Final Exam Schedule

When: 3:30pm-5:30pm, Tuesday, May 2\textsuperscript{nd} 2017

Where: BH 208 (same classroom as lectures)
ECE 541/ME 541
Microelectronic Fabrication Techniques

MW 4:00-5:15 pm

Microscopy Technique for Micro-/Nano-fabrications

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Nano-Characterization Techniques

- Optical Microscopy
- Scanning Electron Microscopy (SEM)
- Scanning Tunneling Microscopy (STM)
- Transmission Electron Microscopy (TEM)
- Atomic Force Microscopy (AFM)
- Scanning Near-field Optical Microscopy (SNOM)
Optical Microscopy

Important features:
- The objective lenses
- The eyepieces (oculars)
- The light source

$$s = \frac{0.61\lambda}{n \sin \theta} = \frac{0.61\lambda}{NA}$$

(NA: numerical aperture)

<table>
<thead>
<tr>
<th>Wave length</th>
<th>Frequency</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>KHz-MHz-GHz</td>
<td>Km-m-cm</td>
</tr>
<tr>
<td>Microwave</td>
<td>GHz-THz</td>
<td>300mm-300µm</td>
</tr>
<tr>
<td>Optical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrared</td>
<td>THz-4.3×10^{14}Hz</td>
<td>300µm-700nm</td>
</tr>
<tr>
<td>Visible</td>
<td>4.3×10^{14}Hz-5.7×10^{14}Hz</td>
<td>700nm-400nm</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>5.7×10^{14}Hz-10^{16}Hz</td>
<td>400nm-30nm</td>
</tr>
<tr>
<td>X-ray</td>
<td>10^{16}Hz-10^{18}Hz</td>
<td>30nm-0.3 Å</td>
</tr>
<tr>
<td>Gamma ray</td>
<td>10^{19}Hz and above</td>
<td>0.3 Å and shorter</td>
</tr>
<tr>
<td>Electrons</td>
<td>0.1 Å-0.01 Å</td>
<td></td>
</tr>
</tbody>
</table>
Scanning Electron Microscopy

\[ \lambda = \frac{h}{m_e V} = \frac{h}{\sqrt{2e m_e V}} = \frac{1.22}{\sqrt{V}} \text{ (nm)} \]

\[ \lambda = \sqrt{\frac{1.5}{V + 10^{-6} V^2}} \text{ (nm)} \]

<table>
<thead>
<tr>
<th>V/kV</th>
<th>( \lambda \propto V^{-1/2} )</th>
<th>( \lambda ) relativistically corrected (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.0086</td>
<td>0.0086</td>
</tr>
<tr>
<td>40</td>
<td>0.0061</td>
<td>0.0060</td>
</tr>
<tr>
<td>60</td>
<td>0.0050</td>
<td>0.0049</td>
</tr>
<tr>
<td>80</td>
<td>0.0043</td>
<td>0.0042</td>
</tr>
<tr>
<td>100</td>
<td>0.0039</td>
<td>0.0037</td>
</tr>
<tr>
<td>200</td>
<td>0.0027</td>
<td>0.0025</td>
</tr>
<tr>
<td>500</td>
<td>0.0017</td>
<td>0.0014</td>
</tr>
<tr>
<td>1000</td>
<td>0.0012</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

\( c = 2.998 \times 10^8 \text{ m/s} \quad e = 1.602 \times 10^{-19} \text{ C} \)

\( h = 6.62 \times 10^{-34} \text{ Js} \quad m_e = 9.108 \times 10^{-31} \text{ kg} \)
Thermionic Electron Gun:

Field emission electron gun:

\[ F = e(B \times V) \]
Backscattered primary electrons and Secondary electrons: SEM
X-ray radiation in SEM: Energy-dispersive spectrometers (EDS)
Auger electrons: Auger electron spectroscopy
Light: Cathodoluminescence
Transmitted/diffracted electrons: TEM
Absorbed electrons: Specimen heating, Electron-Beam-induced current (EBIC)
TEM of ZnO:Mn

Cross-Sectional TEM

HRTEM of Interface and Film

Electron Diffraction Pattern

DP in ZnO:Mn

DP: Diffraction Patterns.

