing the analyst to access and feely vary operational parameters for all electron lenses in the column, in addition, an external computer system permits independent access and control to the scan coils and detector systems.

It should be appreciated that the SCEM mode is not a standard operating mode in any commercial instrumentation, which by default, are specifically configured to operate in well-defined and characterized operating modes. This is in marked contrast to a research and development instrument as embodied in the ANL AAEM. Nevertheless, under a collaborative licensing arrangement, the Cerium Labs instrument was modified to reach a configuration, which partially emulates that of the ANL instrument. This necessitated resetting and realigning the pre and post specimen lenses, and alignment coils as well as determining the approximate electron-optical equivalent positions of the various apertures and detectors. The technical details and the implementation porocured of achieving the SCEM mode at Cerium Labs is not within the scope of this paper, as our purpose is to evaluate SCEM in the context of metrological work. The results presented below demonstrate our success, however, it should be appreciated from the onset that a customized instrument specifically optimized to achieve ideal SCEM conditions will perform significantly better than some of the results we report herein.

Experimental Results

In order to compare these results, we analyzed the same specimen in both the ANL and CeriumLabs instruments. For the sake of brevity results in this paper will be referred to as ANL-SCEM and Ce-SCEM respectively to indicate the instrument employed. In Figure 2, we begin by presenting a conventional 300 kV TEM mode image of a > 3 micron thick region. Multiple scattering within the sample obscures virtually all information about this area of the specimen, and renders any metrological measurements useless. By comparison, Figure 3, presents the same area of the specimen imaged in Ce-SCEM mode. It is straightforward to recognize that quantitative measurements of line widths, and morphological details are now immediately accessible to the analyst by switching from conventional TEM mode and to the SCEM mode.

While Figures 2 and 3 succinctly illustrate the usefulness of SCEM in metrological application, the implementation in a conventional commercial instrument is not without limitations. In figure 4 we demonstrate the field of view of the Ce-SCEM, and compare that to the same sample when imaged in the ANL-SCEM (Figure 5). The red-circled region in the upper left hand quadrant of Figure 5 (ANL-SCEM) is the same imaged region shown in Figure 4 (Ce-SCEM). The areal field of view in the ANL-SCEM is over 100x greater that of the Ce-SCEM. The reasons for this are entwined within the functionalization of SCEM mode in this (or any) conventional instrument. By suitably adjusting the post specimen optics it is possible to extend the areal field of view of the Ce-SCEM nearly 10 fold (Figure 6) albeit at the expense of severe image distortion. While this can be compensated for in part by image processing, an electron optical solution is obviously the more appropriate solution.

Experimental measurements of the nominal resolution of the ANL-SCEM as a function of the device thickness are presented in Figure 7. They show that nanometer scale resolution is readily attainable even in thick specimens. More details of those experiments are available in Ref. [4, 6]. For thin specimens (<200nm) SCEM does not show advantage

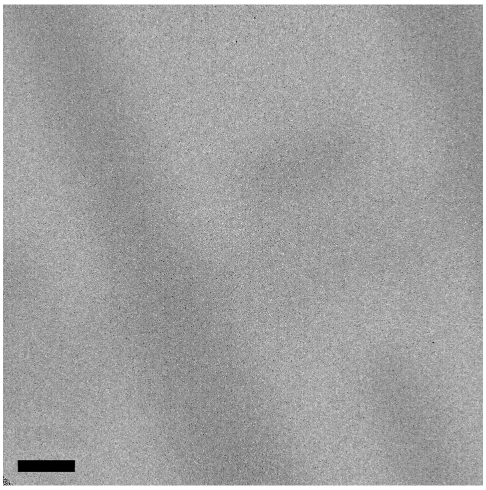

Figure 2 TEM image acquired in Cerium Labs CM300F of a >3 µm thick specimen, illustrating that Metrological measurements are not possible

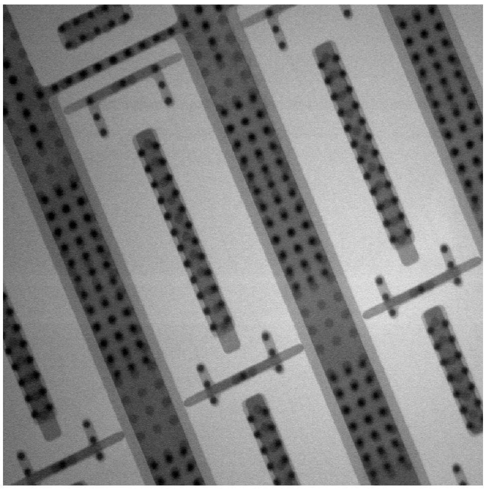

Figure 3 Ce-SCEM image of the same area of the specimen as in Figure 2.

