Introduction
• **Required Textbooks:**
  None.

• **Lecture notes:**
  [https://courses.engr.illinois.edu/ece518/](https://courses.engr.illinois.edu/ece518/)

• **Reference books (partial list):**
  – Handbook of Semiconductors and Nanodevices, by Balandin and Wang, 2006 (in reference section in Grainger)
  – Epitaxy of nanostructures, By Shchukin, Ledentsov, Bimberg, Springer, 2004
  – Semiconductor Nanostructures for Optoelectronic Applications, By Steiner, Artech House, 2004
Nanotechnology: Facts and Hype

• Google Scholar search –
  – Nano: 2,590,000
  – Nanotechnology: 877,000
  – Nanowire: 391,000
  – Quantum Dot: 1,320,000

• Popular Press

• Scientific Journals targeting Nano specifically
  – Nature Nanotechnology
  – Nano Letters
  – ACS Nano
  – Nanotechnology
  – Small
  – IEEE Transactions on Nanotechnology
“Nanomaterial Safety Plan”

Nanomaterials Might Be Present

ECE ILLINOIS

Shirley Gibson, Scotland
Kypros Kyprianou, England
Nanotechnology: introduction

• The definition and who owns it?
  – Nano: “dwarf” in Greek
  – Chemists and Biologists: atoms (3Å), DNA (2 nm), colloidal chemistry
  – Engineers: QW laser, nano-transistors

"It is not who is right, but what is right that is of importance.“ T. H. Huxley
There is plenty of room at the bottom.

Richard Feynman

https://www.youtube.com/watch?v=4eRCygdW--c
When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc.

Richard Feynman, December 1959
## Syllabus

<table>
<thead>
<tr>
<th>Topics</th>
<th>Examples</th>
<th>Lectures* (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Introduction of nanotechnology</strong></td>
<td></td>
<td>1 - 2</td>
</tr>
<tr>
<td><strong>2. Formation of nanotechnology building blocks</strong></td>
<td>fundamentals (MOCVD, MBE, etc.)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>SK quantum dots</td>
<td>2</td>
</tr>
<tr>
<td>Bottom-up: epitaxial growth</td>
<td>VLS nanowire growth</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>SAE nanowire growth</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Van der Waals epitaxy</td>
<td>1</td>
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<tr>
<td>Top-down: lithography and etching</td>
<td>MacEtch</td>
<td>2</td>
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<tr>
<td>Combination:</td>
<td>Regrowth, SRUM</td>
<td>2</td>
</tr>
<tr>
<td>Surface passivation</td>
<td>ALD etc.</td>
<td>1</td>
</tr>
</tbody>
</table>

*Lectures are not necessarily scheduled in the order listed.
*A few guest lectures will be scheduled.*
### 3. Characterization of nanotechnology building blocks

<table>
<thead>
<tr>
<th>Category</th>
<th>Techniques</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural – morphology, orientation,</td>
<td>SEM, TEM, AFM, STM, X-ray, EBIC</td>
<td>0.5</td>
</tr>
<tr>
<td>crystallinity, strain, compliance, and defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical – composition and impurity</td>
<td>SIMS, EDS, EELS, Auger, XPS</td>
<td>1</td>
</tr>
<tr>
<td>Optimal</td>
<td>PL, CL, RAMAN, NSOM, time resolved pump-probe</td>
<td>1</td>
</tr>
<tr>
<td>Electrical</td>
<td>IV, CV, conductive AFM, STM</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Midterm exam (topic-oriented literature report and presentation)** 1 - 2

### 4. Nano-devices

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Nanowire lasers</th>
<th>Nanowire detectors</th>
<th>Nanowire solar cells</th>
<th>Nanowire thermoelectric devices</th>
<th>3D FETs</th>
<th>Compound semiconductor FETs</th>
<th>2D beyond graphene FETs</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>for photonics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>1</td>
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<tr>
<td>for energy</td>
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<td></td>
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<td>2</td>
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<tr>
<td>for electronics</td>
<td></td>
<td></td>
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<td></td>
<td>1</td>
</tr>
</tbody>
</table>

