Lecture 16
Field-Effect Transistors 1
Schroder: Chapters 2, 4, 6

Announcements

Homework 3/5:
• Is online now.
• Homework 3 covers Lectures 12-15 (inclusive).
• Due Friday May 15\textsuperscript{th} at the start of the lecture (09:00am).
• I will return it one week later Friday May 22\textsuperscript{nd}.

Homework 4/5:
• Will be posted on Monday May 18\textsuperscript{th}.
• Homework 4 will cover Lectures 16-18 (inclusive).
• Due Monday May 25\textsuperscript{th} at the start of the lecture (09:00am).
• I will return it one week later Monday June 1\textsuperscript{st}.
**Last Time**

- We carried out a set of thoughts experiment to rationalize observed capacitance-voltage curves.

![Diagram](image)

**Other Sources of Information**

- It turns out that the information on transistors in Schroder is not well organized. It is spread across multiple chapters.
- There are some other good sources of information on this subject if you are interested:
  - Review Articles:
    - [https://pubs.acs.org/doi/abs/10.1021/cr0501543](https://pubs.acs.org/doi/abs/10.1021/cr0501543)
    - [https://pubs.acs.org/doi/abs/10.1021/cm049391x](https://pubs.acs.org/doi/abs/10.1021/cm049391x)
  - Books:
  - Course
    - ECE 617 – Thin Film Electronics, John Labram, Fall 2020.
Lecture 16

• Introduction to Transistors.
• Types of Transistor.
• Inversion Mode FETs.
• Accumulation Mode FETs.
• Carrier Types.

Introduction to Transistors
What is a Transistor?

- The word *transistor* is a portmanteau of *transfer* and *resistor*.
- It is a 3-terminal electronic switch, whose resistance between 2 terminals is defined by the voltage applied to a third.

- Primarily they are used to either:
  - Amplify a signal.
  - Process information (when combined).

Water Analogy

- Consider an analogy of water flowing in pipes.
Water Analogy

• Consider an analogy of water flowing in pipes.
Water Analogy

• Consider an analogy of water flowing in pipes.

Source - Drain Flow

Gate Pressure

Flow Meter

Source - Drain Flow

Gate

Source

Gate Pressure

Drain
Electrical Behavior

- A transistor can be considered to behave in a similar way:

![Diagram of transistor with gate voltage, drain voltage, source-drain current, and ammeter connections.]
Electrical Behavior

• A transistor can be considered to behave in a similar way:

   ![Diagram of a transistor with labels for gate voltage, drain voltage, source-drain current, and gate voltage.]
Electrical Behavior

- Real transistors do not show this ideal behavior in reality:

Types of Transistor
Transistor Types

• Broadly there are two types of transistors.

Bipolar Junction Transistor

Field-Effect Transistor (FET)

• Their behavior is (basically) the same.
• Their operation mechanisms are significantly different however.

Bipolar Junction Transistors

• We will not be covering bipolar junction transistors (BJTs) in this course.
  • They are covered in the graduate-level course ECE616.
  • They are transistors formed of three adjacent regions of a semiconductor with different doping types:

![Bipolar Junction Transistor Diagram](image)

Fig. 1  Symbols and nomenclatures of (a) n-p-n transistors and (b) p-n-p transistors.

ECE / ChE 613 – Electronic Materials Characterization
Spring 2020 - John Labram
FET Family Tree

- Today we are going to be talking about field-effect transistors (FETs).
- There are several subcategories of FET (many more sub-divisions exist):

  - Field-Effect Transistor (FET)
  - pn-junction Gate FET (JFET)
  - Insulator-Gate FET (IGFET)
  - Metal-Semiconductor FET (MESFET)
  - Metal-Oxide-Semiconductor FET (MOSFET)
  - Heterostructure FET (HFET)

JFETs

- One type of FET is the Junction gate field-effect transistor (JFET or JUGFET).
- It is similar (but distinct) to a BJT.

- Formed of adjacent p-type and n-type regions
JFETs

- When placing a p-type and n-type semiconductor in contact, holes and electrons will cross the barrier and annihilate.

- This leads to a depletion region (i.e., a region with low carrier concentration) at the interface between the two materials.

JFETs

- In a JFET we therefore spontaneously create a depletion region between the n- and p-regions.

- This is also happens in pn-junction diodes.
  - E.g., ECE 615.

- If we apply a voltage between the source and drain ($V_{DS}$), current will flow between the terminals.
**JFETs**

- If a gate field \( V_{GS} \) is applied, the depletion width increases.
- The current flow is impeded.
- This is a **normally-on** (depletion-mode) device.
- There exist dual-gate JFETs as well.