FFT in ZnO:Mn

FFT: Fast-Fourier Transform

Large Range Z-contrast Images


Scanning Tunneling Microscopy (STM) (I)

STM is one member of a family, which is called Scanning Probe Microscopy (SPM):

- Scanning Tunneling Microscopy ✓
- Atomic Force Microscopy ❌
- Near-field Scanning Optical Microscopy ❌
- Magnetic Force Microscopy
- Electric Force Microscopy
- Lateral Force Microscopy
- Scanning Capacitance Microscopy
- Scanning Ion Conductance Microscopy
- Scanning Thermal Microscopy
- Scanning Noise Microscopy
- Scanning Near-field Acoustic Microscopy
- Scanning Electrochemical Microscopy
- Force Modulation Microscopy
- Magnetic Resonance Force Microscopy
- etc.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Optical Microscope</th>
<th>Scanning Electron Microscope</th>
<th>Scanning Probe Microscope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample operating environment</td>
<td>Ambient air, liquid or vacuum</td>
<td>Vacuum</td>
<td>Ambient air, liquid or vacuum</td>
</tr>
<tr>
<td>Depth of Field</td>
<td>Small</td>
<td>Large</td>
<td>Medium</td>
</tr>
<tr>
<td>Resolution: x,y</td>
<td>0.2-1.0(\mu\text{m})</td>
<td>5.0nm</td>
<td>2-10nm for AFM 0.1nm for STM</td>
</tr>
<tr>
<td>Resolution: z</td>
<td>N/A</td>
<td>N/A</td>
<td>0.1nm for AFM 0.01 nm for STM</td>
</tr>
<tr>
<td>Effective Magnification</td>
<td>(1\times10^3\times)</td>
<td>(10\times - 10^6\times)</td>
<td>(5\times10^2 \times - 10^8\times)</td>
</tr>
<tr>
<td>Sample preparation requirement</td>
<td>Little</td>
<td>Little to substantial</td>
<td>Little or none</td>
</tr>
<tr>
<td>Characteristics required of sample</td>
<td>Sample must not be completely transparent to light wavelength used</td>
<td>Surface must not build up charge and must be vacuum compatible</td>
<td>Sample must not have local variations in surface height &gt;10(\mu\text{m}).</td>
</tr>
</tbody>
</table>
Atomic Force Microscopy (AFM)
Outline

- History of Atomic Force Microscopy (AFM)
- Instrumentation
- Static force-distance curves and force spectroscopy
- Dynamic AFM and force gradient spectroscopy
- Imaging
- Applications and emerging areas
The starting point - STM


Binnig and Rohrer awarded Nobel Prize in Physics in 1986 for STM

If $V_t$ is small compared to workfunction $\Phi$, and tunneling current is given by $I_t(z) = I_0 e^{-2\kappa_t z}$ where $z$ is the gap $l_0$ is a function of the applied voltage and the density of states in the tip and the sample, and $\kappa_t = \sqrt{2m\Phi / \hbar}$

For most metals, $\Phi \cong 4eV$, so that $\kappa_t = 1\text{Å}^{-1}$

Most current carried by "front atom" blunt tips, so atomic resolution possible even with relatively blunt tips

Only electrically conductive samples, restricting its principal use to metals and semi-conductors
The AFM


FIG. 1. Description of the principle operation of an STM as well as that of an AFM. The tip follows contour B, in one case to keep the tunneling current constant (STM) and in the other to maintain constant force between tip and sample (AFM, sample, and tip either insulating or conducting).

The STM itself may probe forces when a periodic force on the adatom A varies its position in the gap and modulates the tunneling current in the STM. The force can come from an ac voltage on the tip, or from an externally applied magnetic field for adatoms with a magnetic moment.

Binnig invented the AFM in 1986, and while Binnig and Gerber were on a Sabbatical in IBM Almaden they collaborated with Cal Quate (Stanford) to produce the first working prototype in 1986.
Early AFM Images


FIG. 3. The AFM traces on a ceramic (Al₂O₃) sample. The vertical scale translates to a force between sample tip and surface of 10⁻¹⁰ N/Å. For the lower trace the force is 3 x 10⁻¹¹ N. The stability of the regulated force is better than 10⁻¹² N. The successive traces are displaced by a small amount along the y-axis.

