CSCI 4974 / 6974
Hardware Reverse Engineering

Lecture 8: Microscopy and Imaging

Data Acquisition for RE

- Microscopy
- Imaging
- Registration and stitching

Microscopy

- Optical
- Electron
  - Scanning
  - Transmission
- Scanning probe
  - AFM
  - SCM

Optical microscopy

- No special prep required
- Full color imagery
- Quick setup
- Little training/experience required
- Limited to ~250nm resolution by diffraction :(

Optical microscopy

- Stereo microscopy
- Metallurgical microscopy
  - Epi-illumination
- Transmitted-light microscopy
  - Light shines through thin specimen
  - Usually not used for semiconductors
  - We won't cover this any further

Stereo microscope

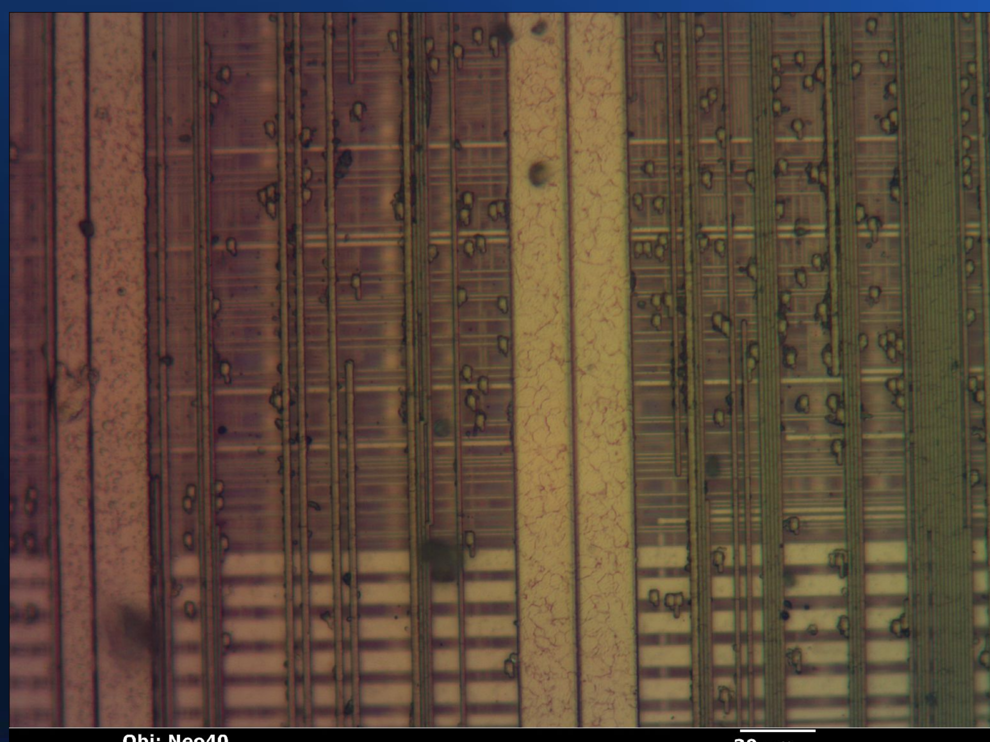
- Low magnification (<50x typical)
- Long working distance (few inches)
- Two objectives
  - Full depth perception
  - Bond wire plucking
  - Rebonding
  - Decap inspection
- Fiber-optic or ring lamp

Metallurgical microscope

- Two eyepieces, one objective
  - Both eyes see same image
- Camera port on top
- BF/DF selector
- Epi-illuminator at back
  - Sample is lit through objective
- X/Y/tilt stage

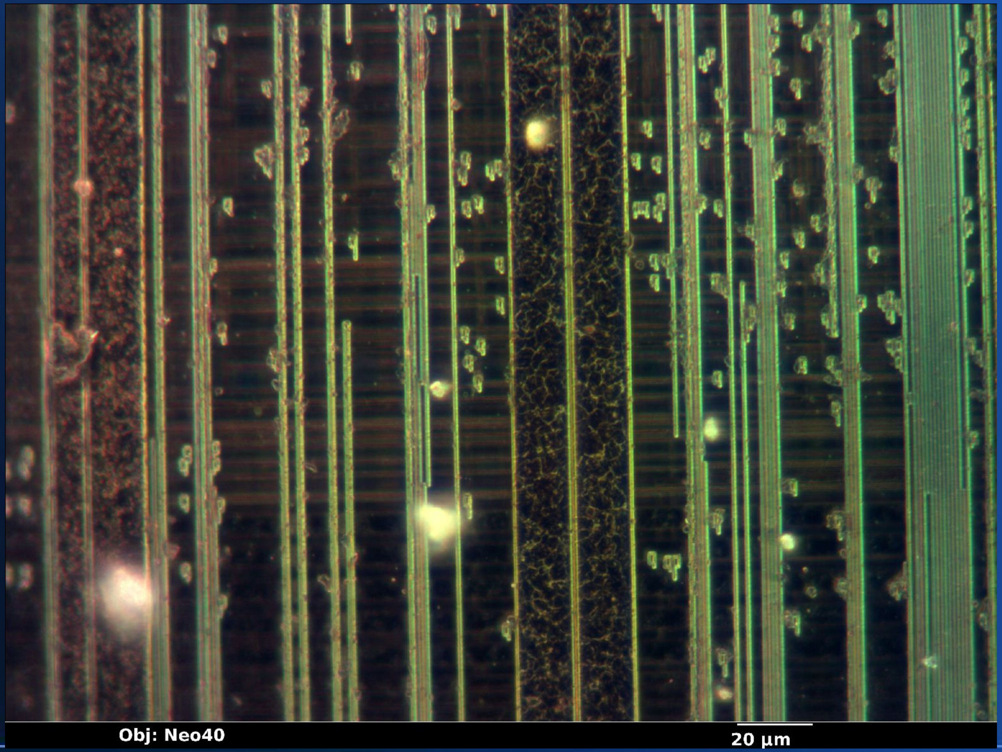
Brightfield metallurgical

- Look at specular reflections from sample
- Shows color / reflectivity variations well



Darkfield metallurgical

- Look at diffuse reflections, ignore specular
- Shows topography better than brightfield

