Lecture 19
Biological Electronics

Announcements

Homework 9/10:
• Is due now.

Homework 10/10:
• Is online now.
• Due Monday December 7th at 2pm
• I will return it by the end of Finals Week
• Homework 10 consists of content covered in Lectures 18 and 19.
Announcements

Course Conclusion

• Today is the last lecture of the course.
• After Homework 10, there is no more assessment for ECE617.
  • There are no examinations.
• I will return your 10th homework during Finals Week.
• I will upload your course grade by the end of Finals Week.
• My next course is ECE615 in Winter (two terminal devices).
• A more detailed course on FET behavior is offered in Spring (ECE616) but I do not teach it.

Lecture 19

• Biological Information Processing.
• Interfacing with Biology.
• Neuromorphic Devices.
• Course Summary.
Additional Sources

• This is a subject the course textbook (Brotherton) does not cover this subject at all.
• Reviews on Bioelectronics:
  • https://pubs.acs.org/doi/10.1021/cm4022003
  • https://pubs.acs.org/doi/abs/10.1021/acs.chemrev.6b00146
• Reviews on Neuromorphic Computing:
  • https://www.nature.com/articles/s41928-018-0103-3

Biological Information Processing
Bioelectronics

- Bioelectronics is a broad term for any electronics which interacts directly with the human body.
- We can describe bioelectronics as either:
  - Receiving information from the body.
  - Providing signals or treatment to the body.

Receiving Information

- For example, we could place electronics on part of the human body and read signals:

Sending Information

- Or we can send electronic signals into the human body.

Biological Signaling

- Before we can consider interacting with the human body, we need to understand how information is transmitted in the biological systems.

- This is an incredibly complicated subject, and we are not biologists (me especially!).
**Biological Signaling**

- For our purposes, we just need to know roughly how information is transmitted in biological systems.
- In conventional electronics we process information with electrons and holes (mainly).
- In biological systems, **ions and molecules** are used to transmit information.
- Molecules come in a wide range of sizes:

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**Inter-Neuron Communication**

- In the brain for example, signals are passed between neurons via mass transport.

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Action Potential

- The charged ions (e.g. Ca\(^{2+}\), Na\(^{+}\)) that cross the boundary then depolarize the cell.

- The charge then travels down the axon as a wave.
  - Roughly 100 m/s.

Interfacing with Biology
Biological Electronics

- One way to detect properties of the human body is to detect chemical properties.
- Certain chemicals are associated with certain biological processes.
- The simplest way one can detect chemicals is to use a chemresistor.

![Chemresistor Diagram]

Chemresistor

- Here we just measure the conductance as a function of exposure to various compounds.
- We need a semiconductor which will change conductance when it comes in contact with a relevant chemical.
- Organic semiconductors are therefore well suited to this application.
- They can change properties when in contact with solvents.

https://www.youtube.com/watch?v=f4K5p2VhWA
**Chemresistor**

- Groups have demonstrated the ability of organic chemresistors to detect the presence of certain solvents.

![Chemresistor](image1)

**Chemical-Sensing TFTs**

- If the conductance can be changed by the presence of chemicals, it should be possible to manufacture thin film transistors which are capable of detecting chemicals / biological compounds.

![Chemical-Sensing TFTs](image2)
Water Gated TFTs

- While solid-gas interfaces are sometimes useful, it turns out that being able to detect the chemical properties of a solution is a lot more powerful.
- Ideally we would like to be able to use our electronics to determine the concentration of some compound in a liquid.
- To do this we could use a water-gated TFT.


If we can assume that the liquid will not significantly permeate the semiconductor, then we could use this TFT geometry:

**TGBC**

- Top-gate bottom contact

**Water-Gated TFT**

- Substrate
Water Gated TFTs

- How does this device work?
- Water is a polarizable medium:
  - It contains mobile ions.
- If you apply a gate bias, ions will be attracted / repelled from the gate electrode.
- A double layer will form at semiconductor-dielectric interface.
- If no ions cross into the semiconductor, this is similar to conventional field-effect gating.

The presence of impurities can affect the ability of the TFT to be gated.

Proteins, DNA etc. will be charged and will have an associated ionic mobility.
OECTs

- We stated that water-gated TFTs that **no ions cross into the semiconductor**.
- Chemicals present in the liquid effect the ability to gate the device, but we are still injecting and transporting **conventional electronic charge**.
- But we know the human body uses ions to signal.
- So if we can develop a device that is able to inject and transport ions, we should be able to interface more directly with the human body.
- These are organic electrochemical transistors (OECTs).