FIG. 4. The AFM traces for another area of the ceramic sample. The curves grouped under A were recorded with additional low-pass filtering. For this set the stabilizing force, f₀, was reduced by thermal drifts as we moved from the lowest to the highest traces of set A. The force f₀ is near 10⁻⁸ N for the highest curve. We note that the structure vanishes on the traces when the sample-to-tip force is reduced below this level. The force f₀ was reset to a higher value near 5 x 10⁻⁷ N for the traces marked B.
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- History of Atomic Force Microscopy (AFM)
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The microcantilever – the force sensor
Detecting deflection

- STM tip
- Capacitance/laser interferometry
- Beam deflection
The beam deflection method

(a) Normal force
- Up: A+B = UP
- Down: C+D = DOWN

(b) Lateral Force
- Left: A+C = LEFT
- Right: B+D = Right
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**Tip-sample interaction forces in AFM**

- Long-range electrostatic and magnetic forces (upto 100 nm)
- Capillary forces (few nm)
- Van der Waals forces (few nm) that are fundamentally quantum mechanical (electrodynamic) in nature
- Casimir forces
- Short-range chemical forces (fraction of nm)
- Contact forces
- Electrostatic double-layer forces
- Solvation forces
- Nonconservative forces (Dürig (2003))
The microcantilever – the force sensor

- From elementary beam theory, if $E =$ Young’s modulus, $l = bh^3/12$ then

- $\delta = w(L) = F \frac{L^3}{3EI}$, and $\theta = \frac{dw(L)}{dx} = FL^2/(2EI)$

- Deflection and slope linearly proportional to force sensed at the tip
- $k = 3EI/L^3$ is called the bending stiffness of the cantilever
Force-displacement curves
- Three distinct regions
- If $k$ is known then from the static-force distance curve, $F(d)$ can be calculated for all $d$ except for inaccessible range near snap-in
- It can be shown that $W_{\text{Cantilever}}$ is related to the $W_{\text{Adhesion}}$
- Slope in III is a good measure of repulsive forces (local elasticity)
Outline

- History of Atomic Force Microscopy (AFM)
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Dynamic AFM

- Cantilever driven near resonance
- Non-contact AFM, Tapping mode AFM, Amplitude Modulated AFM, Frequency Modulated AFM are all dynamic AFM
- The cantilever's resonant frequency, phase and amplitude are affected by short-scale force gradients

Attractive gradient equivalent to additional spring in tension attached to tip, reducing the cantilever resonance frequency.

Repulsive gradient equivalent to additional spring in compression attached to tip, increasing the cantilever resonance frequency.
Dynamic AFM & force gradient spectroscopy

- Variation of amplitude, resonance frequency, and phase measured as Z is decreased
- From this it is possible to reproduce the Force gradients between the tip and the sample
- Even non-conservative interactions can be resolved
- Offers many advantages over static-force distance curve based force spectroscopy
- Quantitative information is hard to come by because the forces are nonlinear
Outline

- History of Atomic Force Microscopy (AFM)
- Instrumentation
- Static force-distance curves and force spectroscopy
- Dynamic AFM and force gradient spectroscopy
- Imaging
- Applications and emerging areas
Contact Mode Imaging

First tip contacts surface with some setpoint normal force which is kept constant during the scan.
In Tapping mode the tip is oscillated at the resonance frequency and the amplitude of oscillation is kept constant while the tip intermittently enters the repulsive regime.
Phase Imaging

- Regular tapping mode implemented but signal phase monitored
- Phase contrasts are related to differences in local dissipation
Outline

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**Carbon nanotube tips (CNT)**

Dynamic AFM images of a 100 nm trench on Si using conventional silicon probe (left) and a MWCNT probe (right)

- Provide high resolution
- Show little evidence of wear
- Promising technology for critical dimension metrology of semiconductors, and nanobiological investigations
- Buckling, friction and stiction of CNT become important
CNT tips – tapping mode

- CNT attached strongly to Force modulation etched Si probe (Ni evaporation)
- Straight MWCNT, diameter 10 nm, length 7.5 μm, Frequency 72.5 kHz
- Repulsive and attractive states do not appear to co-exist for long CNT tips
Static force-distance curves

- CNT buckles, slips, and slides
- High adhesion on the CNT sidewalls

Raman et al., Nanotechnology (200
Shorter CNT tips- noncontact mode

- Divot artifacts associated with switching between attractive (noncontact) and repulsive (tapping states)
- Ringing artifacts associated with CNT adhesion and stiction to sidewalls

