Lecture 16
The Future of Electronics

Announcements

Homework 4/4:
• The final homework is due now.
• Please bring it up to me if you have not already done so.

“Homework 5”
• On Tuesday December 3rd I will upload “Homework 5”.
• This is optional and will not be graded.
• It is a set of questions covering Lectures 11-16 to help you prepare for the final examination.
• I will upload the solutions at the same time as the questions, but I strongly suggest you attempt the questions at least once before looking at the answers.
Last Time

• We looked at etching.

Lecture 16

• Information on Final Examination.
• The End of Moore’s Law
• Phase Change Materials.
• 2-Dimensional Materials.
• Carbon Nanotubes.
• Neuromorphic Computation.
• Quantum Computation.
• Course Overview
Information on Final Examination

Final Exam Details

- Friday December 13th at 09:30am in Kearney Hall 124.
- Exam will last 80 minutes.
- The exam will start exactly at 09:30am!
- Closed book and closed notes.
- You can, and are expected to, use a calculator.
- Choose 2 out of 3 questions.
- If you answer 3 I will take best 2 scores.
- It will contribute 20% of overall grade for class.
- The exam will cover lectures 11-16 (inclusive).
- There will be 50 marks per question. 100 total.
Final Exam Details

- The format will be similar to the midterm.
  - Several sub-questions per question.
- The number of marks will be shown at the end of every sub-question. E.g. [5 marks].
- Read through all questions before deciding which 2 you wish to answer.
- There will be a mixture of descriptive and quantitative questions.
- I will not expect you to conduct any numerical methods (e.g. numerical differentiation / fitting).
- I would provide the results of such a method.

Front Page of Midterm

- This is the front page of the midterm exam:

  Answer 2 out of 3 questions. If more than 2 questions are answered, the 2 questions with the highest marks will be considered.

  A maximum of 50 marks will be awarded for each question. The mark assigned to each part of the question is indicated by a number in square brackets at the end of the sub-question. e.g. [3 marks].

  You have 80 minutes to complete this exam; please pace yourself accordingly.

  No notes of any kind are allowed. You may use calculators for this exam.

  Questions Start on page 5.

- The final will be similar.
Equations

- All relevant formulae will be provided.
- Parameters will be labeled as clearly as possible.

Constants

- All constants will also be provided.
- Even $\pi$!

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental unit of charge</td>
<td>$e$</td>
<td>$1.60 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>Boltzmann Constant</td>
<td>$k_B$</td>
<td>$1.38 \times 10^{-23}$ J/K</td>
</tr>
<tr>
<td>Pi</td>
<td>$\pi$</td>
<td>3.14</td>
</tr>
<tr>
<td>Rest mass of electron in a vacuum</td>
<td>$m_e$</td>
<td>$9.11 \times 10^{-31}$ kg</td>
</tr>
<tr>
<td>Planck Constant</td>
<td>$h$</td>
<td>$6.63 \times 10^{-34}$ Js</td>
</tr>
<tr>
<td>Vacuum permittivity</td>
<td>$\varepsilon_0$</td>
<td>$8.85 \times 10^{-12}$ F/m</td>
</tr>
</tbody>
</table>
Grading

- Hopefully I will not have to curve.
- But it depends on results.
- I may try to ~match grade distributions from previous years.
- Although if everyone does well the mean will be higher.

Preparation

- Go through the lectures and consider what questions you could be asked on the notes given.
- Go back through the homework and solutions, and make sure you understand everything (not just memorize a procedure).
- The textbook is another good resource – it explains things in more depth.
  - There are plenty of good problems to study.
  - I have purposely not used any of the problems in the textbook for homework, so they should all be new to you.
- An extra “homework” and solutions will be put online on Tuesday December 3rd to help you prepare.
The End of Moore’s Law

• From The Economist 2016:

Is Moore’s Law Ending?