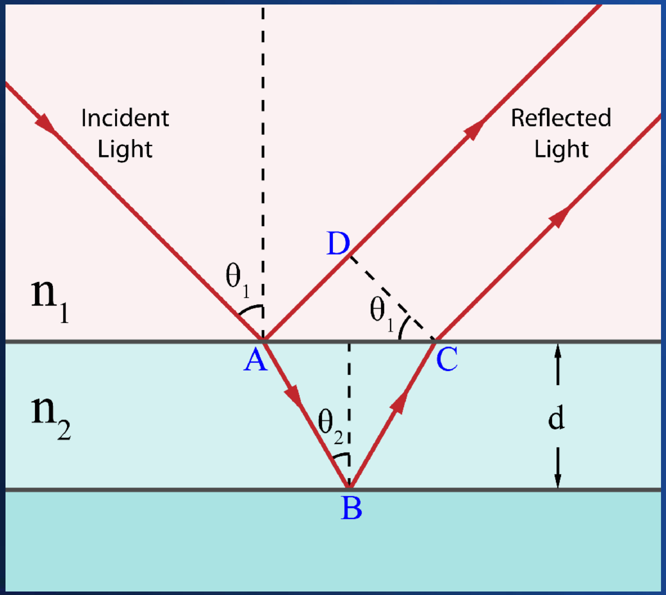


Optical image capture

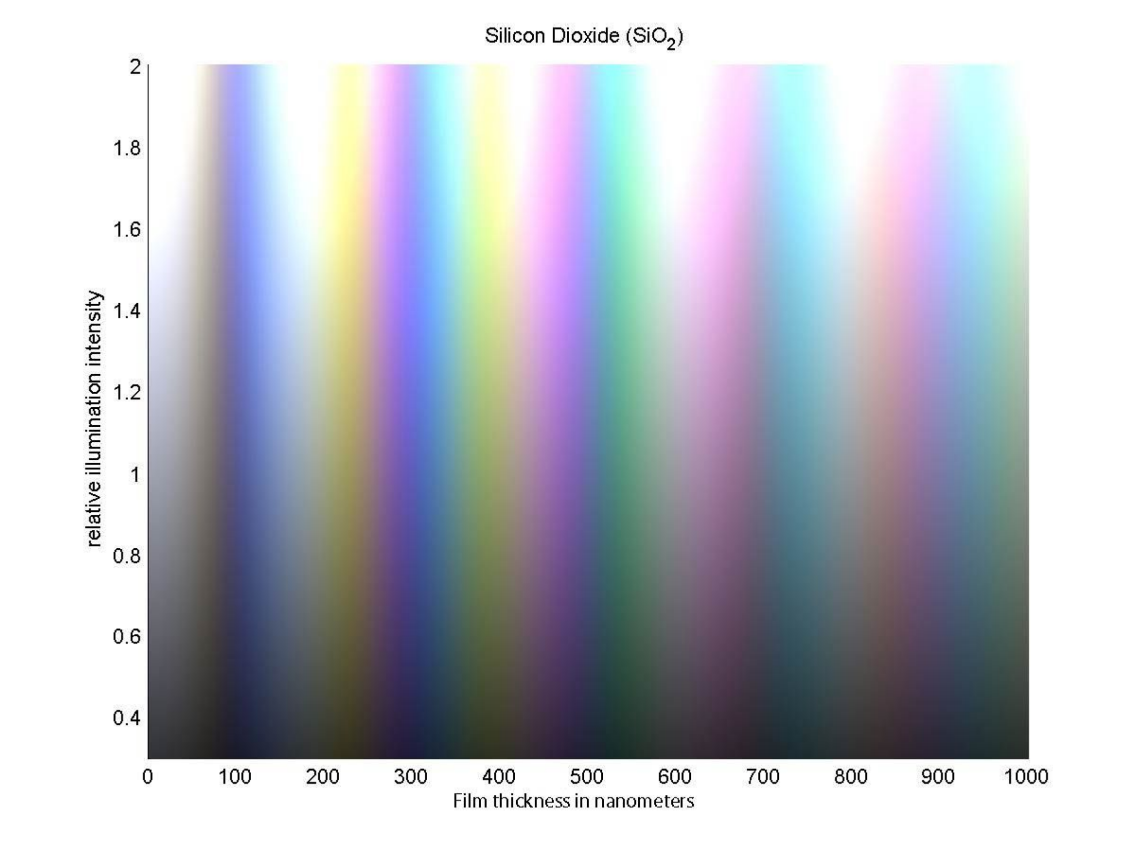
- Insert beamsplitter before eyepiece(s)
- Direct some light to camera
- Eyepiece and camera may not be parfocal :(

Thin-film interference

- Light reflects from film and substrate
- Beams interfere at multiples of path length
- Color depends on angle + refractive index

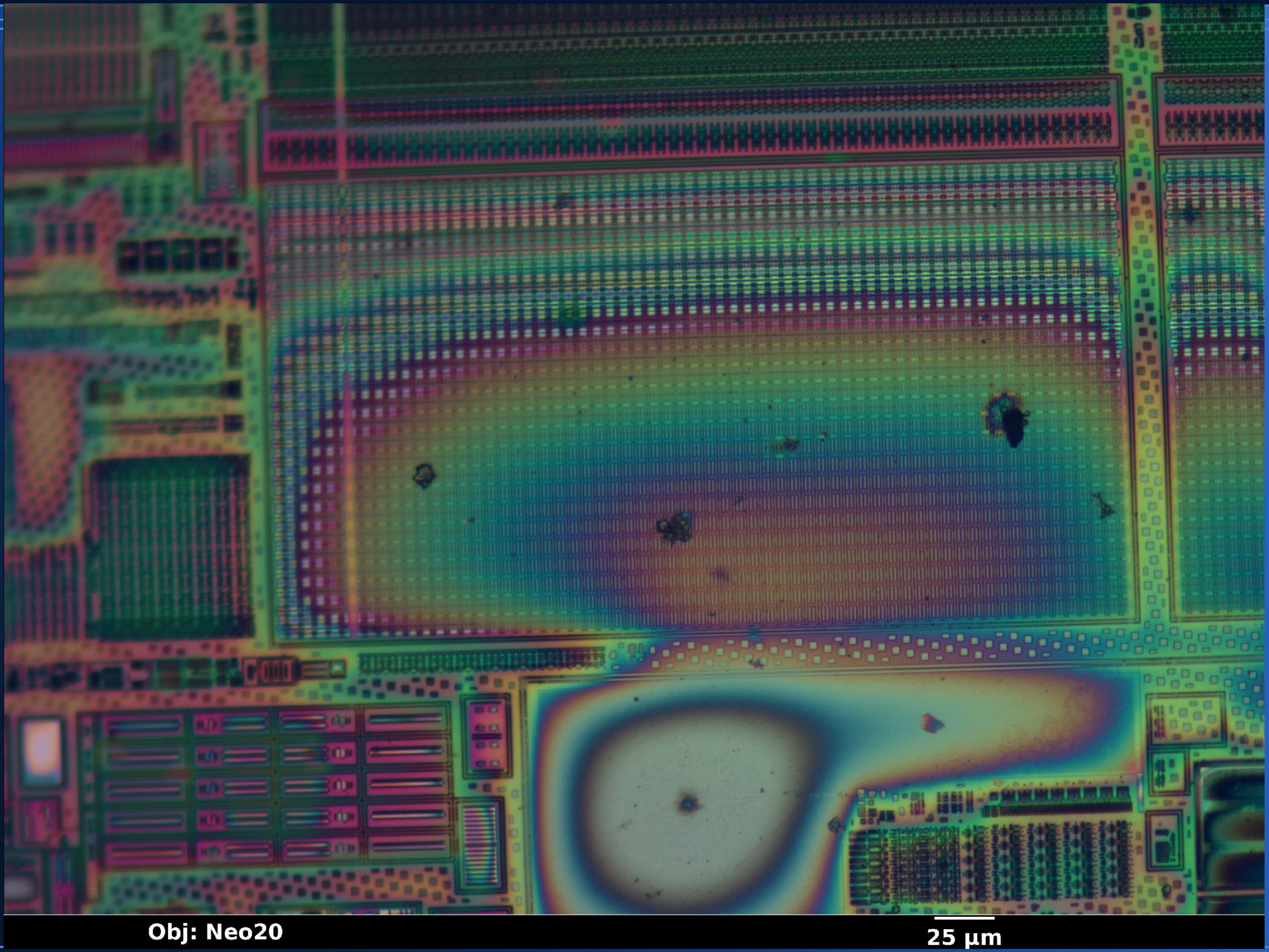


Thin-film interference



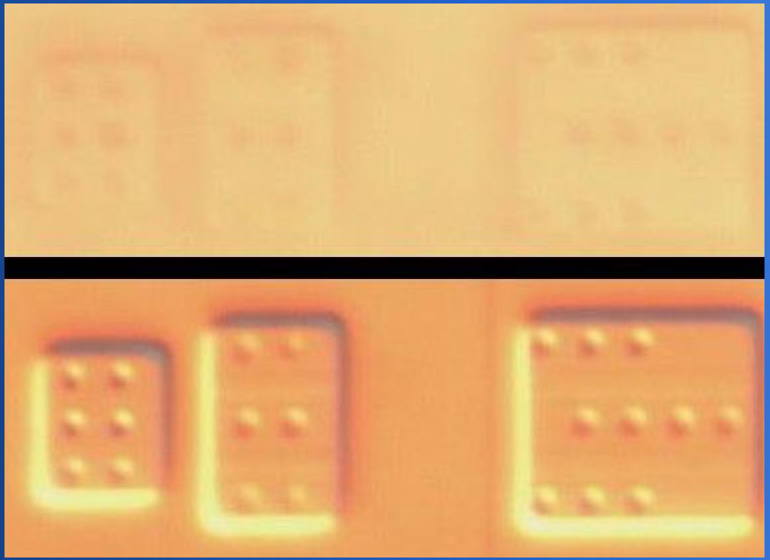
- *image from cleanroom.byu.edu*

Thin-film interference



NIC/DIC

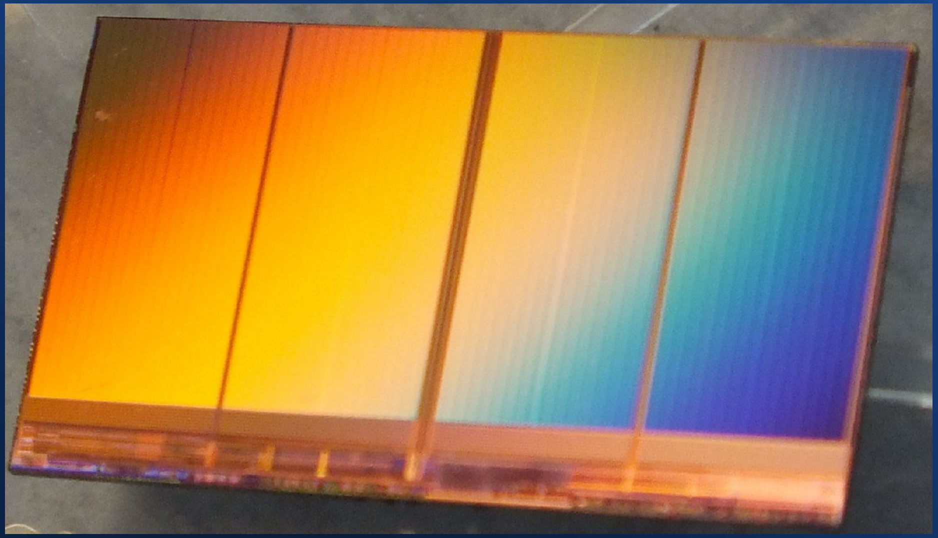
- [Nomarski|Differential] Interference Contrast
- Split beam into two polarizations
- Shine beams on sample at slight offset
- Recombine beams
- Highlights glass thickness

