Announcements

Homework 7/10:
• Is due now.

Homework 8/10:
• Is online now.
• Due Monday November 23rd at the start of the lecture (2:00pm).
• I will return it one week later (November 30th).
• Homework 8 consists of content covered in Lectures 14 and 15.
Lecture 15

• Data Storage.
• Volatile Memory.
• Non-Volatile Memory.
• Memory Using Thin Film Materials.
• Three Terminal Memory.
• Two Terminal Memory.

Additional Information

• Brotherton does not provide much detail on this subject unfortunately.
• These are a few review articles which could be useful:
  • https://www.nature.com/articles/s41578-019-0159-3.
• But these notes will be your best resource in general.
Storing Information

- Last time we looked at the basics of integrated logic circuits.

- These circuits take some input binary information and process it in some way.
Storing Information

- At some point we will want to store this information to be accessed at a certain point in the future.
- While not the case for display backplanes, there are some desired applications of thin film electronics that will require the ability to read / write data.

Traditional Data Storage

- Data storage is not a problem specific to thin-film electronics.
- It is something we are all familiar with.

- Before we talk about memory for thin film electronics we should know how these memory systems work.
Types of Memory

• One way to categorize memory is as either volatile or non-volatile.

• **Volatile:**
  • Data will be wiped when power is removed from memory.
  • E.g. DRAM.

• **Non-Volatile:**
  • Data is preserved after power is removed.
  • E.g. Flash drives.

Volatile Memory
**DRAM**

- Dynamic Random Access Memory (DRAM) is the most common form of volatile memory.
- In DRAM, a bit is stored using a 1C1T (one capacitor, 1 transistor) design.

![DRAM Diagram](image1)

**DRAM Operation**

- Information is represented as charged (1) and uncharged states (0) on the capacitor.
  
  ![DRAM Operation Diagram](image2)

- After the gate voltage is removed, the channel is insulating and the capacitor will only discharge slowly through it. Remember: \( \tau = RC \).
**DRAM Operation**

- The state of the bit is then read by applying a voltage to the gate only, and allowing the charge to flow backwards.

![Diagram of a MOSFET with gate, drain, source, and capacitor. The gate has a +1V voltage applied to it, and the drain and source are at 0V.]

- In short, we use the gate to control the charge / discharge rate, and the drain to choose the direction of charge flow.

**DRAM Operation**

- These bits are arranged into a two-dimensional array, often $\gg 1000$ by $\gg 1000$. 

![Diagram of a two-dimensional array of MOSFETs, each connected to a word line and bit line.](ECE617-ThinFilmElectronics-Fall2020-JohnLabram)
**Reading From DRAM**

- The whole section of memory is read at once.

![Diagram of DRAM reading process]

**Writing to DRAM**

- Because reading is destructive, we must re-write after every read.

![Diagram of DRAM writing process]

- Read / write frequency depends on clock speed.
Volatility

- It turns out this necessary anyway, because even without a gate voltage applied our capacitor will discharge.

![Diagram of capacitor with 0V at drain and source](image)

- This is what makes DRAM volatile.
- So the bits have to be written / read frequently.

Non-Volatile Memory
Flash Memory

- Flash memory is currently the cheapest and widely used non-volatile form of memory.
- It’s operating principle is completely different from DRAM.

![DRAM and Flash Diagram]

Floating Gate Transistors

- Each bit in flash memory is stored using a special type of field effect transistor.
- Between the dielectric and the semiconductor we have inserted an extra metal and thin dielectric.
Flash Memory

- Perhaps counterintuitively, we define a “0” as when the floating gate is charged with electrons, and a “1” as when the floating gate is neutral.

![Logic 0 and Logic 1 diagrams]

- These electrons are assumed to be trapped in the floating gate.

Reading from Flash Memory

- Reading is then simply a case of addressing a transistor, and seeing if the current flows as expected.
- Start with Logic 1 (no electrons):

![Current vs. Gate Voltage graph for Logic 1]
Reading from Flash Memory

- What about with the extra electrons in the floating gate (i.e. Logic 0)?
- We apply the same voltages to measure the current.
- I.e. we observe a different $V_T$. 

![Diagram showing reading from flash memory]

Writing to Flash Memory

- How do we get the electrons into this floating gate in the first place?
- We exploit a quantum mechanical tunnelling.
- We talked about this previously in terms of charge transport and charge injection.
- Here the process is pretty similar but we have an insulator in between the metal and semiconductor.
Fowler–Nordheim Tunneling

- Let’s look at the band diagram under the gate.
- We will ignore band-bending, image force lowering and other non-idealities.