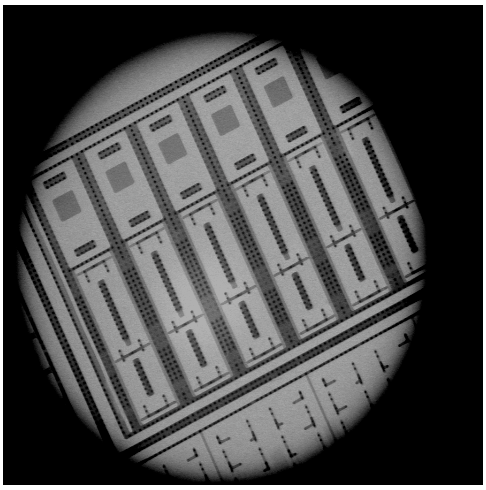

Figure 4. Ce-SCEM field of view (FOV) at lowest magnification.

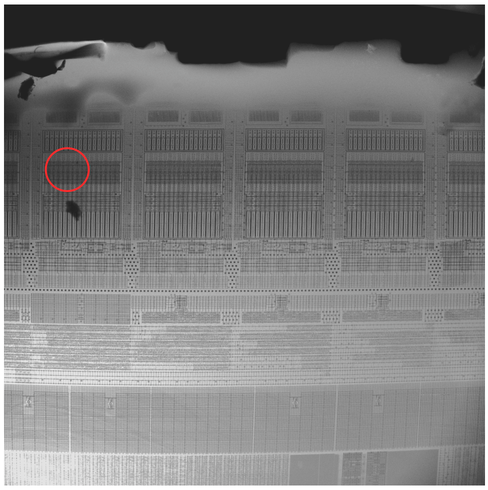

Figure 5. An ANL-SCEM image taken from the same specimen. The circle in the upper left quadrant indicates the field of view of the Ce-SCEM (compare with Fig 4).

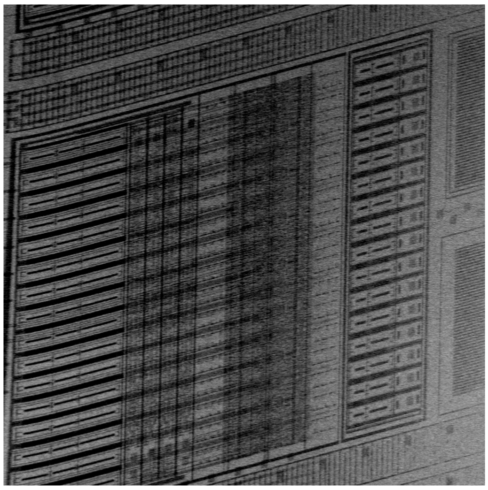

Figure 6 Ce-SCEM image obtained in Free Lens Control mode. Note distortion in image, but larger FOV.

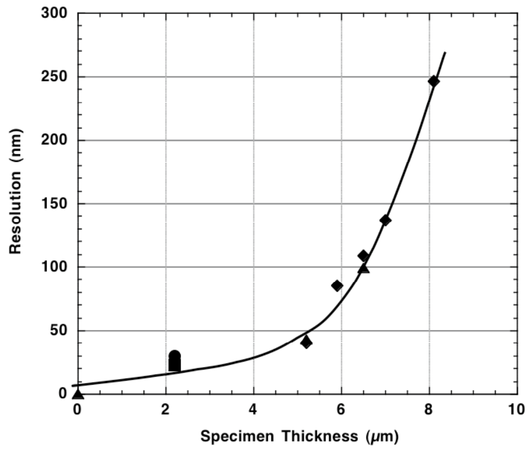

Figure 7 ANL-SCEM resolution as a function of specimen thickness.

over traditional bright/dark field STEM, as one would expect, since STEM is a subset of the more general SCEM mode. SCEM permits imaging through thick specimens in cases where high resolution bright and/or annular dark field STEM is more applicable to thinner specimens. In case of Ce-SCEM we were successful in imaging through samples up to 4µm thick, while at ANL specimens as thick as 8 microns have been successfully studied.