[Graph showing transistor growth over time]

The End of Moore’s Law

- Peter Lee (Microsoft): “There’s a law about Moore’s law, The number of people predicting the death of Moore’s law doubles every two years.”

http://www.economist.com/technology-quarterly/2016-03-12/after-moores-law

The End of Moore’s Law

Continue The Lg Scaling Path

The End of Moore’s Law

• We know the lattice spacing of Si is 5.43Å.
• So there is a fundamental limit...
• Even before we get there, the electron wave-function will not be contained in the device.

The End of Moore’s Law

• There are economic reasons:

http://www.economist.com/technology-quarterly/2016-03-12/after-moores-law
Short Term Solutions

• Extreme UV lithography (EUV) should get us down to < 10nm.
• However there are many challenges:
  • Absorption of light by many components of the system.
  • New photoresists are required.
  • Mirrors and sources need to be carefully designed / selected.

\[ \frac{C \varepsilon_0 A}{x} \]

- \( C \) = capacitance.
- \( \kappa \) = relative permittivity.
- \( \varepsilon_0 \) = vacuum permittivity.
- \( A \) = device area.
- \( x \) = dielectric thickness.
Short Term Solutions

- High $\kappa$-dielectrics allow a higher capacitance with the same thickness.
  \[ C = \frac{\kappa \varepsilon_0 A}{x} \]

- With a higher $\kappa$ dielectric, a thicker gate dielectric layer might be used which can reduce the leakage current flowing through the structure as well as improving the gate dielectric reliability.

Short Term Solutions

- FinFETs can be used to apply a field from 3-sides rather than 1:

- Capability to get better performance from same space.
Phase Change Materials

• Some materials change their stable structure as a function of temperature.

• This is referred to as a structural phase transition.

• Sometimes such a change is accompanied by a significant change in electronic properties.

Vanadium Oxide

- Vanadium(IV) oxide (VO$_2$) is an interesting compound that significant change in conductivity as it changes temperature.

- Notice how the phase transition temperature is close to room temperature.

Vanadium Oxide

- What if we could somehow induce a similar phase transition with an electrical field?

- What if we could induce a phase transition with an electric field?
- We could then make electronic with discontinuous switching.
Vanadium Oxide

- The idea is that an applied field can change the structure / apply strain.
- Peierls distortion or something similar.

2-Dimensional Materials
Carbon

- Carbon, like silicon, is a group 14 element, and shared some properties.
- Has 4 electrons in outer shell.
- Tends to bond covalently, via hybridized orbitals.

Graphite

- One form of carbon is graphite:
  - The carbon atoms form layers, with each atom covalently bonded to 3 others in the layer.
  - The layers are weakly (\(\pi\)) bonded.
  - Graphite conducts electricity in plane.
Graphene

- Graphite is just multiple stacked layers of graphene.

- Graphene is a single atomic layer of carbon.
- For a long time it was considered a hypothetical material. It was isolated in 2004.\cite{1}

\cite{1}Novoselov et. al. Science 306 (2004) 666.

Graphene

- Carbon has 4 outer electrons, yet in graphene only 3 participate in bonding. What happens to the remaining electron?

- A detailed answer is beyond the scope of this course, but broadly-speaking it is free to move (conduct).
Charge Transport in Graphene

- Electrons are coherent and delocalized across the sheet (a bit like c-Si).
- We will not derive it, but the band structure of graphene turns out to look like the following:
- The points at which the bands touch are called the **Dirac Point**.
- The surface here is called the **Dirac Cone**.

To derive the band structure, we can sketch it in 1 dimension as:

\[ E(k) = \frac{\hbar^2 k^2}{2m^*} \]

Traditionally, the effective mass is evaluated from the 2nd derivative of \( E \) wrt \( k \):

\[ m^* = \frac{\hbar^2}{\frac{d^2E}{dk^2}} \]

Since for graphene \( E \propto k \), the effective mass would here be \( \infty \).
Charge Transport in Graphene

- For this reason, charges are described differently for this system.
  - The effects of special relativity need to be considered.
  - However very high mobilities are reported in graphene (~ $10^6$ cm$^2$/Vs at low temperatures).
  - There is however one major problem with graphene.
  - It has no band gap.