- We will assume the tunnel dielectric is $\lesssim 5\text{nm}$ thick.

Fowler–Nordheim Tunneling

- What happens if we ground the gate, and apply a voltage to the drain?
Fowler–Nordheim Tunneling

• Let’s just look at the semiconductor, tunnel dielectric and floating gate.

• Let’s look at the conduction band and consider where electrons are allowed:

- We know that because they are quantum mechanical, electrons are able to tunnel through very high barriers if they are small enough.

- When tunneling through the entire barrier like this, the probability is primarily due to the thickness of the dielectric itself.

- Difficult to control tunneling with a voltage in this case.
Fowler–Nordheim Tunneling

• However if we apply a very large bias across this structure the effective tunneling distance can be reduced significantly.

Fowler–Nordheim Tunneling

• Tunneling across the top of the barrier like this is called **Fowler–Nordheim Tunneling**.

  • The important aspect of this phenomenon is that the angle of the tunnel barrier, and therefore the tunneling rate is highly dependent on the applied voltage.

  • This allows us to control the rate of tunneling by changing the voltage offset between the gate and semiconductor.
Writing to The Floating gate

- We hence can write a 0 to the floating gate by injecting charge into the semiconductor and applying a large field between gate and drain.

- Once in the floating gate, the charge cannot get out. It will remain there for decades.

Writing to The Floating gate

- To clear electrons from the floating gate, and hence write a logic 1, we connect the source and drain both to 10V.

- Similarly, the logic 1 state is stable for > 10 years.
Memory Using Thin Film Materials

Thin Film Memory Devices

• So can we achieve similar things for the sort of devices we are targeting?
• It would be challenging to make ultra-thin (<5nm) layers using the techniques we are talking about.
• So we need other approaches.

https://www.youtube.com/watch?v=zfH4U65E8Z8
Requirements

- Before we develop a strategy, we should first define some requirements for our memory.
- **On-off Difference:**
  - I.e. how large (in either voltage or current) is the difference between our defined 1 state and our 0 state.
  - This will affect how easy it is for the supporting circuity to distinguish these states.
  - It is similar to noise margin for circuits.

Requirements

- Before we develop a strategy, we should first define some requirements for our memory.
- **Read Time:**
  - How long it takes for to access the state of the memory element.
  - This is more than simply the time to for detect a single element – it will depend on the read circuit and algorithm.
- **Write / Erase Time:**
  - Depending on the design, this can be substantially longer than read time.
Requirements

• Before we develop a strategy, we should first define some requirements for our memory.

• **Cycling Endurance:**
  • How many times can the memory be read from and written to before it is physically damaged?
  • This is never $\infty$, and for some systems (e.g. Flash) can be as low as 1000.
  • 1000 cycles is the equivalent of 3 read/write cycles per day for one year.
  • This is heavily dependent on the operating mechanism.

• **Retention Time**
  • How long data is preserved when the power supply is removed?
  • For DRAM it is only a few ms.
  • For Flash it can be decades.
  • In general we want this to be long (non-volatile memory), but we can make use of volatile memory for certain applications if it is very fast (e.g. DRAM).
Requirements

• Before we develop a strategy, we should first define some requirements for our memory.

• **Power Consumption**
  • How much power is used to keep this data source operational (while in use).
  • Normally much higher for read and write cycles.
  • Can be high for systems like DRAM (constant reading and writing) and HDD (spindle rotation).
  • Typically expressed in units of W/GB or similar.
  • Varies significantly by mechanism and matters hugely for flexible and portable devices.

Requirements

• Before we develop a strategy, we should first define some requirements for our memory.

• **Rectification**
  • This one is a little more subtle but is important.
Requirements

- Before we develop a strategy, we should first define some requirements for our memory.

Rectification

- This is a phenomenon called “sneak currents”.
- It is one of the primary reasons why we need very well-defined, and well-separated, on and off states.
- If not, you can expect the parallel current to easily overwhelm the desired signal.
- This effect can be effectively reduced using rectifying elements.
Requirements

• Before we develop a strategy, we should first define some requirements for our memory.

• **Ruggedness**
  • Traditionally this refers to what you would expect to happen if you dropped your memory device on the floor for example?

https://www.youtube.com/watch?v=CVxjKI3cw0c

• For mechanically flexible devices, this is a lot more important as we have to consider bending cycles.

https://www.youtube.com/watch?v=mo6nF-T58PA
Requirements

• Before we develop a strategy, we should first define some requirements for our memory.
• **Data Density**
  • How much data can we store per unit area of our memory unit?
• **Cost**
  • Arguable this is the most important consideration in most cases.
  • We have to know that what we are planning is economically viable.