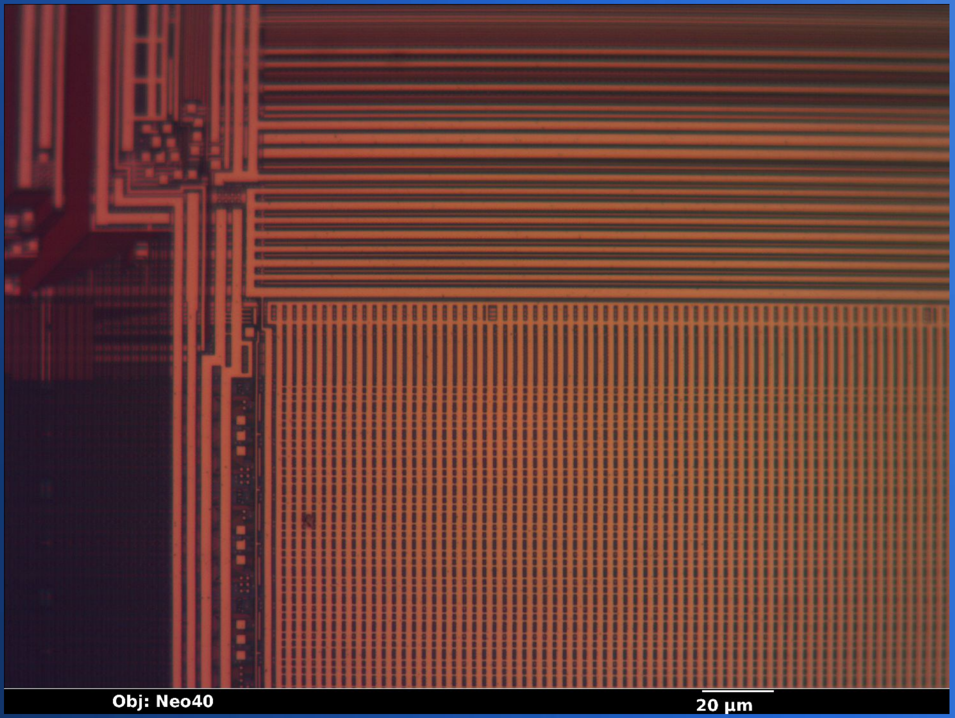


Optical diffraction

- Wires on top metal layer often have pitch comparable to the wavelength of light
- Die surface acts as reflective diffraction grating
- Colors vary massively with viewing angle and often go away when magnified

Diffraction on Intel 64Gb NAND





Electron microscopy

- Electrons have wavelength << photons
  - Much smaller diffraction limit
  - Better resolution
- Causes electron flow to sample
  - Sample will build up charge unless grounded
  - Sample typically must be (made) conductive
- Significantly more complex, requires more operator skill and setup/sample prep time

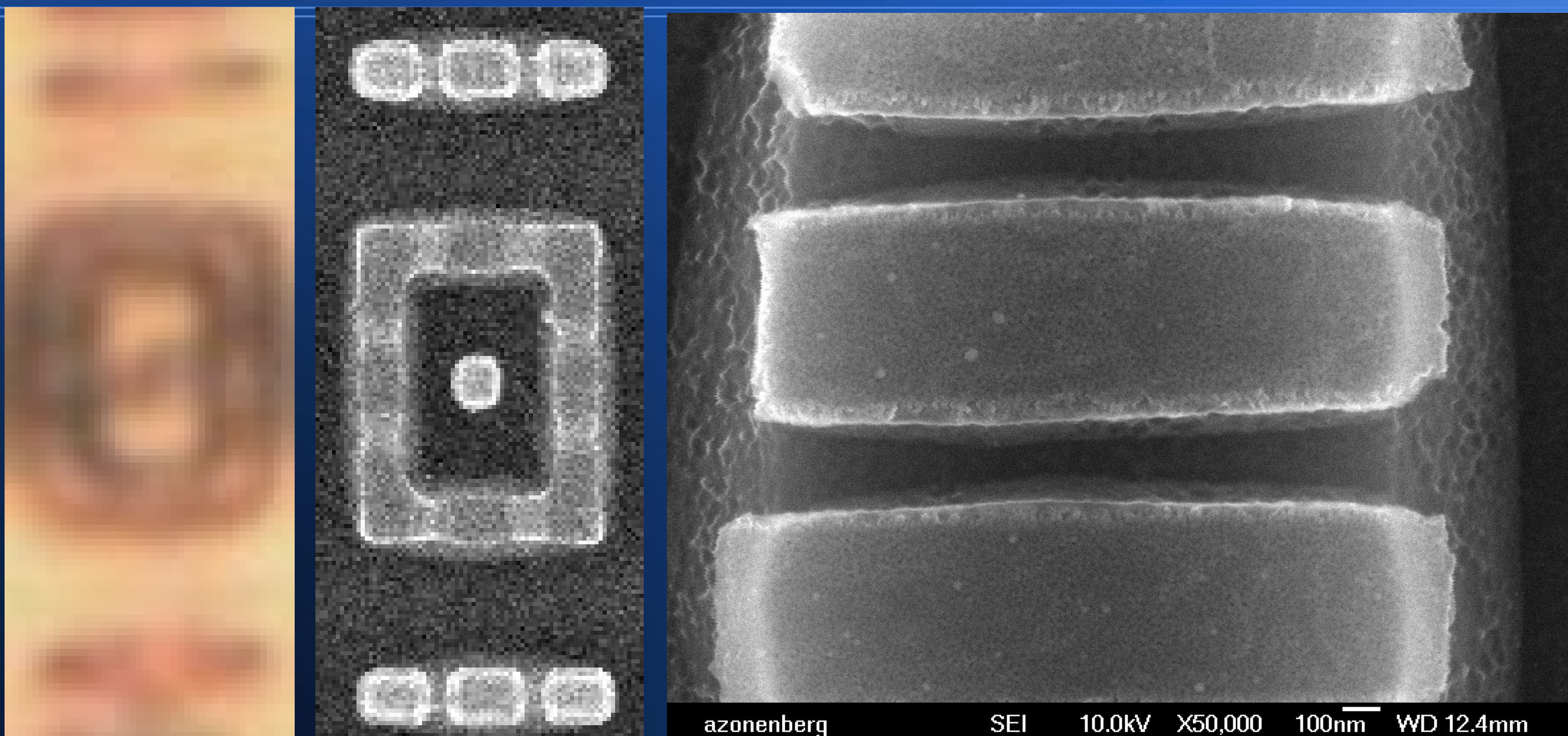
Transmission EM (TEM)

- Shine electron beam through very thin sample
- Requires extensive sample prep
  - Slicing sample is destructive
- Highest resolution (near atomic)
  - Useful for process RE, but not circuit analysis
  - We won't cover TEM in this class

Scanning EM (SEM)

- Raster-scan e-beam over sample
- Feed return signal to CRT or digital sensor
- Images surface, can work with bulk materials
  - Nondestructive in general case
    - May cause problems with sensitive materials