Graphene Transistors

- The band structure below illustrates that conduction band and valence band touch (at the Dirac Point).
  - Graphene transistors have very low on/off ratios.

2-Dimensional Materials

- Despite graphene failing to find a useful application (yet), it has spawned a new field of electronic materials: 2D Materials.
- Other 2D materials are semiconducting.

Carbon Nanotubes
Carbon Nanotubes

- Carbon nanotubes (CNTs) are basically sheets of graphene rolled up.

- Their aspect ratio (length to diameter ratio) is typically $10^2$ to $10^7$.
- Unlike graphene, there are many forms of CNTs.

Multiple Walled CNTs

- Carbon nanotubes do not need to consist of a single layer of carbon.
- Carbon nanotubes can be multi-walled:

- The following abbreviations are often used:
  - SWCNT: Single walled carbon nanotube.
  - MWCNT: Multi-walled carbon nanotube.
Chirality

- The diameter and arrangement of carbon atoms can be varied.

- The chirality of the carbon nanotube will determine the electronic properties.

Band Structure of CNTs.

- Some CNTs have band gaps, other are like graphene.

- The density of states has a series of discontinuous spikes (Van Hove singularities).
Purification

- For electronic applications, we require semiconducting CNTs.
- During synthesis, a wide range of diameters and chiralities are formed.
- So semiconducting CNTs need to be separated from a mixture of metallic and semiconducting CNTs.
- Even a small amount of metallic CNT in the mixture can cause devices to short circuit, or have low on/off ratios.
- To be effective this is generally a costly procedure.
- See: https://www.nature.com/articles/nnano.2008.135

Single CNT Transistors

- Transistors can be made using just a single CNT as the channel.
- These devices exhibit high mobilities ($\sim 10^5$ cm$^2$/Vs).
- But manipulating and positioning CNTs has traditionally been a big challenge.
**CNT Microprocessor**

- However there has been a recent report from MIT of a 16-bit microprocessor based entirely on CNTs.


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**Neuromorphic Computation**
Pattern Recognition

• A lot of very sought-after algorithms require pattern-recognition.
• For example, I can look at this picture and work out who it is.
• This is very challenging for a conventional (Von Neumann) computer, and requires a lot of processing power.

Neural Networks

• In the last few years, we have tried to replicate the behavior of the brain in software.
Neural Networks

- How do neural networks work?
- We will use as an example, the identification of a hand-written number.

Using conventional (Von Neumann) computation this would be incredibly difficult.

Input

- In this example the input is a set of pixels, that can have a brightness between 0 and 1.
Computation

• We then apply a weight (positive or negative) to each pixel and set the value of each new neuron between zero and one.

  ![Diagram of neuron connections](https://www.youtube.com/watch?v=aircAruvnkk)

  • This intermediate neuron can represent anything.
  • E.g. certain part of the image

  ![Image](https://www.youtube.com/watch?v=aircAruvnkk)

Computation

• With the weights set appropriately, one of these second neurons will be high if this region roughly matches what we expect or low if not.

  ![Diagram of neuron connections](https://www.youtube.com/watch?v=aircAruvnkk)

  ![Image](https://www.youtube.com/watch?v=aircAruvnkk)

• Irrelevant pixels would have a weighting of zero.
Computation

- The whole network could look something like the following:

Weights

- How do you actually set the weights? There are far too many to set by hand.
- The network will be trained on real data.
- E.g. images of numbers, with real values stored.
- Guess is compared to reality, weights updated.
Training

- You need to take an average of all inputs and outputs, and optimize all connections!

- Even for a simple neural network this is incredibly costly using conventional computers.