Requirements

• So what is acceptable for what we have in mind?
• There is no simple answer to this – it very dependent on the application.
• Storage needs can range from about 40 bits for a barcode to $>10^{13}$ bits for some hard drives.
• For example, if we want to store history on food packaging temperature would 1MB (comparable to a floppy disk) be sufficient?
Requirements

- A retention time of 1 year is probably fine for applications like food packaging but is less than the shelf life of most commercial electronics products.
- The read and write speed again will depend strongly on the application.
  - As a benchmark a rate of roughly 1MB/s is sufficient for real-time audio.
- For portable and flexible electronics we will generally expect the power consumption requirements to be more strict than for conventional memory.

Types of Thin Film Memory

- We can broadly split thin-film memory devices we consider into two types:
  - Three terminal.
  - Two terminal.
- Within each of these categories there are various potential approaches to memory storage.
Three Terminal Memory

- These should be reasonably familiar to us.
- We want transistors to retain user-specified information after they lose power.
- Flash memory is transistor-based.

However we cannot really use tunnel layers for our systems.
Three Terminal Memory

• Recall the way flash memory works.

• All we are doing is changing the threshold voltage and using different values of $V_T$ to define different memory states.


Three Terminal Memory

• We have already observed three terminal memory devices in this course, we just were not aware of it:

• We inadvertently changed the threshold voltage by applying a voltage.

  Brotherton Figure 9.2
Three Terminal Memory

• So the question is, are we able to controllably change the threshold voltage, and can it retain this change for a long time?

• There are a few ways we can achieve this. We will discuss a few briefly:
  • Charge trapping.
  • Ferroelectric transistors.
  • Floating gate transistors.

Charge Trapping

• When we first introduced the threshold back in Lecture 4,
  • It is trapped charge that modifies the required gate voltage to induce charge carriers.
  • Although most dielectrics will revert to their original after a short period of time.
Charge Trapping

• Scientists have engineered dielectrics which can possess an electric charge or polarization.
  • These are called electrets.
• If engineered correctly, they can retain this charge for a very long period of time, until charge is forced onto or off of the electret with a large field.
• It is a little like a floating gate but it is a dielectric, not a metal.

In this case charge is injected into the electret by applying a voltage of +100 V to the gate (writing) and the state is erased by applying -120 V to the gate.

• The device is then stable to be measured as a normal transistor, as long as the voltage are much lower than this.
Charge Trapping

- In this case they found they had to mix two semiconductors (i.e. an ambipolar blend) in order to get the erase operation to work effectively.

- A typical way to characterize a memory device like this is to repeatedly program and erase, and then measure the current at the relevant voltage.

- There are various ways to evaluate retention time, but in most cases some extrapolation is required.
Ferroelectric Materials

- Another strategy is to exploit a property of certain materials called ferroelectricity.
- This is the electric field analog to ferromagnetism.
- Ferroelectric materials possess a net electric dipole, which can be preserved over long periods of time.

Ferroelectricity

- If you measure electric polarization ($P$) as a function of electric field ($E$) of a material, there are a number of different possible responses.

Normal Polarization

Paraelectric Polarization

Ferroelectric Polarization

Relative permittivity is constant

Relative permittivity changes with applied field

Relative permittivity changes with applied field, and retains state
Ferroelectricity

- On a molecular level this can be achieved in a number of ways, but this is a commonly used example:

![Ferroelectric diagram](image)


- In PbTiO$_3$ the Ti is off center in the unit cell but can be pushed either side with an applied field.

Ferroelectric Polymers

- It turns out this is also possible using solution-processable materials.
- There are certain fluorine containing polymers which possess dipoles.

![Ferroelectric polymer diagram](image)

Li et al., Polym Int 2020; 69: 533-544
Stadlober et al., Chem. Soc. Rev., 2019, 48, 1787-1825
Ferroelectric Polymers

- We can use these materials to modify $V_T$:

Notice however the required voltage is lower than our previous example.

Floating Gate Transistors

- The third approach goes back to the conventional approach used in flash memory.
- However, as we have previously mentioned it is very challenging to make continuous ultra-thin films using the techniques we plan to use.
  - ALD is an exception.
  - Ultra-thin solution-processed films are possible but reports on this are still very preliminary.
Floating Gate Transistors

- One approach is to use a nano-scale metal, but this time as nanoparticles rather than a thin metal.

  ![Image of gold nanoparticles in an insulating polymer](image1)

- Here we have gold nanoparticles embedded into an insulating polymer.