### 5. Nano-systems and manufacturing

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Integration, printing and assembly</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emerging nanodevices</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

**Final exam (written proposal and oral presentation)** 2 - 4
ECE 518

• Homework and pop quizzes: ~ every 2 weeks
• NanoLab: Beta version! ~ 2 weeks
• Exams
  – Mid-term: literature review and class presentation
    • Topic of your choice
    • Page limit: 3 pages (references not included)
    • Presentation: 10 mins
  – Final: proposal
    • Group project (2 – 4 students self-assembled)
    • Page limit: 12 - 15 pages total
    • Presentation: 20 mins
• Grades
  – 15% HW, 15% Lab, 30% Mid-term, and 40% Final
• TA: Lecture - Wen Huang;
• Lab instructor: Dane Sievers; Lab TA: Paul Froeter.
• Office hour: by appointment
## Midterm Exam Grading Rubrics

### Grading Rubrics for literature summary of self-selected topics

<p>| | | | | | | | | | | | |</p>
<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Was the topic well defined?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2</td>
<td>Was the presentation well organized and clearly articulated?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td>Was the survey of journals and other resources adequate?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>Was the presenter able to answer questions well?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>Were the presentation slides free of typos and grammatical errors, figures labeled clearly, references cited?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>6</td>
<td>Other aspects: please explain.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Final exam (proposal) grading rubrics

**Technical contents**
The problem the proposal is addressing was very well defined and explained

The importance of the proposal and its broader impact was clearly defined

The proposed activity suggests and explores creative, original or potentially transformative concepts

Ideas were well-articulated, feasible and supported by evidence.

The proposed activity is well-conceived and organized.

**Writing skills**
Text has few grammatical errors

Paper is the correct length and format

Writer cites relevant examples from literature

Relevant figures with descriptive captions

Paper is written logically
Semiconductor world map

- Direct band gap
- High mobility
- Versatile heterojunction
Quantization of Density of States

$E_v$ and $E_c$ split into overlapping subbands
- successively narrower as the electronic motion is restricted in more dimensions

Saleh and Teich, Fundamentals of Photonics, Ch.15
Electronic Properties vs Size

Quantum confinement $\Delta E_g$:
Aspect Ratio Dependence

Particle-in-a-box approximation

QDs: colloidal nanocrystals

- CdSe quantum dots that are increasing in size (left to right).
Quantum Well Lasers

- QW – in most commercial diode lasers
- Quantum size effect – discrete energy level – constant DOS at each step
  - Lower threshold
  - Narrow linewidth
  - Temperature stability

Fig. 1. Square-well potential that is characteristic of an Al$_x$Ga$_{1-x}$As-GaAs-Al$_x$Ga$_{1-x}$As quantum-well heterostructure. For well thickness $L_z \lesssim \lambda$ (the carrier deBroglie wavelength), size quantization occurs and results in a series of discrete energy levels given by the bound state energies of a finite square well. A potential well exists in both the conduction band and the valence band giving rise to a series of bound states $E_n$ for the electrons, $E_{hhn}$ for heavy holes, and $E_{ln}$ for light holes.

Holonyak, 1980
Moore’s Law

• Nanotechnology is essential to continue the scaling process

• More than Moore
  – CNT
  – Graphene
  – III-V
  – TMDC
  – Spintronics
  – 3D FETs
  – TFET

Electronic Properties vs Size
Beyond Si-MOSFET Technology

- 2014 worldwide IC chip sales ~ $280 B
- All compound semiconductor devices and chips ~ $28B: mostly photonic devices and chips
- Why Si dominant?
  - Si is inferior electronic and photonic materials compared to e.g. GaAs
  - Si is cheap
  - SiO$_2$ – electronically exquisite, in contrast, nearly all compound semiconductor native oxides are inferior
  - Reversibility of ion-induced damage in Si
  - Lack of a viable non-silicon MOSFET technology during the early R&D efforts hampered its development.
  - Stay on a revised Moore’s Law path