Vector-Matrix Multiplication

- Let’s briefly return to our weightings.

- We see that the output value of $y_1$ is dependent on every input ($x_i$) and weighting ($w_{i,1}$):

$$y_1 = w_{1,1}x_1 + w_{2,1}x_2 + \cdots + w_{n,1}x_n = \sum_{i=1}^{n} w_{i,1}x_i$$

Vector-Matrix Multiplication

\[ y_1 = w_{1,1}x_1 + w_{2,1}x_2 + \cdots + w_{n,1}x_n = \sum_{i=1}^{n} w_{i,1}x_i \]

- This is just to evaluate \( y_1 \).
- To evaluate all values of \( y \) we need to consider the weights as a matrix.

\[ y_j = \sum_{i=1}^{n} w_{i,j}x_i \]

- For every stage we need to carry out matrix multiplication.

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However, we can emulate this behavior, by using Ohm’s law:

\[ I = \frac{V}{R} = VG \quad y_j = \sum_{i=1}^{n} w_{i,j}x_i \quad \rightarrow \quad I_j = \sum_{i=1}^{n} G_{i,j}V_i \]

- E.g. we could have a matrix of variable resistors with conductances / resistances representing weights:
Resistor Matrix

- With this approach we can rapidly sweep the voltages of every input to evaluate the output currents.
- But this approach requires variable resistors we can program.
- I.e. we need to be able to update the resistance of each node as we train the network.
- To do this we need circuit elements which can retain history of previous states.

\[ I_j = \sum_{i=1}^{n} G_{i,j} V_i \]


Memristor Crossbar Arrays

- Certain elements show hysteresis in current-voltage characteristics.

Memristor Crossbar Arrays

- Progress has been very fast in this field:

  ![Memristor Crossbar Arrays Image]


Inter-Neuron Communication

- An alternative approach is to more-accurately emulate the brain and use simulated spiking neurons.

  ![Inter-Neuron Communication Image]

Inter-Neuron Communication

- We still don’t really understand how the brain processes and stores information, but we do know that the weighting of connections between neurons depends on the phase offset between spikes.

- This is called Spike-Timing Dependent Plasticity (STDP). Or: “those who fire together, wire together”.

Neuromorphic Processors

- Like memristor crossbar arrays, this is a field which has seen a lot of progress:
Neuromorphic Processors

- You can already buy neuromorphic processors.


Quantum Computation
Classical Computing

- Classical computers process information as **bits**.
- E.g. consider this NOT gate:

\[
\begin{array}{c|c}
V_{in} & V_{out} \\
0V & 5V \\
5V & 0V \\
\end{array}
\]

- We could define 0V = 0, 5V = 1:

\[
\begin{array}{c|c}
V_{in} & V_{out} \\
0 & 1 \\
1 & 0 \\
\end{array}
\]

Classical Computing

- We can then represent numbers in this form:

<table>
<thead>
<tr>
<th>Denary</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0000</td>
</tr>
<tr>
<td>1</td>
<td>0001</td>
</tr>
<tr>
<td>2</td>
<td>0010</td>
</tr>
<tr>
<td>3</td>
<td>0011</td>
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</tr>
<tr>
<td>7</td>
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</tr>
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<table>
<thead>
<tr>
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<th>Binary</th>
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<tbody>
<tr>
<td>8</td>
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<td>1001</td>
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<tr>
<td>10</td>
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<td>11</td>
<td>1011</td>
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<tr>
<td>12</td>
<td>1100</td>
</tr>
<tr>
<td>13</td>
<td>1101</td>
</tr>
<tr>
<td>14</td>
<td>1110</td>
</tr>
<tr>
<td>15</td>
<td>1111</td>
</tr>
</tbody>
</table>
Classical Computing

• We can then in-turn represent other data (e.g. characters) in binary:

<table>
<thead>
<tr>
<th>ASCII TABLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td></td>
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<tr>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Qubit

• If correctly engineered, we could create a system where we can access and manipulate the quantum mechanical properties of a single quanta.