  ![Diagram of floating gate transistor](image2)

- This was achieved by depositing Au nanoparticles onto a thin (~20 nm) insulating layer of polystyrene, then coat that with a thicker (\(\gg 100\) nm) dielectric.

  ![Diagram of band structure](image3)

- The band structure is then not dissimilar from traditional Flash memory.

  ![Diagram of band structure comparison](image4)
Floating Gate Transistors

- The proposed read / write mechanism is shown to the right:
- In reality, it is likely that the nanoparticles have diffused into the polystyrene (PS).
- So you could view the band picture like this.
- The tunneling is likely to rely on percolation.

 Floating Gate Transistors

- Once again, these are devices which show the desired behavior.
- They are using a p-type transistor in this case.
Two Terminal Memory

2 Terminal Memory Devices

- While three terminal devices are how non-volatile devices have traditionally been designed, it is possible to achieve the same thing with a 2-terminal device.

- At first glance it may seem impossible to be able to distinguish between read and write operations with just two terminals.
2 Terminal Memory Devices

- However, if we could read a device without disturbing it with a low voltage, then write using a much higher voltage, then this could be possible.

\[ I \rightarrow V \]

Erase  Read  Write

Memristor

- This sort of behavior is what we would call **memristive**.
- We would call the circuit element a **memristor**.
- It’s a portmanteau of **memory** and **resistor**.

- It was invented in 1972\[^1\] and realized* in 2008\[^2\].

\[^1\] L. Chua, IEEE Transactions on Circuit Theory, 18, 5, 507-519, 1971
2 Terminal Memory Devices

- Regardless of whether we can strictly call devices that behave like this a memristors is irrelevant to us.
- We want devices to show this behavior for our memory applications.
- So the question is, how do we achieve this in reality?
- A few strategies exist, and again, we will just cover a few:
  - Charge trapping (again).
  - Redox reactions.
  - Filamentary conduction.

Charge Trapping (Again)

- Previously, with the three-terminal devices, we used traps to modify the threshold voltage.
- With a two-terminal device we wish to change the conductance of the device by applying large high or low voltages.
- One approach is to embed semiconducting nanoparticles inside an insulating polymer matrix.

Charge Trapping

- Their proposed mechanism is something like this.
- Charges percolate as usual.
- This gives us the normal relationship between current and voltage.

\[
\begin{align*}
E_{ZnO} & \quad PMMA \\
\text{hole} & \quad \text{hole} \\
\text{hole} & \quad \text{hole} \\
\end{align*}
\]

However, at a certain field there is a big enough driving force for holes to transfer to the PMMA.
- The charge will inhibit any other normal charge flow
- Current will drop significantly.
**Charge Trapping**

- The result is the behavior we want.
- Although the magnitude is the opposite of our previous example.

![Graph showing current vs. cycles](image)

- These devices show good cycling endurance.

**Redox Reactions**

- Another approach is to exploit reduction and oxidation (redox) reactions in one of the materials.
- Below is a redox reaction occurring in one of the organic electrode materials in a memory device.
Redox Reactions

- The exact strategy depends heavily on the materials used, but generally rely on the ability to change a material’s electrical conductivity by driving a reversible reaction.

These systems have been shown to be compatible with mechanically flexible substrates.

- This has been exploited for a different application: Neuromorphic Computing (see Lecture 19).
Filamentary Conduction

• The final mechanism we are going to talk about is something called filamentary conduction.

• Essentially it is the formation of a metallic bridge of some kind between the electrodes.

• A common mechanism is field-induced diffusion of one of the electrodes into the semiconductor itself.

• This is more likely in soft semiconductors.


Filamentary Conduction

• This has been directly observed using transmission electron microscopy (TEM).

• The silver is observed to diffuse into the channel after applying 5V.

• The process is partially reversible.

Filamentary Conduction

- These devices are observed to possess well-defined on and off states.

- The states have good retention times.
- Physical movement of material is highly stable.

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Filamentary Conduction

- In reality, a number of processes could lead to what is called filamentary conduction.
- A field can cause the degradation of parts of the semiconductor into a metal.
- In this case the metal comes from the semiconductor itself rather than the electrodes.
- The metal still moves under the applied field.
Filamentary Conduction

- Conducting networks are not the only thing that qualifies as filamentary conduction. For example you could have some high mobility pathways in an otherwise low mobility semiconductor.

- Broadly, we would define filamentary conduction as a process which occurs locally at certain parts of the device rather than uniformly throughout the film.

Next Time

- Power Sources.