Resolution comparison



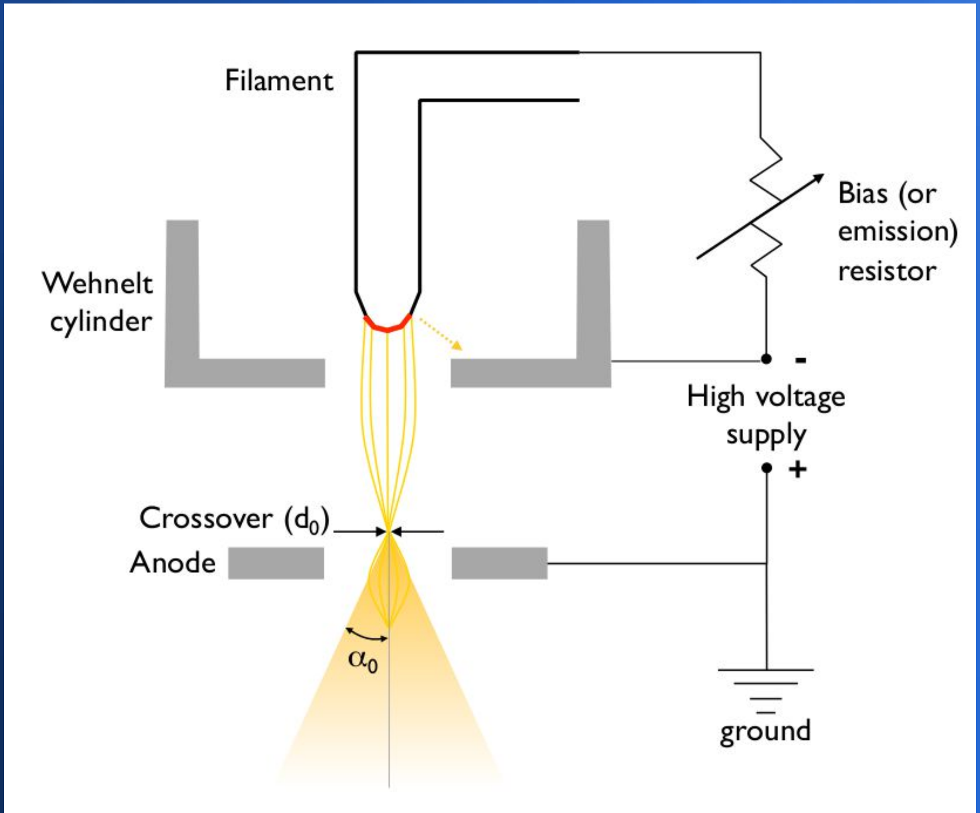
Left = Olympus BH2 optical microscope, Mitutoyo 100x objective (total mag 1000x)
Center = JSM-6335 SEM, 2,500x
Right = JSM-6335 SEM, 50,000x

SEM column construction

- Electron gun
- Condensor lenses and aperture
- Astigmatism correction
- Scan coils

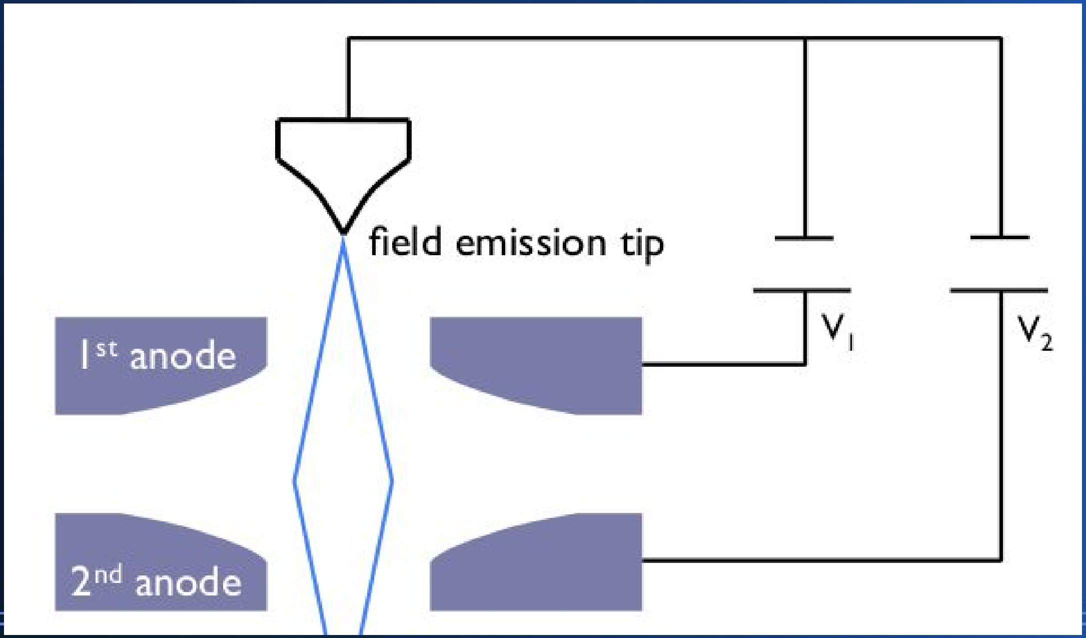
Thermionic electron gun

- Can run in low vacuum
- Cheap and simple
- Short lifetime
- Lower resolution



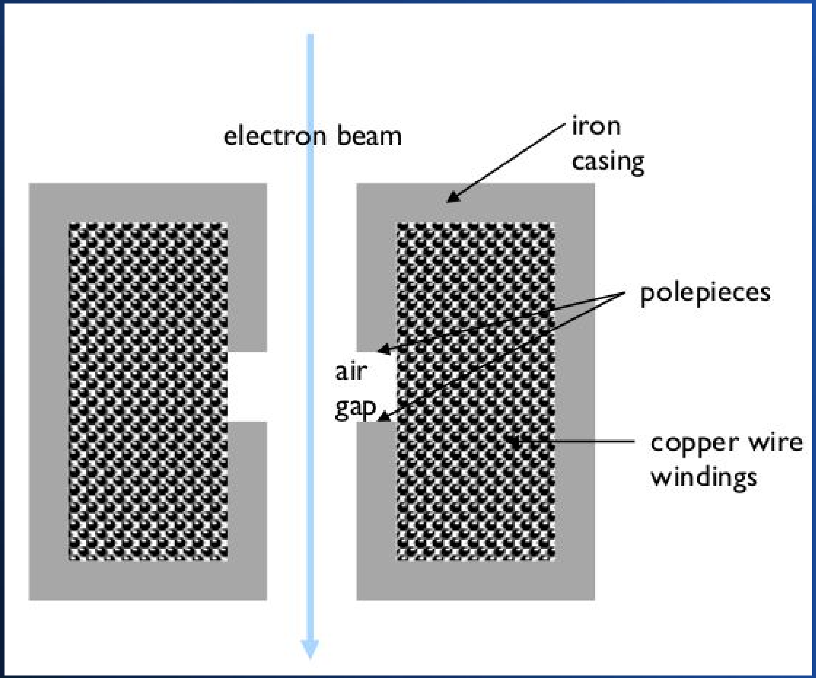
Field emission electron gun

- Somewhat more complex setup
- More intense, focused beam
- Generally gives higher resolution