• For example, let’s consider phosphorus doped silicon.

  but in this case we somehow put in just one phosphorus atom.

  This extra electron and proton is almost identical to a hydrogen atom, but it is fixed in a lattice.
Qubit

• Let’s say we can access and change a property of this atom. For this example we will say it is the spin of the electron.

• For our purposes we will say that spin is the angular momentum of the electron, and it can take two possible values:

  ![Spin Up and Spin Down](image)

  “Spin Up”

  “Spin Down”

• We could say that Spin Up = 1 and Spin Down = 0.

• So far, this is equivalent to a traditional bit.

• But remember, this is a single electron, not a solid.

• Because it is a quanta, we describe the particle as a wave:

\[
|\psi\rangle = \alpha |\uparrow\rangle + \beta |\downarrow\rangle
\]

• \( \alpha \) and \( \beta \) are coefficients that describe the probability of each state.
Superpositions

• In quantum mechanics we are forced to describe systems via probabilities.
• This means that we can not know the exact nature of a system until we measure it.
• E.g. we could measure the spin of an electron 100 times and discover it to be in the spin-up state 64 times and the spin down state 36 times.
• Before we carry out the measurement we can only describe the particle in terms of the probability of each state.

\[ |\psi\rangle = \frac{4}{5} |\uparrow\rangle + \frac{3}{5} |\downarrow\rangle \]

• I.e. the coefficients are:
  \[ \alpha = \frac{4}{5} \quad \beta = \frac{3}{5} \]
• It turns out the probability of each state depends on the prefactor squared:
  \[ P_\uparrow = \alpha^2 = \frac{16}{25} = 64\% \quad P_\downarrow = \beta^2 = \frac{9}{25} = 36\% \]
Classical Operations

- We can think of our (classic) bits as special cases of this wavefunction:
  \[ |\psi\rangle = 0|\uparrow\rangle + 1|\downarrow\rangle \quad \text{Or} \quad |\psi\rangle = 1|\uparrow\rangle + 0|\downarrow\rangle \]

- In classical computers we (at the lowest level) process information by carrying out bitwise operations

  ![NOT gate diagram]

  |\( V_{\text{in}} \) | |\( V_{\text{out}} \) |
  |---|---|
  | 0  | 1  |
  | 1  | 0  |

- For example, we could use a NOT gate (inverter).

Quantum Operations

- We can also carry out the equivalent operation on our qubit:
  \[ |\psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle \quad \Rightarrow \quad |\psi\rangle = \beta|\uparrow\rangle + \alpha|\downarrow\rangle \]

- Or for our specific example:
  \[ |\psi\rangle = \frac{4}{5}|\uparrow\rangle + \frac{3}{5}|\downarrow\rangle \quad \Rightarrow \quad |\psi\rangle = \frac{3}{5}|\uparrow\rangle + \frac{4}{5}|\downarrow\rangle \]

- In quantum computation terminology this would be called a Pauli-X gate or bit-flip gate.
Quantum Operations

- There also gates that have no classical equivalent.
- E.g. a **Hadamard** gate.
- This will take a 0 or 1 state and put it into an equal superposition.

\[
|\psi\rangle = 1|\uparrow\rangle + 0|\downarrow\rangle \quad \text{Definitely up}
\]
\[
|\psi\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle
\]

\[
|\psi\rangle = 0|\uparrow\rangle + 1|\downarrow\rangle \quad \text{Definitely down}
\]
\[
|\psi\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle
\]

- This could be used to setup your quantum system.

Entanglement

- Until now, it is still not really clear why a quantum computer is would be any faster than a classical computer.
- Let’s consider two qubits.