300 nm Tungsten nanorods

Conventional AFM

0.4 μm CNT
Exploiting anharmonic oscillations

- NC vibration spectrum depends on local adhesion properties
- Experiments performed using 47 kHz microcantilever on wild and mutant bacteriorhodopsin membrane
- 2\textsuperscript{nd} bending mode freq \(\sim 7 \times 1\textsuperscript{st}\)
Further reading

ECE 541/ME 541
Microelectronic Fabrication Techniques

MW 4:00-5:15 pm

Mask Design

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Masks

- Cr on soda lime glass (most common)
- Cr on fused silica
- Cr on quartz glass (transparent to deep UV, expensive)
- Photographic emulsion on soda lime glass (less expensive)
- Fe$_2$O$_3$ on soda lime glass (semi-transparent to visible light)
- High resolution laser printing on transparency
  - Dimensions: 4” x 4” for 3 inch wafers, 5” x 5” for 4 inch wafers, …
  - Polarity:
    - “light-field” = mostly clear, drawn feature = opaque
    - “dark-field” = mostly opaque, drawn feature = clear
Masks

- If you need one, buy it!
  - There are many companies that exclusively make masks
  - There are also many companies that make masks according to your design
- If you need to do it on your own:
  - E-beam writer
  - Same as lithography…
**Mask Costs**

- Lithography accounts for about 1/3 of total IC fabrication cost
- Technology performance is often set by lithographic control
- From 15-25 different masks in a typical process (up to 30)!
- Mask making has become a costly, materials intensive, time consuming process (predicted cost of a mask set for 65nm node is $3M)
- Any defect in the mask propagates through all wafers - Cleaning, pellicles, FIB, and laser mask repair
Pellicle on a Reticle

The particle on the pellicle surface is outside of optical focal range.

Antireflective coatings
Depth of focus
Mask material

Pellicle film
Chrome pattern
Frame
Reticle

ECE541/ME541 Microelectronic Fabrication Techniques
Reticle (mask) Enhancement Technology (RET)

Optical Proximity Correction (OPC)
   Add shapes to design data (GDS ll)
   Corrects for litho optics & process

   **Rule based OPC** - one mode fits all

   **Model-based OPC** - customized to shape neighborhood

Phase-Shift
   **“Strong” PSM** - Phase mask + binary ("cut") mask
   Used for gate printing CD, sheet rho, control

   **“Weak” PSM** - Via clear areas include attenuator

Tiling
   **Rule based tiling** - Doesn’t guarantee global planarity
   **Model-based tiling** - POR for future reticles
Diffraction

Long and narrow aperture

Rectangular aperture
Fresnel diffraction

Separation Depends on Type of System

Incident Plane Wave

Mask Aperture

Resist

Wafer

Light Intensity at Resist Surface

Proximity

Projection

Contact
OPTICAL PROXIMITY CORRECTION IMPROVES PRINTING
(ADD SHAPES TO MASK)

No OPC

With OPC

Photo downloaded from MicroUnity
(now ASML MaskTools) web site

ECE541/ME541 Microelectronic Fabrication Techniques
Mask engineering: Optical proximity correction (OPC)
**Phase-Shifting**

- Uses phase-modulation at the mask level to further the resolution capabilities of optical lithography

**Benefits:**
- Smaller feature sizes
- Improved yield (process latitude)
- Dramatically extended useful life of current equipment
- Performance Boost
- Chip Area/Cost Advantage

for Embedded Systems

Printed using a \(~0.18 \, \mu m\) nominal process
Phase-Shifting Mask

a) BIM

b) APSM

c) Rim PSM

Electric field on mask

Electric field on wafer

Intensity on wafer

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Rule-Based Tiling

- Done with Boolean operations
- Only density of the template is variable
- Not adequate for arbitrary design
Model-Based Tiling - Large Manufacturability Enhancement

Untitled reticle (768A)  
(unmanufacturable)

Conventional  
Rule-Based Tiling  
(702A)

193 nm ASML Stepper N.A. = 0.85!!!

Model-Based Tiling  
(152A)  
(80% uniformity improvement)
Alignment and Exposure

Modern memory chip production processes have some 25 lithographic steps.

In all steps the masks have to align, otherwise no proper connections are made.

The total misalignment budget is about 1/3 of the feature size, i.e. 40 nm for the 130 nm node.