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OECTs

- Organic electrochemical transistors (OECTs) are devices in which ions actually enter the semiconductor films, and effect (electronic) charge transport.
- You can think of them as being water-gated TFTs, where ions cross the boundary between the liquid and the semiconductor.
- What happens in such a device?
PEDOT:PSS

• It turns out that the best OECTs are based on the conducting polymer blend PEDOT:PSS.

• The PSS is negatively charged, and the PEDOT compensates with mobile electronic positive charge (holes).

PEDOT:PSS

• Because the PSS is negatively charged, there are free holes in the PEDOT and, the blend is hence a p-type conductor

• It is often used as a quasi-transparent conductor in organic photovoltaic cells (OPV) in combination with ITO.
**PEDOT:PSS**

- If we made a TFT using PEDOT:PSS as the channel material, we would just have a conducting channel.

![PEDOT:PSS Diagram](image)

- I.e. current could flow with no applied $V_G$.
- But this is only conducting because the PSS is charged.

**Depletion Mode TFTs**

- So an OECT is actually a rare example of a **depletion-mode** TFT.
  - I.e. under equilibrium conditions it is on, and we have to provide a signal to turn it off.
  - A lot of traditional MOSFETs are depletion mode transistors.
**OECTs**

- Instead of applying a bias, ions that enter the PEDOT:PSS will neutralize the PSS, and stop the blend from being conductive.

![Diagram showing OECT behavior](image1)

- So OECTs will strongly change their characteristics based on ionic content in the solution.

![Diagram showing OECT characteristics](image2)
OECTs

- These devices have been demonstrated as glucose sensors:


- These can potentially be used for diabetes sufferers.

OECTs

- They are able to differentiate different types of DNA.

OECTs in the Body

- These devices can clearly be used to help us determine chemical composition in solutions, but how does this work when in the human body?

- OECTs have been put onto probes and inserted into rat brains. Electrical activity can be tracked.

OECTs in the Body

- One approach is to develop the TFTs on a flexible (non-toxic) substrate.
- The probe is then placed on the brain.
Ion Pumps

- So what about providing treatment to the body?
- This is a little more challenging, because generally we want to inject ions (not electrons) into the body.
- One strategy is to use an ion pump:

   ![Diagram of ion pumps](Simon et al., Chem. Rev. 116 (2016) 13009.)

   - By applying a bias we can electronically inject the ions into the target when we want.

   ![Diagram of ion pumps](Tybrandt et al., Adv. Mater. 21 (2009) 4442.)

   - By having high spatial resolution, the delivery of ions can be made very controllable.
Ionic Conductors

- For our ion pump to work we need a material that is capable of transporting our ions.
- It turns out that PEDOT:PSS is a good ionic conductor.

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Neuromorphic Devices
Inter-Neuron Communication

- We talked earlier about action potentials, and how information is transmitted between neurons.

- And we talked about how signals are transmitted as a polarization wave down the axon at ~100 m/s.

Information Processing

- So if information travels so slowly, how can we process certain types of information so much more efficiently than a traditional computer?
- For example, I can look at this picture and work out who it is.
- This is very challenging for a computer, and requires a lot of processing power.
- Although it is becoming a more desirable technology.
Information Processing

- You may have noticed that a neuron does not just receive a signal from one other neuron and pass it on to one other.
- It receives information from many cells and sends the signal on to many other cells.
- The brain is **massively parallel**.
  - The brain has ~100 billion neurons.
  - The brain has \( \sim 10^{14} \) neural connections.
  - The brain has a computing power of \( \sim 10^{18} \) flops.
  - IBM AC922 was benchmarked at \( 2 \times 10^{17} \) flops.

Neural Networks

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

- One objective is to apply this technology to currently unsolvable problems (e.g. protein folding)

[Image of protein structure]

https://www.nature.com/articles/d41586-020-03348-4

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Neural Networks

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

[Image of hand-written number and neural network diagram]

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

https://www.youtube.com/watch?v=aircAruvnKk
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.
  
  • This intermediate neuron can represent anything.
  • E.g. certain part of the image

https://www.youtube.com/watch?v=airc4eu3Tkk
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.