**Price/performance**
III-V MOSFETs: why not the incumbent?

- 1966, Brody and Kunig, InAs MOSFET both depletion and enhancement mode
- Expensive
- Materials quality
- Surface Fermi Level Pinning
  - the bane of III-V MOSFET technology development
- Chemistry
  - Reversibility of ion-induced surface/interface damage – impervious to damage
  - Oxide solubility, etching selectivity
Fermi Level Pinning and Ohmic Contact for III-V Nanostructures

- The surface or interface Fermi energy is nearly invariant with respect to processing technologies, and has a characteristic value which depends on the semiconductor material.
- Ohmic contact resistance can and will dominate the transport properties of nanowire devices.
- The physics of bulk surfaces and interfaces may be able to point the way to enable ultra-low resistance nanowire ohmic contacts.

- Highly doped surfaces (tunneling contacts)
  - example: M/LT-GaAs/n++GaAs/nGaAs
- Graded heterojunctions
  - example: M/InAs/graded InGaAs/GaAs

Jerry Woodall
Thermal Conductivity vs Size

Spatial confinement of phonons in nanostructures modifies phonon behaviors

Thermal Conductivity vs Size

- Thermal conductivity decreases with decreasing size
  - Enhanced phonon scattering at boundaries - diffuse phonon scattering (when $L \sim \text{MFP}$)
  - Phonon confinement effect – increased phonon scattering on defects/dislocations (when $L \ll \text{MFP}$) – reducing in-plane thermal conductivity in free-standing thin films or nanowires
- Thermal conductivity decreases with roughness
  - Specular scattering fraction $p$

### Table I. Phonon transport regimes.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Phonon dispersion</th>
<th>Dominant scattering processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L \gg \text{MFP}$</td>
<td>bulk dispersion</td>
<td>three-phonon Umklapp</td>
</tr>
<tr>
<td>$\lambda_0 \ll L \leq \text{MFP}$</td>
<td>bulk dispersion</td>
<td>point defects</td>
</tr>
<tr>
<td>$\lambda_0 \leq L \ll \text{MFP}$</td>
<td>modified dispersion with many phonon branches populated</td>
<td>three-phonon Umklapp</td>
</tr>
<tr>
<td>$L &lt; \lambda_0$</td>
<td>modified dispersion; only lowest phonon branches populated</td>
<td>point defects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>boundary scattering</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ballistic transport</td>
</tr>
</tbody>
</table>

Spatial confinement of phonons in nanostructures modifies phonon behaviors
Spatial confinement of phonons in nanostructures modifies phonon behaviors

Nanophotonics: phonon engineering in nanostructures and nanodevices, Balandin, J. Nanoscience and Nanotechnology, 2005
Surface/interface effect on Resistivity

- Carrier scattering:
  - Impurity (Coulomb) scattering (donors/acceptors): $\mu = T^{3/2}/N_i$
  - Lattice scattering (phonons):
    - GaAs $\mu_e \propto T^{-1}$; $\mu_h \propto T^{-2.1}$
    - Si: $\mu_e \propto T^{-2.4}$; $\mu_h \propto T^{-2.2}$
    - Can be ignored at low T
  - Surface scattering: space-charge double layer; combination of $\mu$ in both layers...
    - Surface roughness
    - Impurity accumulation
    - Charge states

Electrical Properties vs Size

Figure From Infineon
Mechanical Properties vs Size

Young’s Modulus Engineering

Effect of Twin Boundaries in Cu films

- Coherent twin boundaries are effective grain boundaries in strengthening materials
  - Strengthening Cu when high densities of nm thick twins are introduced in sub-μm sized grains.
  - Below 15 nm twin thickness, Cu starts to soften -- scale dependent nature of the plastic deformation of nanoscale materials

- Two competing mechanism for hardening:
  - dislocation-dislocation interaction in coarse twins
  - Dislocation- twin boundary hardening in fine twins

Nanotechnology

**Building Blocks**
- Quantum wells
- Quantum dots
- Nanotubes and nanowires
- Nanomembranes

**Formation Mechanism**
- Bottom-up
- Top-down

**Advantages**
- Electronic confinement
- Surface sensitivity
- Mechanical compliance

**Challenges**
- Size and density control
- Surface states
- Precision placement
- Integration