ECE541/ME541 Microelectronic Fabrication Techniques
Grid of Exposure Fields on Wafer
Step-and-Repeat Alignment System

Alignment System Components

i-Line illuminator
C-scope (off-axis)
B-scope (off-axis)
Alignment Light Source (ALS)

Optical fibers

iA-scope (on-axis)
TV AA/FRA
Optical fibers
TVPA (off-axis)

X-Y Stage Reference Block
Front
Alignment Marks

RA, Reticle alignment marks, L/R
GA, Wafer global alignment marks, L/R
FA, Wafer fine alignment marks, L/R

ECE541/ME541 Microelectronic Fabrication Techniques
On-Axis Versus Off-Axis Alignment System

On-Axis Alignment System

- Microscope objectives for video camera
- Reticle
- Alignment laser (633 nm)
- Projection optics
- Alignment BLC fiducial
- Wafer stage

Off-Axis Alignment System

- Off-axis alignment unit
- Video
- Optical fiber
- Alignment laser (633 nm)
Effects of Defects

Positive resist more desirable!
Mask Error
Mask Repair

- Usually protected by Pellicles
- Focused Ion Beam (FIB)
- Laser Ablation
Photomask and Reticle for Microlithography

1:1 Mask  

4:1 Reticle
Clear Field and Dark Field Masks

Clear Field Mask

Simulation of metal interconnect lines
(positive resist lithography)

Dark Field Mask

Simulation of contact holes
(positive resist lithography)
Example 3: IBM-DuPont-Altis Supply Chain
Importance of Mask Overlay Accuracy

The masking layers determine the accuracy by which subsequent processes can be performed.

The photoresist mask pattern prepares individual layers for proper placement, orientation, and size of structures to be etched or implanted.

Small sizes and low tolerances do not provide much room for error.

Figure 13.4
Masks

- Transparent substrate coated with patterned, UV-opaque material
- Hard
- Flexible
- Reflective
Mask Material

- Substrate: Flat, Stable, Transparent
- Soda-lime, Borosilicate, Quartz, Mylar

![Spectral Transmittance Curve (2.3mm Thick Substrate)](image)

- Absorber: Patternable, UV-opaque, Cleanable, Damage Resistant, Defect-Free
- Chrome, Iron Oxide, Ink

Substrate info from nanofilm, www.nanofilm.com
Mask Design Flow
Device Concept
Fabrication Process Flow
ID Photolithographic Steps
Determine Resist Type(s)
Determine Alignment Needs
Make CAD
Send CAD to Mask Foundry
Basics of Mask Design

- Smaller Features -> Higher Cost
- Complex Features -> Higher Cost
- Larger Area -> Higher Cost

Feature Size ↔ Resolution
Alignment Accuracy

- Mark Resolution
- Stage Resolution
- Microscope Resolution
- Operator Patience
- Design to Relax Alignment
Alignment Mark Design

- Lock and Key
- Vernier Scale
- Mark “Material”
  - Etched
  - Deposited
- Tool Requirements
  - For MJB4, 3.5cm separation; MA6, 5cm
ECE 541/ME 541
Microelectronic Fabrication Techniques

MW 4:00-5:15 pm

E-beam Lithography (EBL)

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Acknowledged to the cleanroom at Harvard University, Dr. Yuan Lu, Dr. Charles Marcus, and some other EBL users there.
E-beam writer

- Many scanning electron microscopes can be used as e-beam writers
- Typically, you need an add-on controller, which can be purchased from various specialized companies
- Professional Mask Manufacturers use dedicated instruments
**Electron Beam Writing**

Types of electron guns
- Thermoionic
- Field emission

Write-field (WF)

Scanning methods
- Raster scan
- Vector scan
**EBL resists**

Important parameters
- Resolution (nm)
- Sensitivity (C/cm²)

Types of resist
- Positive resist
  Polymethyl methacrylate (PMMA)
- Negative resist

![Scheme I](image)
ECE 541/ME 541
Microelectronic Fabrication Techniques

MW 4:00-5:15 pm

Metrology and Characterization

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➢ Ellipsometry

➢ Ohmic contacts

➢ I-V, C-V, Hall effect measurements

➢ Material Characterization
  PL, Raman, XRD, XPS, SIMS, EDX, etc
- Ellipsometry
- Ohmic contacts
- $I-V$, $C-V$, Hall effect measurements
- Material Characterization
  - PL, Raman, XRD, XPS, SIMS, EDX, etc
Ellipsometry
What is ellipsometry?