• 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 ($w_{i,1}$):

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

• 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.
Vector-Matrix Multiplication

- However, we can emulate this behavior, by using Ohm’s law:
  \[ I = \frac{V}{R} = VG \]
  \[ y_j = \sum_{i=1}^{n} w_{i,j} x_i \]
  \[ I_j = \sum_{i=1}^{n} G_{i,j} V_i \]

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

\[ \begin{bmatrix}
  I_1 \\
  I_2 \\
  \vdots \\
  I_n
\end{bmatrix} =
\begin{bmatrix}
  V_1 \\
  V_2 \\
  \vdots \\
  V_n
\end{bmatrix} \begin{bmatrix}
  G_{1,1} & G_{1,2} & \cdots & G_{1,n} \\
  G_{2,1} & G_{2,2} & \cdots & G_{2,n} \\
  \vdots & \vdots & \ddots & \vdots \\
  G_{n,1} & G_{n,2} & \cdots & G_{n,n}
\end{bmatrix} \begin{bmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_n
\end{bmatrix} \]

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.
Memristive Devices

• We saw in Lecture 15 that we can make 2-terminal devices which can be programmed and read at different voltages.

Memristive Devices

• There are a few ways to achieve this.
Memristor Crossbar Arrays

- Oxides are typically found to give highest device density.


Memristor Crossbar Arrays

- Progress has been very fast in this field:

**Inter-Neuron Communication**

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

  ![](image1.png)


  ![](image2.png)

  Kuzum et al., Nanotechnology **24** (2013) 382001.

- 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.

  ![](image3.png)

  "those who fire together, wire together".

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**Neuromorphic Processors**

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


- You can already buy neuromorphic processors.

Neuromorphic Transistors

- However, we could instead use our OECT.
- We know these devices have a long retention time.
- We could wire up the network so it will program the conductance of each OECT depending on training results.
- Such a device would be considered a neuromorphic thin-film transistor.


Programing OECTs

- To effectively train the network we need the states to be retained.
- OECTs happen to be very well suited to this.
  - Ionic motion is slow.
  - Certain systems can be optimized for chemical reactions to occur,
- This could potentially enable real-time training of neural networks.

**Mimicking the Brain**

- Depending on time-constant, we can program the OECTs with pulses rather than a constant bias.

This sort of behavior much more closely resembles real (biological) neural networks.
- Memories are stored states in neurons.
  - Time constants from ms to years can exist.
  - We are however still a very long way off understanding the brain, let alone reproducing it.
Course Summary

Course Objectives

• Overall, the goals of this course were are as follows:
  • Introduce the concept of thin-film transistors (TFTs) and their operation mechanisms.
  • What sort of performance we need from these devices, and how we would characterize them.
  • Give you an overview of the materials that can be used for TFTs. Their respective pros and cons.
  • What we can do to optimize / improve TFTs.
  • How we can use TFTs as sensors / emitters, in circuits, for biological applications.
  • Some issues for flexible electronics.
TFT Operation

- We discussed the concept of thin-film transistors (TFTs) and their operation.

![TFT Diagram]

TFT Characterization

- Some details on how we measure / test TFTs.
- What are the figures of merits and how do we evaluate them?
Models

• How do we describe charge transport in systems without long range order?

Materials

- Silicon
- Oxides
- Organic Semiconductors
- Hybrid Halide Compounds
- Chalcogenides
- Carbon Systems
Growth Technique

- We talked about the different growth and deposition techniques for these materials.

Dielectrics / Electrodes

- We will discuss the other components of the TFT device: the dielectrics and electrodes.
Integrated Circuits

• We covered some very basic integrated circuits, how we characterize them and what we can do to improve them.

Ambipolar TFTs

• We talked about transistors that are capable of injecting and transporting both holes and electrons, and how we need to give them extra consideration.
Memory Devices

- How can we retain information over long periods of time in these systems?

Power

- How do we provide and store power for portable devices?
Phototransistors
• We can also use transistors for other functions such as light sensing.

Flexible Electronics
• We studied some of the specific problems of flexible electronics.
Biological Electronics

- Finally, we today talked briefly about how we can use thin-film electronics to interact with the human body.

My Course Objectives

- The goal for me was to provide the following:
  - The ability to understand and measure TFTs, and extract parameters from current-voltage characteristics.
  - Information about what semiconductor material system(s) are best suited for what particular application.
  - Some ideas about what you can do to optimize and improve TFTs.
  - An intuition about what TFTs are capable of, could possibly be capable of in the futures, and what they could never do.
- The goal was not the following:
  - Get you to memorize a load of formulae, acronyms, etc. you will forget immediately after the exams.
Thank You!