What is Transmission Electron Microscopy?

Transmission electron microscopes use electromagnets to focus a high energy (100-300 kV) beam of electrons through a very thin sample (<100nm) generating an image based on the electron scattering of the materials in the sample. The more dense areas appear dark and less dense areas light.
Why use TEM?

- 10 + years ago Scanning Electron Microscopy (SEM) was used regularly to characterize microelectronic devices. Whether collecting process information or performing FA on failed circuits, SEM resolution was sufficient for the technology.
- With the technology now at 28 nm, greater resolution is required. Conventional TEMs have image resolution of ~2 Å and the latest microscopes are being spec’d with 80 picometer (1 pm = 10^{-12} m) resolution.
- In addition to gate metrology, transmitted electrons can be analyzed to determine elemental composition with Electron Energy Loss Spectroscopy (EELS). X-rays generated during the interaction between the electron beam and sample can also be used to determine chemical composition with Energy Dispersive Spectroscopy (EDS).
Why use TEM?

- Crystallographic information, such as the degree of order in polysilicon and crystalline defects in active areas can be seen in TEM images. **Diffraction analysis** can be used to determine crystallographic orientation of various materials. Diffraction pattern analysis can be used to identify material phases such as TiSi and TiSi$_2$. 
Drawbacks

• Sampling size is only about 10-20 microns.
• Sample preparation requires precision methods to prepare thin samples (40-80 nm) for best resolution and without artifacts.
• Image interpretation requires knowledgeable individuals with background in materials science, physics, and chemistry.
• 3-4 hours are required to complete a single sample.
• Tools are expensive. ($2-4M + $1-2M for prep tools)
SAMPLE PREPARATION
Focused Ion Beam (FIB)

- FIB allows preparation of specific transistors, contacts, or defects that can not be obtained with traditional means.
- Beam of Ga\(^+\) ions are focused to specific sites to sputter away material near area of interest allowing for further analysis by SEM or TEM.
- Dual beam FIB, SEM systems allow users to view sample with electron beam while milling with the ion column.
Focused Ion Beam (FIB)

- FEI Strata dual beam FIB/SEM - 7 nm ion resolution, 3 nm SEM resolution
- Latest generation dual beams can achieve 4.5 nm ion resolution and sub-nanometer SEM resolution.
- Full wafer systems (FEI XL830, 835) equipped with wafer navigation for defect analysis on inline material.
- Failure Analysis/Circuit edit capabilities
  - Mill contacts
  - Deposit metal for circuit testing
TEM sample prep process by FIB

1. Area of interest is capped with protective metal layers so it is not damaged by ion beam during milling process.
2. Bulk mills from front and back of area. Sample is ~1um thick at this stage.
TEM sample prep process by FIB

3. The sample is then lifted out of the well using the Omniprobe- in situ sample transfer system. This process requires the ion beam to cut the sample free from the wafer and weld it to the grid with in situ metal deposition. The sample is left well protected for this reason.
TEM sample prep process by FIB

4. After attaching the sample to the grid finer milling conditions are used to thin sample to electron transparency (40-80 nm).
TEM sample prep process by FIB

SEM image of TEM lamella – Top down view. Lamellae shown is ~ 40 nm thick
From the 3D sample the TEM will produce a 2D image. Image artifacts will occur if there are variations within the sample or if the structures being looked at are smaller than the sample is thick.
TEM sample prep process by FIB

X-section of TEM lamellae (TEM of TEM) – Original lamellae is found to be ~100nm thick. With ~20 nm of amorphorization on either side caused by ion beam. Ideally, the full thickness of lamellae is a single material so the image is clear. Amorphous material in the lamellae will spread the electron beam creating a soft or fuzzy image.
TEM ANALYSIS
TEMs at Cerium Labs

- JOEL 2010 – 200 kV TEM configured with EDS
- Philips CM300 – 300 kV configured with EELS, EDS and HAADF detectors.
TEM Modes of Operations

Bright Field Imaging

An imaging mode that uses only unscattered electrons to form the image. Contrast in such an image is due mostly to thickness and density variations in a sample. Bright field is the most commonly used mode when only metrology information is needed from TEM images.
TEM Modes of Operations

Dark Field Imaging
Using a single diffracted beam to form the image in a TEM. This causes only regions of the specimen with specific crystal structure and orientation to appear bright; all other areas appear dark ("dark field") in the final image; allowing crystallographic phase differentiation visually in the TEM.

Images above are of a titanium silicide material. The left image is standard BF and the right image is a DF image. 
http://www.imim-phd.edu.pl/contents/TEM.php
TEM Modes of Operations
TEM Modes of Operations

Scanning TEM (STEM)

A focused beam of electrons is scanned on the sample, similar to SEM. The small convergent probe allows sampling of ~2 Å diameter volumes in the samples revealing localized chemical and crystal structure.

A variety of detectors can be used to analyze the scattered electrons and related signals.

- STEM - EDS
- STEM - EELS
- STEM – High Angle Annular Dark Field
STEM - EDS

STEM Image with analysis trace

EDS-line profiles

- C
- Si
- O
- N

Position (um)

Counts

0.00   0.05   0.10   0.15

0       20     40     60     80     100
TEM Modes of Operations

Diffraction - Scattering of electron waves when they interact with an atomic lattice and subsequent interference of the scattered waves, as described by Bragg's Law. This scattering from a periodic structure is useful in determining the spacing of the lattice. In electron microscopy the spacings being determined are those between atoms in a crystal.

CBED: Convergent Beam Electron Diffraction
An electron probe is tightly focused on a TEM specimen and the resulting pattern of diffracted electrons is observed. The patterns contain information on the crystal symmetry and atomic and electronic structure of the sample. Regions as small as 0.2 nm may be examined. Highly specialized technique for materials science.

SAED: Selected Area Electron Diffraction
An aperture is used to define the area from which a diffraction pattern is formed in a TEM specimen. The resulting patterns contain information about phases present (lattice spacing measurement) and sample orientation. Can be used to evaluate mismatch in lattice orientations.

SAED
TEM Modes of Operations

High-resolution Imaging

Direct imaging of the specimens lattice in a HRTEM. This is accomplished by allowing some of the diffraction image to overlay the bright field image, enhancing the contrast along the lattice lines. Allows direct measurement of lattice parameters, inspection of individual defects and grain orientation.
Electron Energy Loss Spectroscopy (EELS)

Some electrons that pass through the TEM lamellae are scattered inelastically. The amount of energy lost is related to the materials present in the sample. These signals can be collected as a spectrum or represented with intensity maps, aka Energy Filtered TEM (EFTEM).
TEM with elemental analysis
Thank you.

The analyses contained in this presentation apply only to the samples analyzed.

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