- Ellipsometry is an optical technique used for analysis and metrology
- Non contact, non destructive method
- It determines the change in polarization state of light reflected from a sample.
- Typically used for characterizing thin films (thickness, optical constants – complex refractive index).
- It is a model-based technique
What is ellipsometry?

- Transparent films from a sub-nanometre up to several microns can be measured using ellipsometry.
- The surface upon which the film is measured can be a semiconductor, dielectric or metal.
- The film can be transparent or absorbing on a transparent or opaque substrate (need contrast)
- The measuring polarized light can range from the ultra violet to the infra-red.
By convention, the polarization of light is described by specifying the orientation of the wave's electric field at a point in space over one period of the oscillation. When light travels in free space, in most cases it propagates as a transverse wave—the polarization is perpendicular to the wave's direction of travel. In this case, the electric field may be oriented in a single direction (linear polarization), or it may rotate as the wave travels (circular or elliptical polarization).
**Polarized and un-polarized light**

Most sources of electromagnetic radiation contain a large number of atoms or molecules that emit light. The orientation of the electric fields produced by these emitters may not be correlated, in which case the light is said to be unpolarized. If there is partial correlation between the emitters, the light is partially polarized. If the polarization is consistent across the spectrum of the source, partially polarized light can be described as a superposition of a completely unpolarized component, and a completely polarized one. One may then describe the light in terms of the degree of polarization, and the parameters of the polarization ellipse.
Polarized light passing through a polarizer

Unpolarized light

Transmission axis

Polarizer

Polarized light

Analyzer

The angle of polarization changes

I_0

I_0 \cos^2 \theta

Decrease in intensity when polarized light passes through a polarizer

I = I_0 \cos^2 \theta

Law of Malus
Crossed Polarizers

Figure 1
Crystal polarizers (II) [birefringence]

isotropic crystal (sodium chloride)

anisotropic crystal (calcite) most stable polymorph of calcium carbonate (CaCO₃)

The 2 output beams are polarized (orthogonal).
Two polarizers

I = I_o \cos^2 \theta

\theta = 0 \quad \theta = 45^\circ \quad \theta = 90^\circ

"Crossed-polarizers"
Polarization by reflection
Un-polarized light can be polarized by reflection at a specific polarization angle $\theta_p$ (Brewster’s angle)

$$\tan \theta_p = \frac{n_2}{n_1}$$
Polarization by reflection

(a) Reflected beam is Partially polarized
(b) Reflected beam is Fully polarized

E is ⊥ to plane of incidence
This E component is absent
- Ellipsometry
- Ohmic contacts
- I-V, C-V, Hall effect measurements
- Material Characterization
  PL, Raman, XRD, XPS, SIMS, EDX, etc
Contact

Outline

Contacts to source, drain and gate are the last step of the MOSFET fabrication before you proceed to characterize the electrical properties of the device. If you were a process engineer, you would deposit a low-resistivity material, such as metal onto those regions to form contacts. Are there any other issues that we need to be aware of?

- Ohmic contact
- Barrier models
- Metal semiconductor interface
- Calculating contact resistance
- Typical processing
What is an ohmic contact?

- Nearly all semiconductor devices receive/transmit signals to/from metal contacts
- *Defn:* Ohmic -> metallization applied to a semiconductor that makes good electrical and physical contact
  - Physical: stability consistent with device requirements
  - Electrical: $R = \frac{V}{I} = \text{constant}$
- Above defn. works well for similar materials
- Unlike materials -> barrier to electrons
  - $R = R(\text{applied bias})$
Practical ohmic contact

- Increasingly important as device dimensions shrink and operating voltages decrease
- Voltage drop across metal/semi interface is negligible compared with the voltage drop across device
- Contacts do not affect device I-Vs
- Choice of metallization depends on device operating conditions
  - High resistance devices tolerate higher contact resistances
  - Conversely, low resistance devices tolerate low...
Schottky Barrier

- Metal-semi contact -> barrier formation
  - Cause is charge separation, analogous to space charge region in diodes
  - Effects of forward/reverse bias are similar to a diode

*ECE541/ME541 Microelectronic Fabrication Techniques*
Ohmic I-V

- Measuring from one metal pad to an adjacent one
- Easier to make good ohmic contacts when the \textit{active} surface carrier concentration is $>5\text{E}18\text{cm}^{-3}$ (depl width is decreased; $w \sim 1/n$)
- Ohmic contacts show good linear I-V characteristics, especially at low voltages
- Bad ohmic contacts (rectifying/Schottky) usually present a kink in the I-V characteristic at low voltages and have a low slope
Barrier Calculation