**MESFETs**

- Another type of FET is the one is **Metal-Semiconductor FET (MESFET)**.
- The p-wells are heavily doped (essentially they are metallic).
- Similar concept to JFETs.
- Device also relies on depletion region.
### MESFETs

- As with a pn-junction, there is a transfer of charge across the interface.
- Holes close to the metal will cross the boundary.
- This leads to band bending, and depletion of the semiconductor.
- Technically, the carriers fill *surface states* on the Si.
- Phenomenologically the behavior is the same for our purposes. It is not important for our purposes.

As before, when a voltage is applied, current flows between source and drain.

- As with JFETs, the size of the depletion width can be controlled by the applied voltage.
- Resistivity of channel is controlled by gate voltage.
**IGFETs**

- An IGFET is a slightly more complicated structure.
- Between the gate and the semiconductor we have place an insulator.
- Each sub-category of IGFET has a different operating principle.

For silicon this can be easily grown as SiO₂.

The operation mechanism of IGFETs is distinct from JFETs and MESFETs.

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**HFETs**

- HFETs (heterostructure FETs), or HEMTs (High-electron-mobility transistor) rely on an interesting principle.

Recall in Lectures 14 & 15 we talked about the various operating regimes of MOS capacitors:

We notice the center of our HFET is similar to an MOS capacitor.
HFETs

- When talking about strong inversion (Lecture 15) we specified that $E_C$ is not below $E_{FS}$:

- An HFET is designed to go beyond strong inversion:

- I.e. we push $E_C$ below $E_{FS}$.

- We create a degenerate state at the interface.

HFETs

- In reality, to create such a situation requires a more complicated heterostructure transistor.

- These devices are beyond the scope of this course.

- Briefly, they enable one to turn on or off a metallic channel through $V_{GS}$.

- The accumulated channel is very thin, and exhibits 2-dimensional properties.

- We say there exists a 2-dimensional electron gas (2DEG) at the interface. Mobility is very high due to 2D transport.
MOSFETs

- Transistors used in integrated circuits are metal-oxide-semiconductor field-effect transistors (MOSFETs).

- There are a range of MOSFET structures.
- Today we will cover the standard MOSFET.

- Graduate courses on transistors: ECE616 (Semiconductor Devices II) and ECE617 (Thin Film Transistors).
MOSFETs

- As with JFETs and MESFETs, a p-type region in contact with an n-type region will lead to the existence of a depletion region.

- In a conventional MOSFET (not HFET) we want to invert the channel (as with our MOSCAP).
- To do this we would apply a positive voltage to the gate.

MOSFETs

- Under applied $V_{GS}$, inversion will occur.
- **Electrons** will accumulate under the gate.
- This is called an **inversion-mode** transistor.
- As long as $V_{DS}$ is small ($V_{DS} \ll V_{DS, Sat}$), the channel behaves like a resistor ($I_{DS} \propto V_{DS}$). The device is Ohmic.
- Measuring $I_{DS}$ as a function of $V_{DS}$ is called an **Output Curve**.
MOSFETs

- At higher values of $V_{DS}$ the fields will distort the depletion region.
- As the difference between $V_{DS}$ and $V_{GS}$ gets smaller, the inversion reduces.
- The charge density is non-linear, and the device is now non-Ohmic.

![MOSFET Diagram]

- As $V_{DS}$ increases further, the region with no carriers increases in size, and the pinch-off point moves across the channel.
- The pinched-off region has a very high resistance.
- Any extra applied voltage is dropped across the pinched-off region.
- Therefore the current is independent of $V_{DS}$ under these circumstances.
Gate Voltage Dependence

- What about the gate field?
- We know from our study of capacitors, that carrier density depends on band bending (and hence applied gate field):

Since conductivity $\propto$ carrier density, we find current increases with $V_{GS}$.

Measuring $I_{DS}$ as a function is called a transfer curve.

Quantitative description is complicated.
Accumulation Mode FETs

• The device we just described was an inversion mode MOSFET.
• I.e. electrons are transported in a p-type semiconductor.
• Could we instead make an accumulation mode FET?
• I.e. something that takes advantage of the accumulation regime we described when talking about capacitors?
Accumulation Mode FETs

- We could do this, but we cannot keep the n-wells.
- The energetic barrier between n and p regions is too high.
- If we got rid of them, we would have no depletion region.
- With the correct metals, holes could flow, but the on-off ratio would be low.
- Accumulation mode devices are instead made from (close to) intrinsic semiconductors.