- We will use a silicon-based quantum computer again.
- Once again, we will assume we can measure and manipulate the spins.
- Don’t worry about how we engineer this!
Entanglement

- The wavefunction can now possess these states:
  
  Both Spin Up  
  \[ |\uparrow\uparrow\rangle \]

  Both Spin Down  
  \[ |\downarrow\downarrow\rangle \]

  Spin 1 Up / Spin 2 Down  
  \[ |\uparrow\downarrow\rangle \]

  Spin 1 Down / Spin 2 Up  
  \[ |\downarrow\uparrow\rangle \]

- We then can **entangle** the qubits, meaning their wavelike properties become combined into a single wavefunction.

We can create gates that encode information onto these 4 coefficients, then manipulate them to carry out calculations.

We have encoded **4 variables onto 2 atoms**.
Entanglement

- What about 3 entangled atoms?
- We can describe our state as something like this:
  \[ |\psi\rangle = \alpha |\uparrow\uparrow\uparrow\rangle + \beta |\uparrow\uparrow\downarrow\rangle + \gamma |\uparrow\downarrow\uparrow\rangle + \delta |\downarrow\uparrow\downarrow\rangle + \varepsilon |\downarrow\uparrow\uparrow\rangle + \zeta |\downarrow\downarrow\downarrow\rangle + \eta |\downarrow\downarrow\uparrow\rangle + \theta |\downarrow\downarrow\downarrow\rangle \]
- Now we have codes 8 variables into 3 atoms.
- The trend will continue as you add more atoms...
  - If we have \( n \) atoms, we can encode and calculate using \( 2^n \) variables.

Entanglement

- What about 300 entangled atoms?
  \[ 2^{300} = 2 \times 10^{90} \text{ variables} \]
- In this computer we can define \( 10^{90} \) variables, then operate on them with a single gate.
- This is where the potential power lies in quantum computation.
- There are between \( 10^{78} \) and \( 10^{82} \) atoms in the universe.
- For certain problems (e.g. cracking RSA encryption) this provides immense performance improvement.
Quantum Computers

- Quantum computers look like this:

- Require low-temperatures (~mK).
  - And probably always will.

Real Quantum Computers

- Commercial quasi-quantum computers already exist.

- These D-Wave computers are designed to solve a specific problem – and do not involve entanglement.
Real Quantum Computers

- You can already run calculations:

Quantum Algorithms

- The operations one can perform on quantum computers are distinct from classical computers.
- There already exist open-source programming languages for quantum computers.
Quantum Supremacy

- Quantum Supremacy is a milestone that shows a quantum computer can solve a problem that a classical computer cannot in a reasonable amount of time (e.g. the lifetime of the universe).
- Google / UC Santa Barbara achieved this last month.
- The combined 53 qubits.

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Course Overview
Course Objectives

• Overall, the goals of this course were as follows:
  • Provide an outline of the processing steps that are followed to take starting materials (sand) through to a fully-processed wafer.
  • Describe the technology and instrumentation required to make this process possible.
  • Introduce and practice using some of the quantitative models to describe growth and processing steps.
  • Simulate some of the basics of the process using dedicated modeling software.
  • Discuss the limitations of the process / industry and future attempts to overcome these issues.

My Course Objectives

• The goal for me was to provide the following:
  • Provide you with the necessary information to talk about all the steps in the process with confidence.
  • Provide you with an intuition of how to quantify a process. E.g. when presented with a particular problem which models you could use and their limitations.
  • Hopefully enable you to develop an opinion on what is good about the process, what is not perfect.
  • Start to think about how this field evolves in the future.
• The goal was not the following:
  • Get you to memorize a load of formulae, abbreviations, etc. you will forget immediately after the exams.
Student Evaluation of Teaching

- Please complete the assessment when you get a chance.
- eSET will open Monday November 27th.
- These scores are taken very seriously by the College of Engineering.
- I’m not tenured → even more important for me.
- The College will not consider scores if less than 6 report.
  - In this case it is as if I have not taught the course.
  - So for a small class like this it is very important.

Good Luck!