Electron lenses

- Can't use normal optics
- Focus / deflect beam with magnetic field



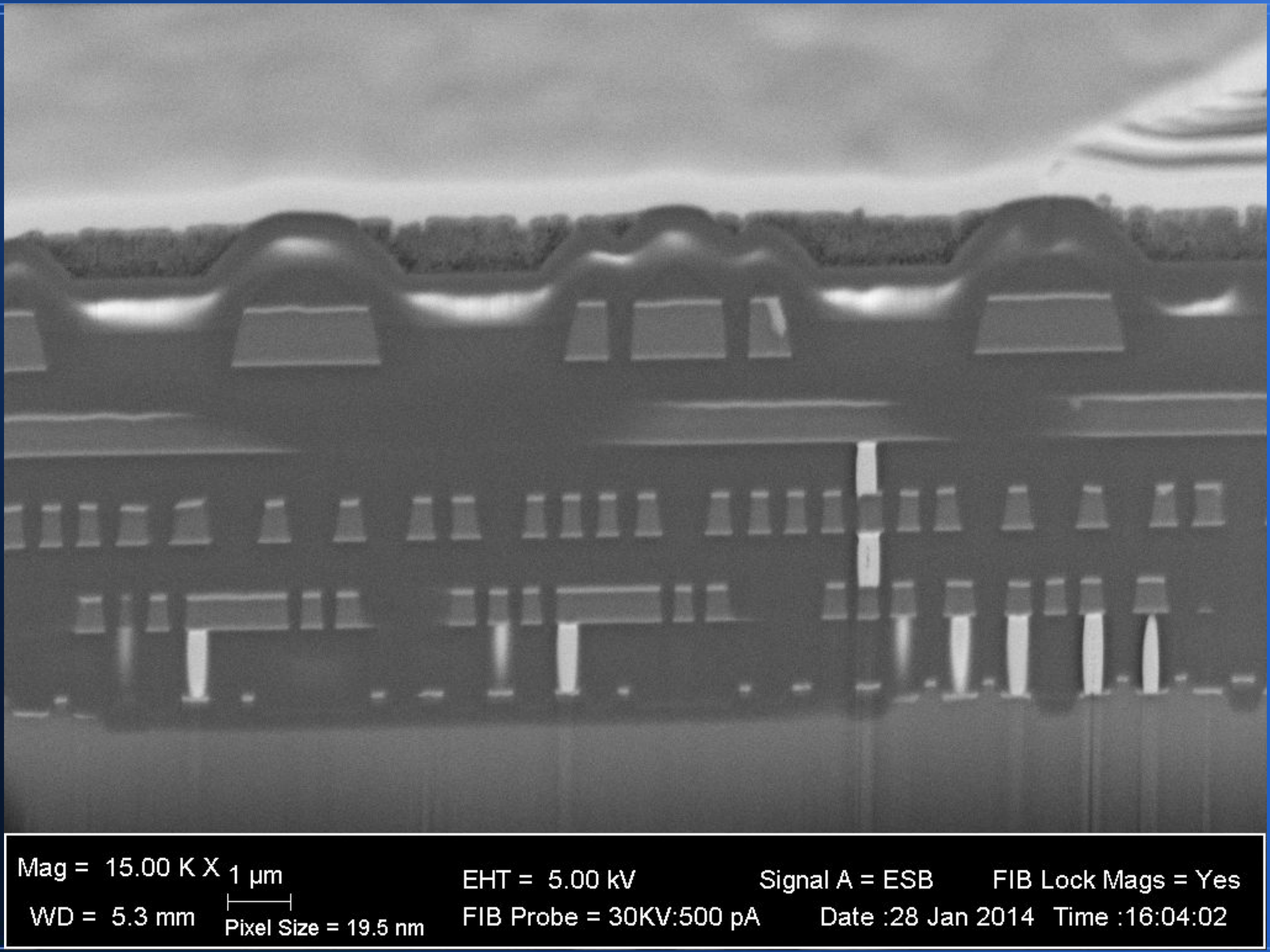
Sample-beam interactions

- Secondary electrons
  - Surface topography
- Backscatters
  - Z-contrast
- X-ray emission
  - EDS, WDS for element ID
  - Useful for process RE but not for circuit analysis
- Others possible but not covered here

Backscatter imaging

- Beam electrons hit nucleus of sample atom
- Elastic collision
- P(backscatter) depends on Z
- Provides atomic number info
  - Usually relative, not absolute
- High energy, can exit sample from fairly deep

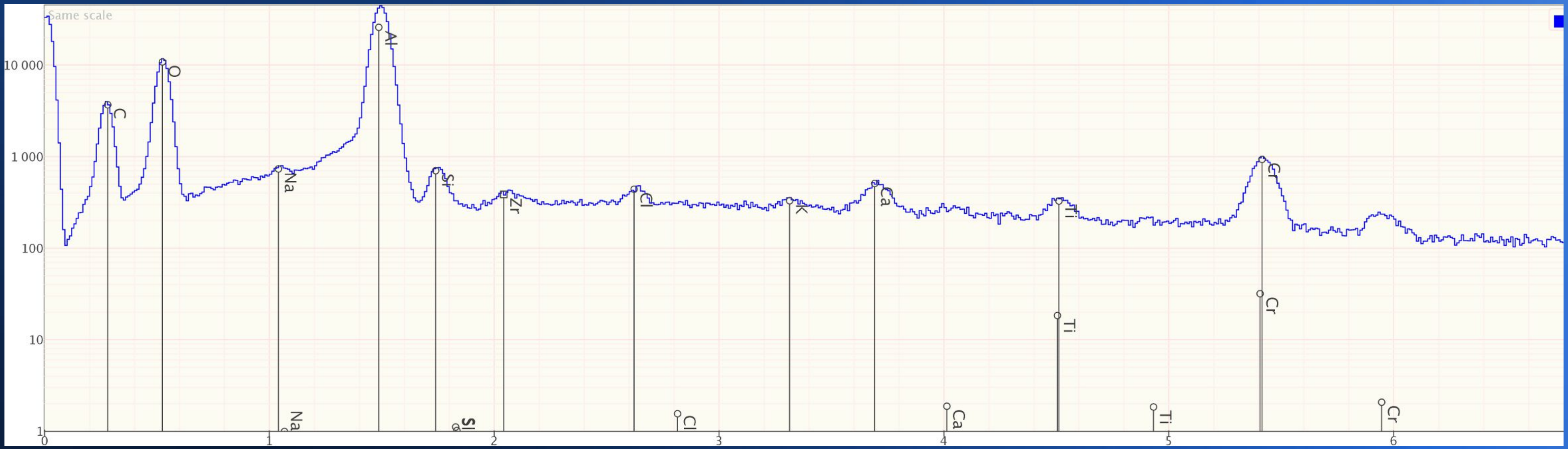
Backscatter imaging



X-ray spectroscopy (EDS/WDS)

- Beam electron nudges shell electron gently
  - Moved to another shell, but not dislodged
  - Electron springs back home and releases X-ray photons
  - X-ray energy level depends on atom
- EDS and WDS are different ways of detecting the same X-rays
  - EDS = fast, lower energy resolution
  - WDS = slow, much more accurate