• $n$-type semiconductor:
  $\phi_{bn} = \phi_m - \chi_s$

• $p$-type semiconductor:
  $\phi_{bp} = E_g - (\phi_m - \chi_s)$

• Example for $n$-GaAs Ti-Au contact
  $\phi_{bn} = 5.25\text{eV} - 4.07\text{eV} \sim 1.2\text{eV}$

• Example for $p$-GaAs Ti-Au contact
  $\phi_{bp} = 1.43\text{eV} - [5.25\text{eV} - 4.07\text{eV}] \sim 0.2\text{eV}$

• Example for $n$-GaAs Cr-In contact
  $\phi_{bn} = 4.1\text{eV} - 4.07\text{eV} \sim 0.03\text{eV}$
Schottky Model Limitations

• Only parameter one can vary for a given semiconductor is metal work function
• In practice, there’s less dependence on metal work function than predicted
• Reasons:
  – Surface states (lattice is terminated)
  – Many states -> charge exchange is with surface states, not bulk
  – Often called Fermi level pinning
• Thin film of native oxide remains on the semiconductor surface
• Metal and semiconductor react (forms a compound; i.e., silicides)
• Other mechanisms
Reactive metal-semiconductor bond

- Usually involves annealing for silicide formation (metal-silicide-silicon or MSi$_x$)
- Low silicide temp formation -> high barrier
- High silicide temp...
- Common silicides:
  - W, Co, Ti, Mo, Ta, Pt (sputter or CVD -> anneal)
  - Co, Ti are common ohmics for both p/n
  - Al spikes into Si
Native Oxide

• Thickness of oxide is a strong function of surface prep and idle time before loading into vacuum
• Effect of metal work function is decoupled; interface states are mediated by the semiconductor-oxide combination
• Generally accepted that if oxide is 20Å or less, then electrons tunnel through and potential drop from the contact is negligible
How to Quantify an Ohmic Contact

• Many do not know the quality of their ohmic contacts and effect on device performance until a fully processed device is tested
  — Rely on inherited recipes
• Use $\rho_c$ (specific contact resistivity) to quantify contact properties during or after processing
• Call such structures PCMs (process control monitors)
  — Hundreds of such structure designs
• Construct TLM (transfer length method) structures to extract $\rho_c$
• Usual target is $< 1 \times 10^{-6} \ \Omega \text{cm}^2$
• Common to have test structures on every wafer for quantifying $\rho_c$
Calculating $\rho_c$

- One of many approaches is to fabricate a series of increasingly spaced contact pads that can be probed
  - Pad width (W): 100um, Spacing: L1, L2, L3, L4, L5 = 5, 10, 15, 20, 25um
  - Add probe metal on top of ohmic (typ. > 2000A Au)
  - May need to add diffusion barrier to alleviate Au migration (W, Pt, TiN)

- Determine sheet resistance of semiconductor (use 4PP in cleanroom, or calculate by van der Pauw)
- $L_T = R_C W / R_{sheet}$
- $\rho_c = R_{sheet} \times L_T^{-2}$

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Use a Mesa to confine current

- A mesa is required for more accurate measurements
- But even if you don’t have a mesa, recommend you still measure
  - May underestimate $\rho_c$

Top view
What to expect

- Compared to as-deposited metallurgy, $\rho_c$ can typically be improved by annealing temperature (promotes diffusion, alloy formation, etc.)
- Usual annealing process is RTP
- Contact degradation is observed above a certain temperature
Ellipsometry

Ohmic contacts

$I-V$, $C-V$, Hall effect measurements

Material Characterization
PL, Raman, XRD, XPS, SIMS, EDX, etc
Semiconductor device measurements setup
I-V test setup

- Probe station
  - Large working distance microscope
  - Movable stage and platform
  - Movable optics
  - Movable electrical contacts
- Semiconductor Device Analyzer (SDA)
Probe Station parts
Micropositioners
Probes
Tips

Metals used: Tungsten, Steel, Palladium, Osmium.
Complete setup
Semiconductor device analyzer
I-V characteristic curve of Diode
What is Four Point Probing

- Four Point Probing is a method for measuring the resistivity of a substance.
How the system works

- In order to measure the resistivity of a substance, four points of contact must be made with the probe and the substance.
- Current goes through the two outer probes, and the difference in voltage is measured between the two inner probes.
- Through this process the resistance can be calculated.
Surface Resistivity

In a regular three-dimensional conductor, the resistance can be written as

\[ R = \rho \frac{L}{A} = \rho \frac{L}{Wt} \]

where \( \rho \) is the resistivity, \( A \) is the cross-sectional area and \( L \) is the length. The cross-sectional area can be split into the width \( W \) and the sheet thickness \( t \).