APPLICATIONS TO DEVICE MANUFACTURING

To demonstrate utility of SCEM in materials failure analysis work applicable to semiconductor device manufacturing we chose an example of direct observation of electromigration voids formed in an over-stressed Al interconnect serpentine structure forming a 150 by 350 µm rectangle. In this case, a well documented end-of-life, thermal stress parameters, and electrical measurements of resistivity changes in Al layer of the test-structure were available. The tests structures were prepared for SCEM evaluation by traditional methods of plane-view specimen preparation. We attached a 1-mm inner diameter aperture support grid on top of oxide material covering the single metal interconnect structure. The grid was placed in such a fashion as to offset the test structure slightly from its center. Afterwards, we used mechanical grinding of excess substrate Si until total sample thickness reached 100µm, followed that with dimpling from back-side to W-light transparency in the center of the grid (~100µm of Si remaining), and ion milled with Gatan-PIPS. At that point, the test-structure area still contained approximately 3µm thick material. We had the following layers represented in the area-of-interest: 100nm of silicon dioxide, 250nm metallization layer stack thickness, 350nm of SiO_2 inter-layer dielectric, a 350nm layer containing active Si islands and shallow trench isolation SiO_2 layer, and portions of substrate wafer. As illustrated in Figure 8 below, the voids in Al interconnect structure were easily identifiable in Ce-SCEM images.

DISCUSSION

These preliminary results illustrate succinctly the ability of the SCEM to provide valuable information for metrological studies of thick non-optically transparent semiconductor devices. The utility of SCEM to failure analysis comes from its ability to provide relatively high-resolution images from thick specimens. In such way, the instrument can bridge the gap between optical SCOM useful for observing features few microns in size, to TEM able which can resolve atomic sized structures but requiring specimens less than 100nm thick to reach the this resolution. The main advantage of SCEM for failure analysis in semiconductor manufacturing is to investigate defects or devices without need to de-capsulate or cross-section. This allows un-disturbed observation.

The disadvantages of SCEM when implemented in the current generation of commercial instrument are similar to those of TEM/STEM instruments. The specimen thickness still needs to be reduced significantly before analysis. The sample preparation for defect inspections is still time consuming. And last but not least, the specimen size and geometry is currently limited to a 3mm diameter disc fitting in a TEM holder.

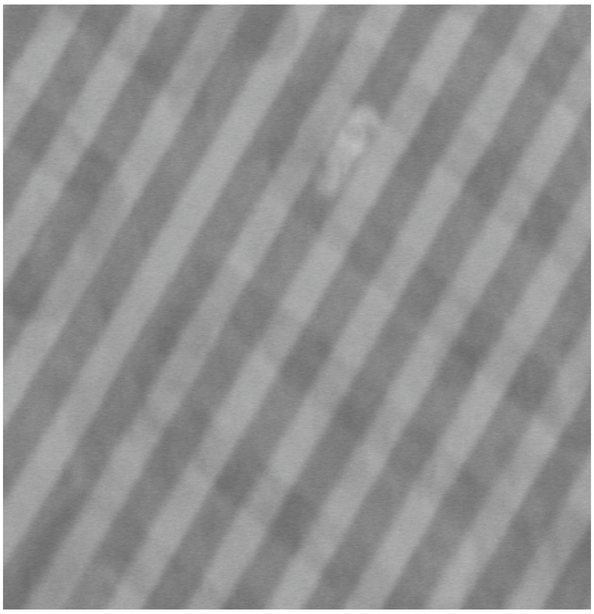

Figure 8 Ce-SCEM image of Al interconnect serpentine structure with known voiding issue. This sample was ~3µm thick and contained Metal-1, IMD-0, active-Si with STI structures, and approximately 1 µm of substrate Si wafer.

CONCLUSION

We have demonstrated that a SCEM mode of operation is retrofitable to existing commercial instruments and can be achieved by pre-configuration of operating software and pre-programming lens conditions. Current commercial instruments are already capable of providing some or all of these functions individually, although an optimized instrument can certainly be custom built which provides a greater range of operating functionality.

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