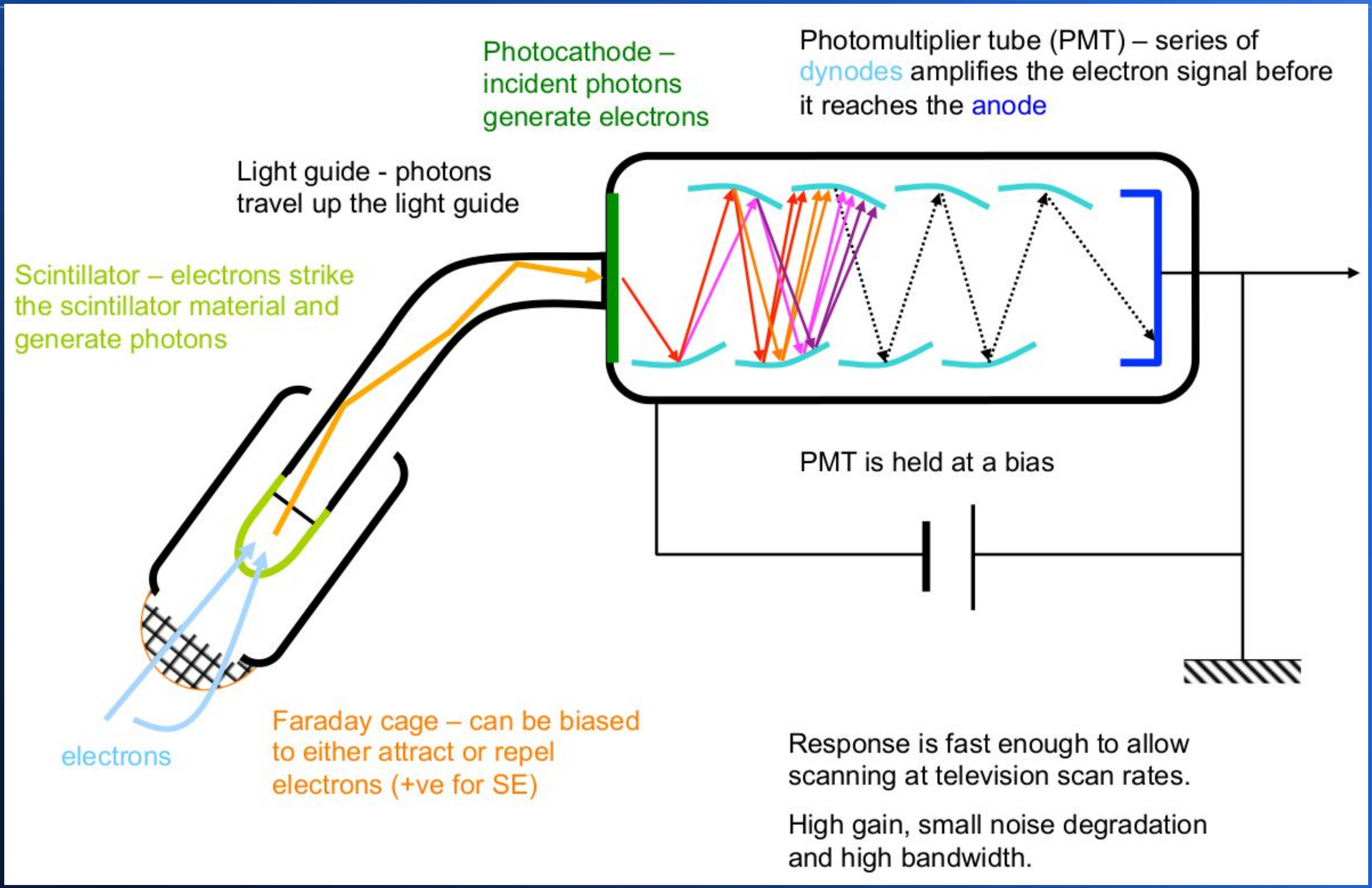
EDS spectrum of purple ceramic



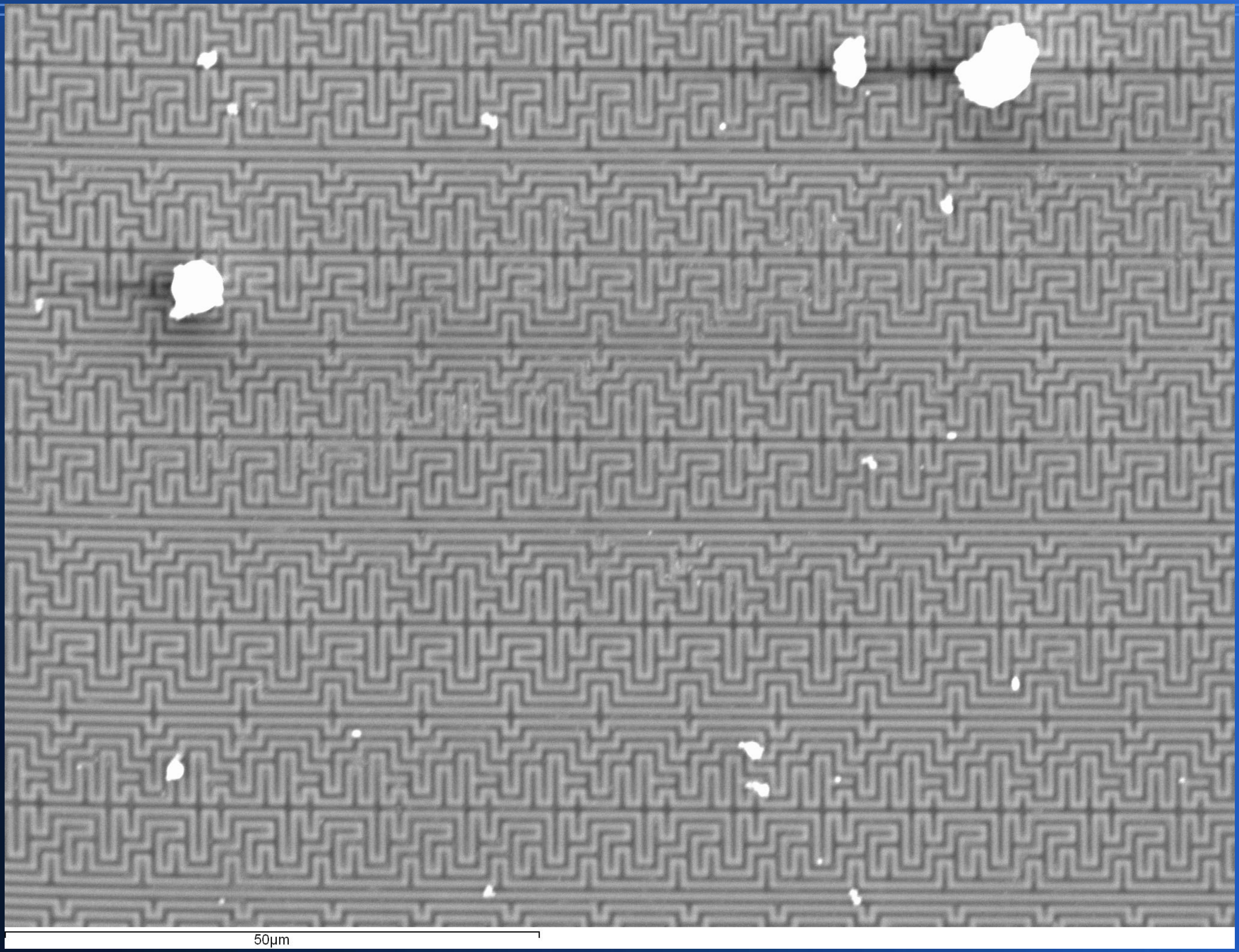
Secondary electron imaging

- Beam electron grazes sample atom
- Knocks outer shell electron free
- Low energy, can't penetrate very far
  - Sensitive to surface topography
  - Surface particles etc are bright
- Most SE detectors also pick up BSE
  - Z-contrast is still present to some degree