By grouping the resistivity with the thickness, the resistance can then be written as:

\[ R = \frac{\rho}{t} \frac{L}{W} = R_s \frac{L}{W} \]

\( R_s \) is then the sheet resistance.
High-accuracy capacitance measurements

An AC signal of known frequency is applied through an internal low value resistor and the capacitor under test in a series configuration. The AC current flowing into the capacitor must also flow through the resistor, creating an AC voltage across the resistor.

The magnitude and phase of this voltage can be measured and compared to the original AC signal, and the capacitance can be computed. Techniques such as this frequency-domain measurement can be very accurate.

LCR meter
(Inductance (L), Capacitance (C), and Resistance (R))
Tools for measurement

Probe Station

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Agilent Semiconductor Parameter Analyzer

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Capacitance – Voltage Measurements

• capacitance voltage (C-V) testing is to determine semiconductor parameters, particularly in MOSCAP and MOSFET structures.

• C-V measurements are also widely used to characterize other types of semiconductor devices and technologies, including bipolar junction transistors, JFETs, III-V compound devices, photovoltaic cells, MEMS devices, organic thin film transistor (TFT) displays, photodiodes, and carbon nanotubes (CNTs).

Metal-Oxide-Silicon (MOS) capacitor
Capacitance – Voltage Measurements

C-V measurements can reveal oxide thickness, oxide charges, contamination from mobile ions, and interface trap density in wafer processes.

A deep depletion C–V curves for an SiO2/Si MOS capacitor. \( N_A = 1017 \text{ cm}^{-3} \), \( t_{ox} = 10 \text{ nm} \), \( A = 5 \times 10^{-4} \text{ cm}^2 \).

The capacitance is determined by superimposing a small-amplitude ac voltage \( v \) on the dc voltage \( V \). The ac voltage frequency is typically 10 kHz to 1 MHz with 10 to 20 mV amplitude.
MOSFET gate as capacitor

Basic structure of gate is parallel-plate capacitor:

\[ V_g \]

\[ \text{SiO}_2 \]

\[ \text{substrate} \]
Basic Physical Phenomena of Hall Effect

- When an electron moves in a direction perpendicular to an applied magnetic field, it experiences a force (Lorentz force) acting normal to both directions and moves in response to this force (see below for an n-type semiconductor)

  - Constant current $I$ (flows along x-axis) in the presence of magnetic field $B$ (z-axis) causes Lorentz force $F$ (y-axis)
  - Causes electron paths to bend towards negative y-axis
  - Charge builds up on the surface of the side of sample, and the potential drop across the two sides of the sample is known as the Hall voltage ($V_H$)

References: 2, 3.

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When electrons flow without magnetic field...

semiconductor slice

+ 

- 

l

t

d

l

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When the magnetic field is turned on ...

B-field

$qBv$
As time goes by...

$qBv = qE$

high potential

low potential
Finally...

B-field

$V_H$
Basic Hall effect measurement system
Ellipsometry

Ohmic contacts

I-V, C-V, Hall effect measurements

Material Characterization

PL, Raman, XRD, XPS, SIMS, EDX, etc

(please also refer to Lecture 16, 17, and 25 for more details)
A laser excites electrons from the valence band into the conduction band, creating *electron-hole pairs*.

These electrons and holes recombine (annihilate) and emit a photon.

The number of emitted photons (intensity) as a function of energy, which is photoluminescence (PL).
Discovery of Raman Spectroscopy

In 1928, Raman discovered that the spectrum of scattered lines of CCl₄ liquid not only consisted of the Rayleigh lines but a pattern of lines of shifted frequency — the Raman spectrum.

Mr. Raman won the Nobel Prize of Physics in 1930, “for his work on the scattering of light and for the discovery of the effect named after him”.

C.V. Raman (1888-1970)
\( \omega_S = \omega_L - \omega_q \)

\( \omega_S = \omega_L + \omega_q \)