Methods for high resolution structure imaging

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Present day research in materials science often focuses on the properties and function of materials with nano scale order. These materials range from catalysts, carbon nanotubes and quantum dots to solid state composite devices. The properties, dimension and characteristics of these nano scale structures often need to be measured in order to understand and improve their functional behavior. There are many tools available that are designed to analyze these functional materials, e.g. the X-ray diffractometer (XRD), the electron probe micro analyzer (EPMA) and SPM and so on. However, these aforementioned techniques have difficulty in accurately locating and analyzing nano scale structures. Since the properties of the nano scale structures can be dramatically affected by the size and composition of the various materials, these structures can be engineered so that the maximum performance can be obtained in the smallest possible dimensions. Each component in a fabricated device or material of interest may have a size comparable to one or several individual atoms. Therefore, it can be challenging to image and measure the composition or chemistry of these nano scale structures.

The transmission electron microscope (TEM) has been used as a dedicated imaging tool that spans six orders of magnitude in magnification, i.e. features ranging in scale from mm to nm can be imaged with high spatial resolution. In the last decade, TEMs equipped with field emission guns (FEG) have become commercially available. The FEG produces a high current, sub-nanometer sized probe, so a field emission TEM (FETEM) can be used to perform both high spatial resolution imaging and chemical analysis. An FETEM is commonly used as an analytical tool when an energy dispersive spectrometer (EDS) and/or an electron energy loss spectrometer (EELS) are installed on the microscope. The analytical FETEM allows easy location of an area of interest in an electron transparent specimen, imaging of its projected morphology at 0.1nm resolution, and analysis of its crystal and chemical structures (composition and bonding state) by electron diffraction or spectroscopy. Measurements with the FETEM require careful calibration to make the obtained result as valid and accurate as possible, far surpassing the performance of XRD, EMPA and SPM

for analysis of nanoscale structures. At this level of sophistication, the FETEM becomes a very unique tool that is essential to characterize nano structures by providing pinpoint accuracy in imaging while simultaneously yielding the highest possible spatial and energy resolved chemical measurements.

For high spatial resolution analyses, scanning TEM (STEM) is very practical since a nano probe is scanned over the area of interest. Using the very coherent FEG probe and a very small bright field detector, bright field coherent STEM imaging can provide an equivalent resolution to TEM imaging. In addition, an imaging technique called high angle annular dark field (HAADF) provides Z-contrast using an annular detector. This technique deals with the electrons that have scattered across a wide range of high angles to realize incoherent imaging. When a probe can be made demagnified using the condenser lenses down to a size that is equivalent of the atomic spacing, it can reveal an atomic structure with little influence of defocus in HAADF. Chemical analysis is commonly accompanied with STEM so that owing to ease of digital beam control, spectral mapping can be also carried out with EELS and EDS.

Recent technical innovations in both hardware and software have been implemented to create an ultimate tool for the highest resolution imaging and analysis. The spherical aberration (Cs) of the objective lens, that governs the resolution in both TEM and STEM, can be corrected and arbitrarily modified. The Cs correctors for STEM and TEM are composed of multiple lenses and these systems are incorporated in the microscope column above and below the objective lens, respectively. The resolution of the instrument after correction is unsurpassed and is expected to be sub-Å using either corrector. The room for this type of microscope should be carefully designed so there will be no interference from vibration and magnetic fields and also the microscopes need to be built with more mechanical and electrical stability than is required for conventional TEMs. The first data out of the Cs corrected TEMs and STEMs showed a resolution close to the target resolution of better than 1 Å. The ability to see atomic resolution images near zero focus value using an extremely low Cs in the TEM avoids the atom delocalization effect and shows the real atomic structure in an interface such as in a multi-layered composite. STEM Cs correction allows a smaller probe size of the illuminating beam. Furthermore, it allows us to use larger opening angles in the illumination lens system which results in more probe current. Since the resolution in HAADF imaging is also improved, a

Cs-corrected STEM HAADF image is expected to yield Z-contrast imaging at the sub-Å level which then improves nano scale chemical analysis capabilities. This new system will be discussed with some data that has been recently collected.

In the semiconductor industry, TEM applications have become more needed and important because device dimensions are constantly shrinking with each new generation of product and there is increasing need for faster turn-around time defect inspection and failure analysis. For imaging and/or critical dimension measurements of the nano scale structure in advanced semiconductor devices, low voltage scanning electron microscopy is being replaced with TEM/STEM. Since TEM/STEM requires specimens that are thin enough for electron transmission, focused ion beam (FIB) technology has now been commonly adopted for rapid turn-around time sample preparation and increased success for specific site samples. Recently, TEM has been used as a unique method to visualize PN junctions using electron holography, and high voltage backscattered electron imaging (BSE) has been developed to observe defects in passivated Cu interconnects far below the sample surface. Both of these microscopy techniques will be also introduced and discussed as part of our new instrumentation.