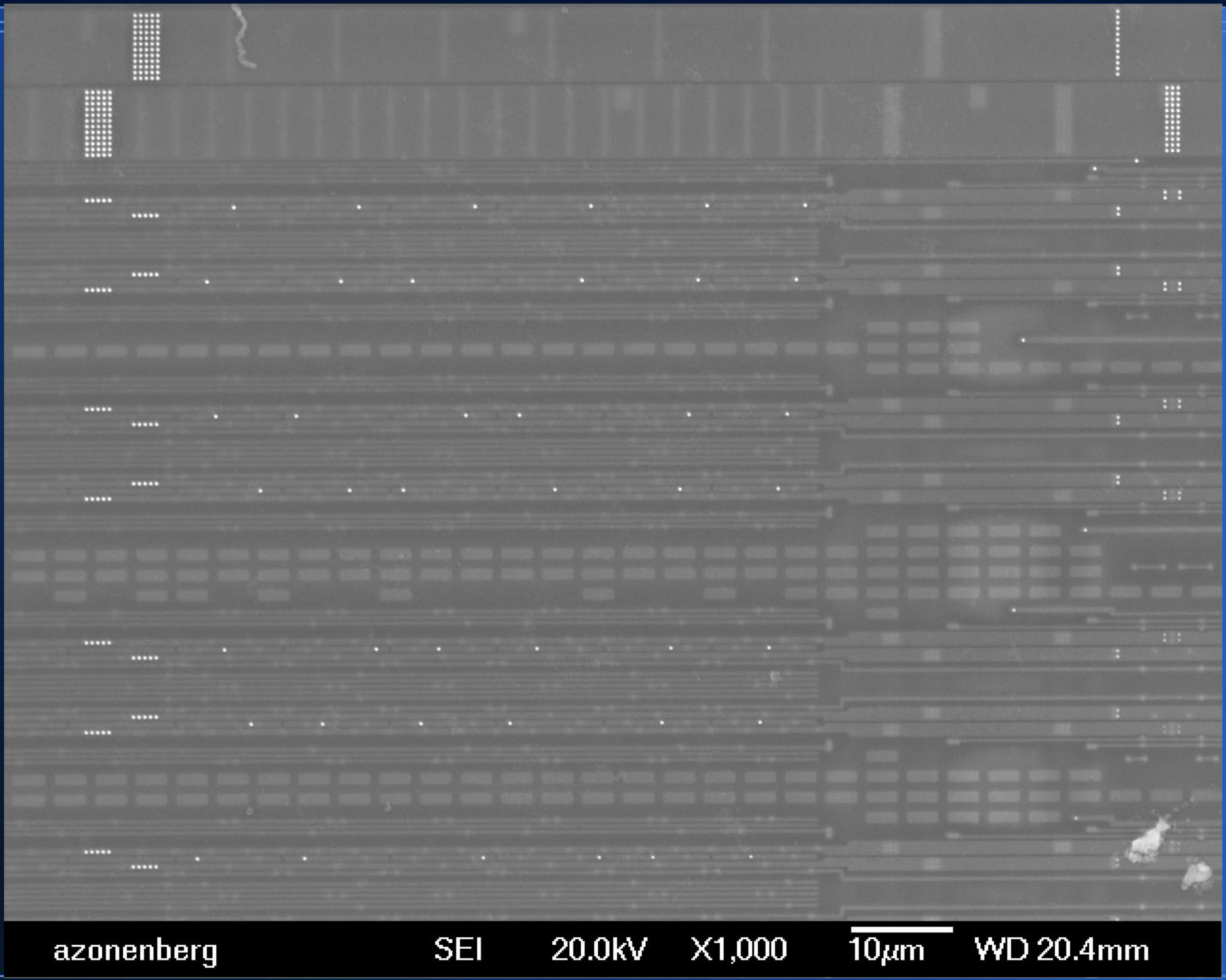
Everhart-Thornley detector



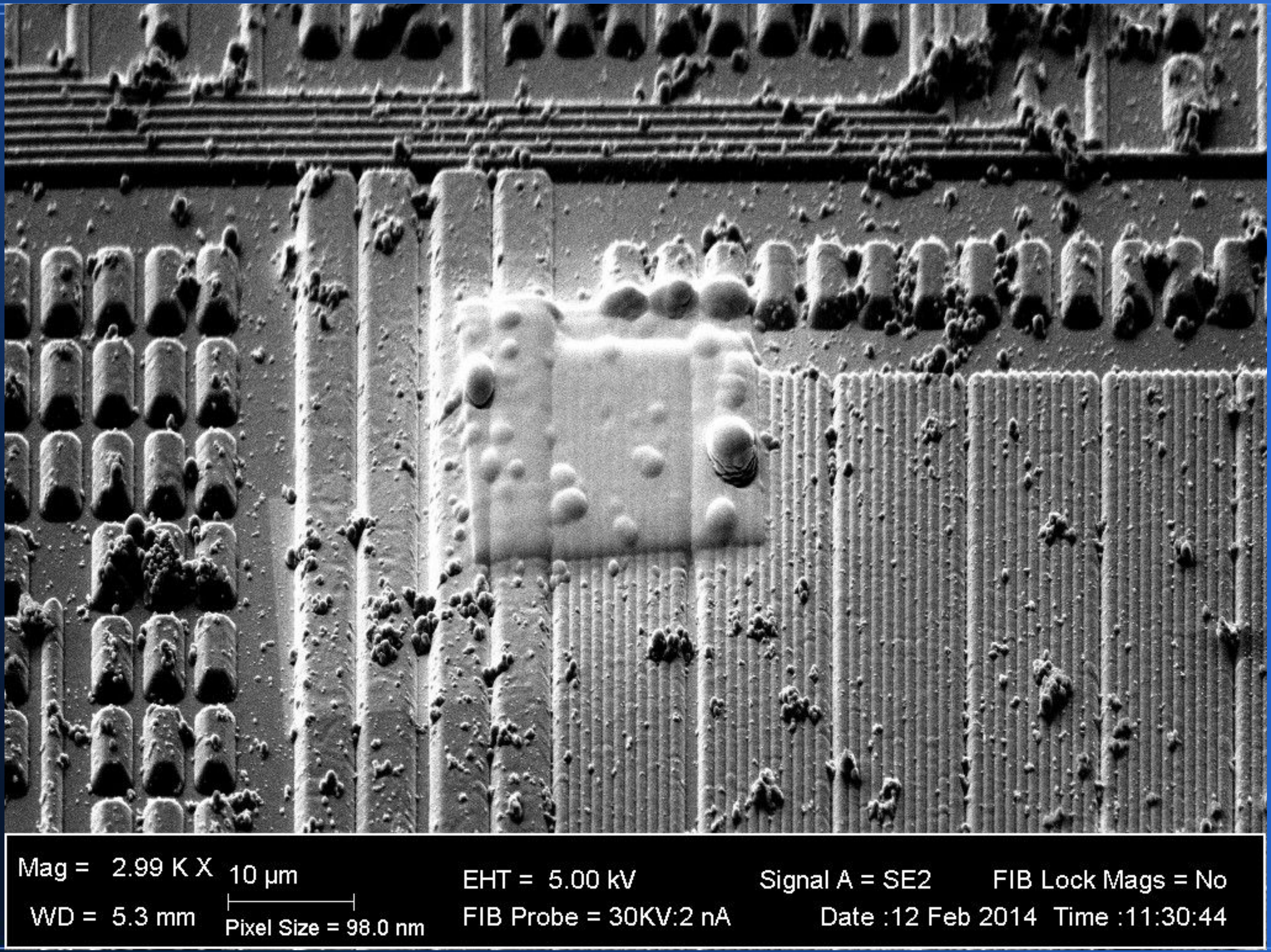
Surface particles on smartcard



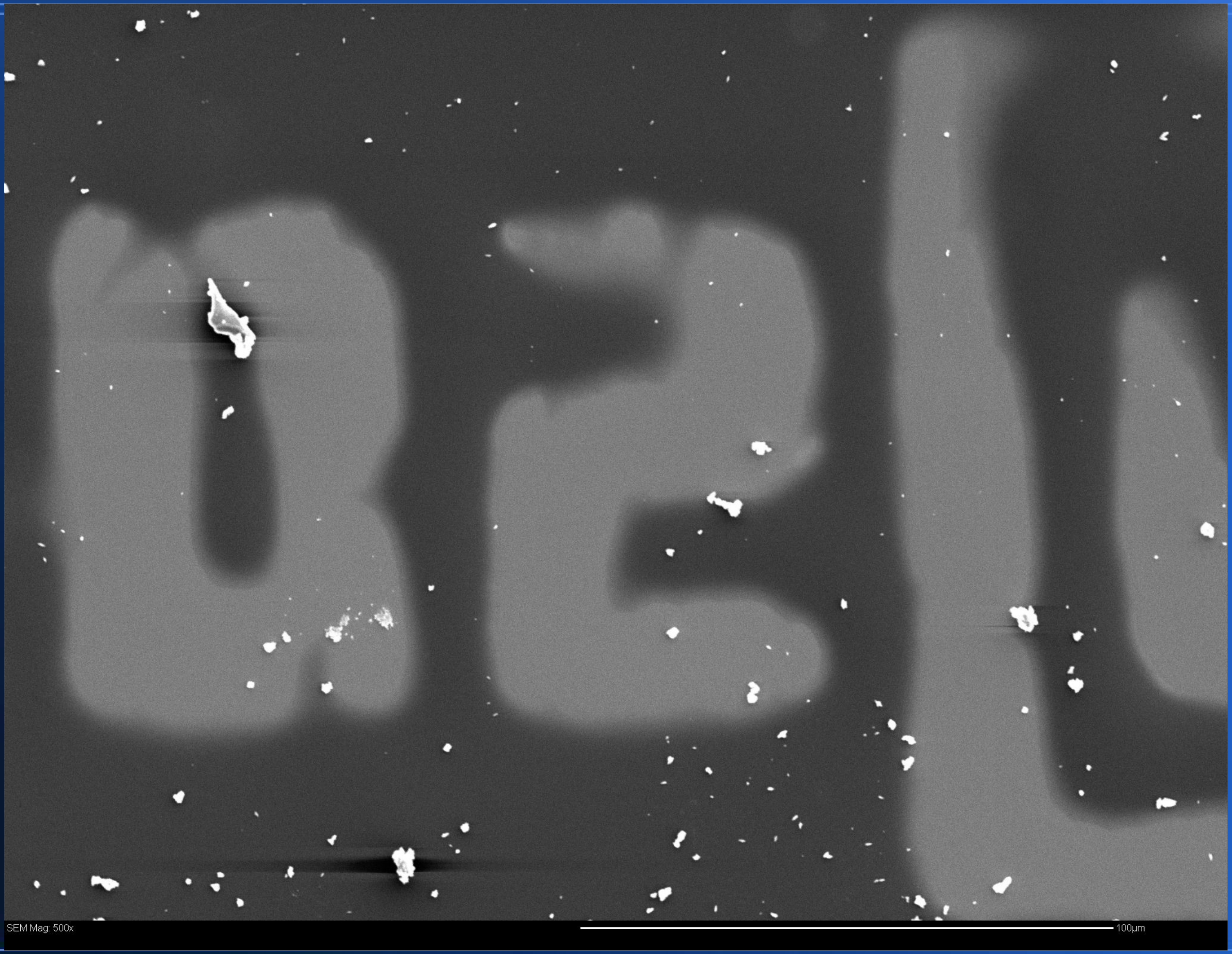
BSE visible in SE image



Tilted specimen with some BSE

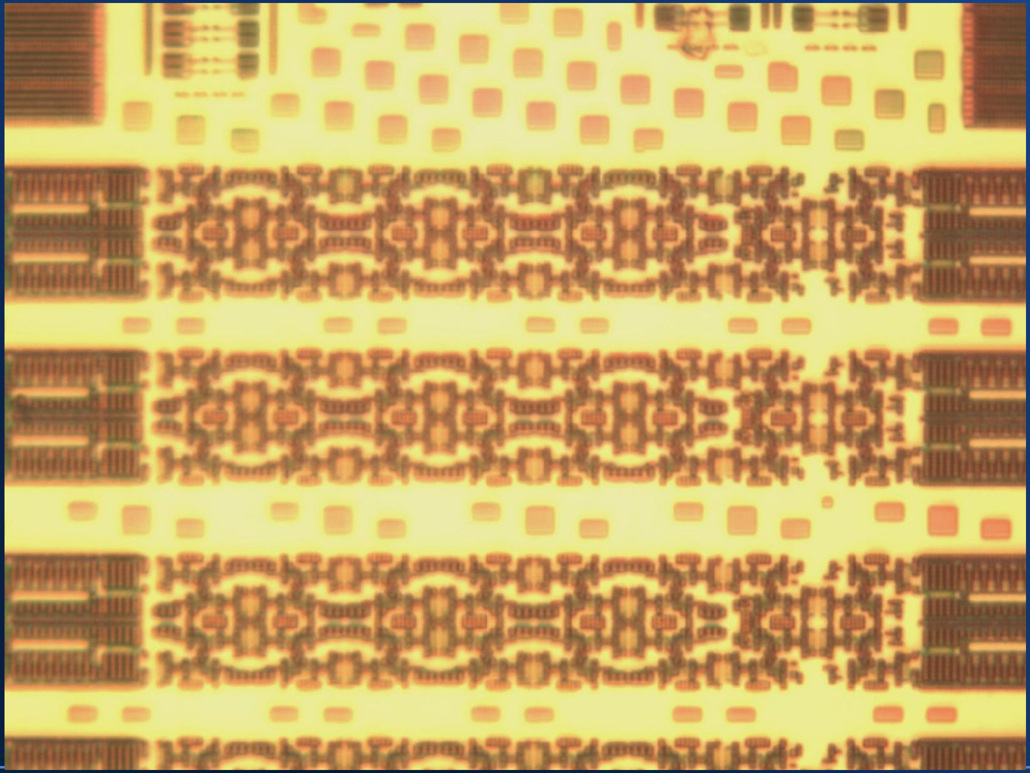


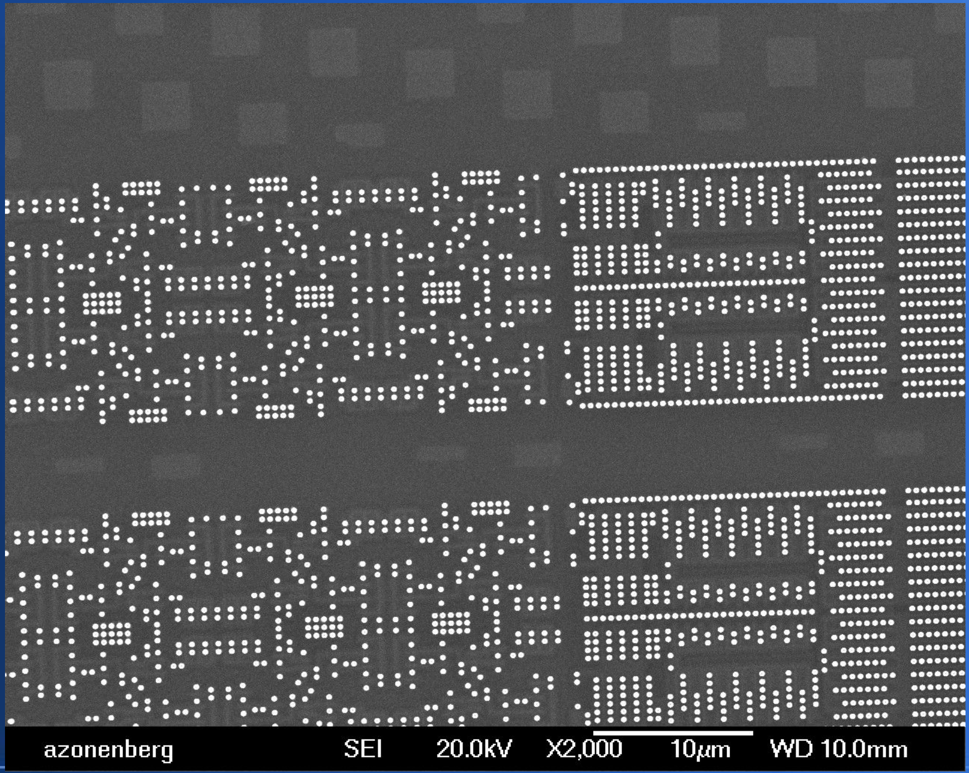
Charging artifacts



Transparent layers

- ~400nm SiO_2 over poly transmits visible light but not electrons





Sample coating

- Sputtered metal (Au / Pd / Pt are common)
  - Doesn't degrade
  - Good step coverage
  - Hard to remove
- Evaporated carbon
  - Poor step coverage
  - Can be stripped in oxygen plasma
- Coatings can cause image artifacts

SEM image capture

- Feed detector output to A/D converter
- Add H/V sync and store to file

Scanning probe microscopy

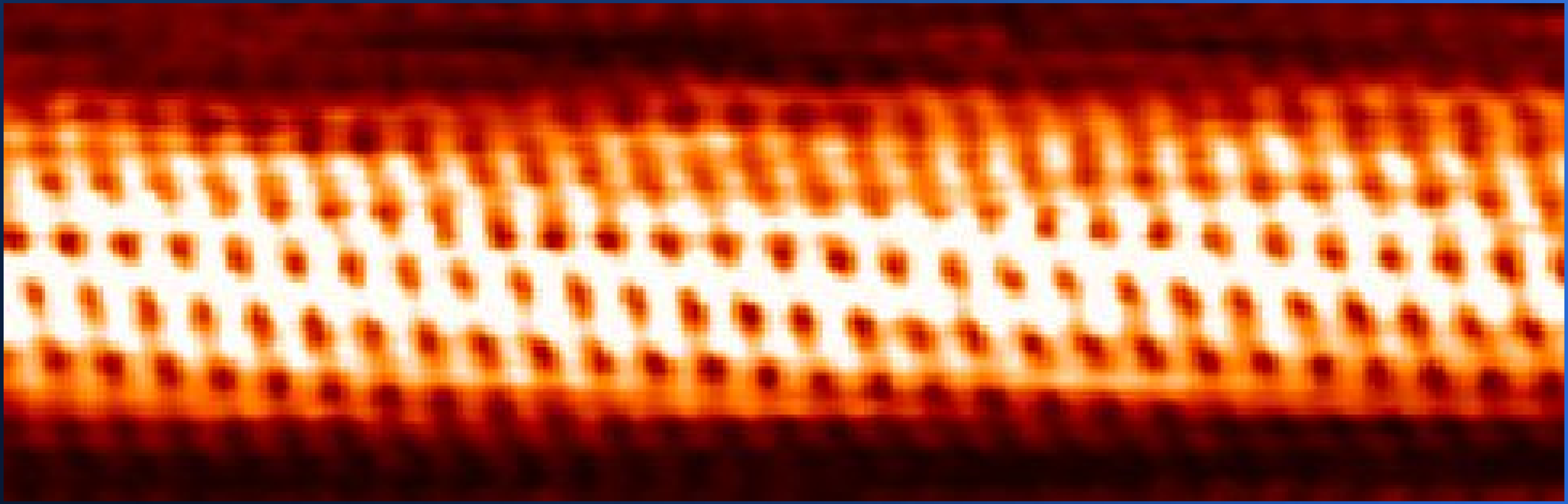
- Scanning Tunneling Microscope (STM)
- Atomic Force Microscope (AFM)
  - Variations (SCM etc)
- Low frame rates (moving physical probe)
- Small scan area

STM

- “Objective” is wire sharpened to single atom tip
- Move across sample without contacting
- Working distance is O(0.5 nm)
- Apply voltage between probe and sample, measure current