Structure of TFTs

- Like an FET, a thin-film transistor (TFT) consists of three metal terminals, a semiconducting channel and an insulating dielectric.
- Source (S) and drain (D) electrodes are (normally) symmetric and in direct contact with the intrinsic semiconducting channel.
- Insulating dielectric separates semiconductor from 3rd (gate) terminal.
Thin Film Transistors (TFTs)

- What makes thin-films transistors (TFTs) “thin”?
- Transistors in integrated circuits are already thin.
- What we really mean when we talk about thin-film transistors, is that they are thin relative to their width.
- These figures are often not to scale, and can be misleading at first glance.

Structure of TFTs

- A wide range of FET structures exist.

Bottom-Gate, Top-Contact

- Semiconductor
- Dielectric
- Metal (Gate)

Bottom-Gate, Bottom-Contact

- Semiconductor
- Dielectric
- Metal (Gate)

Top-Gate, Bottom-Contact

- Gate
- Dielectric
- Substrate (Insulator)
Operating Principles of TFTs

• For our purposes we will consider a Bottom-Gate, Top-Contact TFT.

• The principles discussed are general.

• As are the models we discuss next lecture.

Operating Principles of TFTs

• Typically source electrode is grounded, voltages are applied to the drain and gate electrodes.
Operating Principles of TFTs

- First, let's consider structure under source electrode.

![Diagram of TFT structure]

- Conduction Band
- Valence Band

- Semiconductor
- Source
- Dielectric
- Metal
Operating Principles of TFTs

• First, let’s consider structure under source electrode.

Operating Principles of TFTs

• Typically source electrode is grounded, voltages are applied to the drain and gate electrodes.
Operating Principles of TFTs

• Application of gate voltage leads to injection of electrons into semiconductor, increasing conductivity.

\[
\begin{align*}
S & \quad \text{Source} \\
E & \quad \text{Dielectric} \\
D & \quad \text{Drain} \\
V_G & \quad \text{Gate Voltage} \\
V_D & \quad \text{Drain Voltage} \\
I_D & \quad \text{Drain Current}
\end{align*}
\]

Operating Principles of TFTs

• Application of drain voltage then leads to a flow of electrons between the source and drain electrodes.

\[
\begin{align*}
S & \quad \text{Source} \\
E & \quad \text{Dielectric} \\
D & \quad \text{Drain} \\
V_G & \quad \text{Gate Voltage} \\
V_D & \quad \text{Drain Voltage} \\
I_D & \quad \text{Drain Current}
\end{align*}
\]
Operating Principles of TFTs

• As $V_D$ increases relative to $V_G$, the field rotates and the distribution of accumulated charges changes.

\[ \text{Source-Drain Current ($I_D$)} \]
\[ \text{Drain Voltage ($V_D$)} \]

Operating Principles of TFTs

• As the distribution becomes inhomogeneous, relationship between $I_D$ and $V_D$ becomes non-linear.
Operating Principles of TFTs

- Eventually channel becomes “pinched off” and no carriers are present adjacent to drain electrode.

\[ V_S \quad V_G \quad V_D \]

\[ S \quad D \]

Dielectric

Metal (Gate)

Source-Drain Current \((I_D)\)

Drain Voltage \((V_D)\)

This region has very high resistance.

Operating Principles of TFTs

- Pinched-off point moves towards center of channel.

\[ V_S \quad V_G \quad V_D \]

\[ S \quad D \]

Dielectric

Metal (Gate)
Operating Principles of TFTs

- Further increasing $V_D$ will not substantially increase $I_D$ but leads to an expansion of the depletion region.

Output Characteristics

- Holding gate voltage constant and sweeping drain voltage.

$Lecture 16 – Wednesday May 13^{th} 2020$
Transfer Characteristics
• Holding drain voltage constant and sweeping gate voltage.

Carrier Types
Polarity of Transistors

- Unlike materials, the type of transistor is determined by the relative position of conduction and valence bands relative to work function of electrodes.

N-Type Transistors

- N-type transistors transport electrons but not holes.
P-Type Transistors

- P-type transistors transport holes but not electrons.

Ambipolar Transistors

- Ambipolar (sometimes called bipolar) transistors are unique in that they can inject and transport both holes and electrons, under the correct biasing conditions.
Next Time...

- FETs Characteristics.

- Quantifying FETs, and extracting parameters.

\[ I_D = \frac{W}{L} \mu C_{ox} \left[ (V_G - V_T) V_D - \frac{V_D^2}{2} \right] \]