  - Depends on spacing

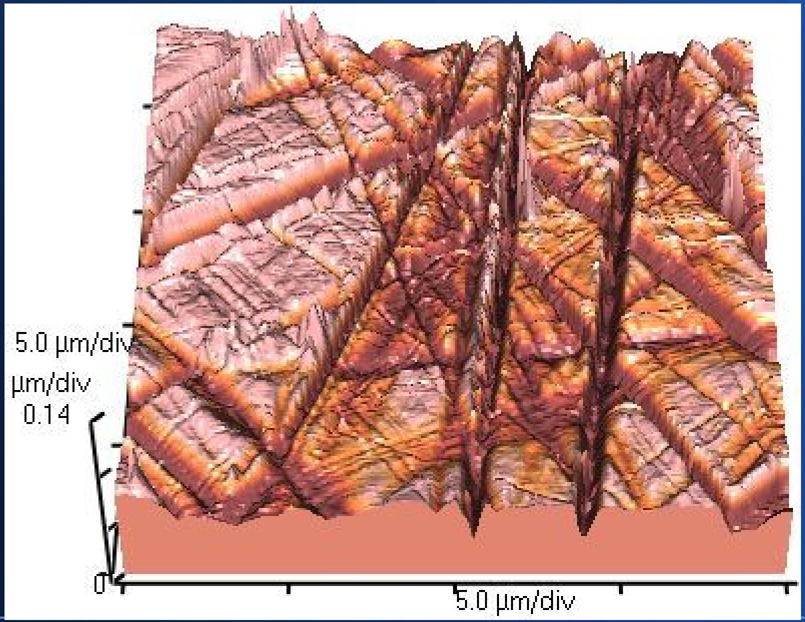
STM

- Can reach single-atom resolution
- Example image of CNT



AFM

- Move pointed tip across sample, measure force
- Can operate in contact or non-contact modes
- Normally detects surface topography



SCM

- Scanning Capacitance Microscopy
- Apply AC signal to conductive AFM probe
- Measure coupling to sample
- Can be used for dopant mapping
  - Potentially higher spatial resolution than Dash
  - Measures doping strength, not just type
- See “Two-dimensional dopant profiling by scanning capacitance microscopy” by Williams

Mass imaging

- Motorized sample stage
- Define corners and step size
- Take many pictures automatically
- Can be done with any microscopy technique
  - Some EM can also do huge scan fields

Registration and stitching

- Take tiles for each layer and line them up
- Merge into one large image
- Align multiple layers with each other

Hugin

- Open source tool for image registration
- In-class demo/exercise

Questions?

- TA: Andrew Zonenberg <azonenberg@drawersteak.com>
- Image credit: Some images CC-BY from:
  - John McMaster <JohnDMcMaster@gmail.com>
  - Prof. Dan Lewis <lewisd2@rpi.edu>