Lecture 13
Ambipolar TFTs

Announcements

Homework 6/10:
• Is online now.
• Due Monday November 9th at the start of the lecture (2:00pm).
• I will return it one week later (November 16th).
• Homework 5 consists of content covered in Lectures 11 and 12.
Lecture 13

• Ambipolar TFTs.
• Ambipolar TFT Operation
• Current-Voltage Characteristics.
• Modelling Ambipolar TFTs.
• Routes to Ambipolarity.

Additional Information

• Brotherton does not really have any information on this subject.
• There are some reviews. The below is one of the best on the subject:

  Electron and Ambipolar Transport in Organic Field-Effect Transistors
  
  Jana Zaumseil and Henning Sirringhaus*
  Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom

  July 31, 2006

  • [https://pubs.acs.org/doi/abs/10.1021/cr0501543](https://pubs.acs.org/doi/abs/10.1021/cr0501543)
Ambipolar TFTs

Charge Injection

- So far we have just talked about n-type or p-type transistors.
- N-type TFTs inject and transport electrons only.
- P-type TFTs inject and transport holes only.
Charged Injection

- Last lecture (Lecture 12) we talked about how injection barriers ($\phi_B$) determine whether or not we can inject charge into our semiconductor.

\[ \begin{align*}
E_F & \quad E \\
\text{Metal} & \quad \phi_B \\
\text{Semiconductor} & \\
\end{align*} \]

\[ \begin{align*}
E_F & \quad E \\
\text{Metal} & \quad \phi_B \\
\text{Semiconductor} & \\
\end{align*} \]

N-Type Transistors

- N-type transistors have a small offset between metal work function and semiconductor CBM.
P-Type Transistors

- P-type transistors have a small offset between metal work function and semiconductor VBM.

![Diagram of P-Type Transistor]

Ambipolar Transistors

- If the both injection barriers are low, then we could (under the correct biasing condition) inject carriers into both the valence band, and the conduction band.

![Diagram of Ambipolar Transistor]
Ambipolar Transistors

- So why would we want ambipolar TFTs?
- We will cover this in the next lecture (and Lecture 17), but we will briefly mention one reason now.
- The first is to do with complementary logic:
- We will see next week (Lecture 14) that for complicated logic circuits, with high yield, we need complementary logic.
- I.e. we need both p-type and n-type transistors.

Complementary Inverters

- Consider this top-down view of a complementary inverter:
- Normally this would require spatially resolved n- and p-type semiconductors.
- I.e. we would need some sort of masking or local deposition → higher cost.
Complementary Inverters

- With an ambipolar semiconductor we could just deposit it everywhere:

- This is a lot more simple from a manufacturing point of view.
- Enables potentially lower costs.

Ambipolar Transistors

- But what happens when you apply voltages to such a transistor?
- The current-voltage characteristics are at first-glance a little surprising.
Ambipolar Transistors

- But what happens when you apply voltages to such a transistor?
- The current-voltage characteristics are at first-glance a little surprising.

![Graph showing ambipolar transistor characteristics.](image)

Ambipolar TFT Operation
Unipolar Characteristics

• Before we talk about the current-voltage characteristics of ambipolar TFTs, let's remind ourselves of why we observe the IV characteristics in a unipolar device.

• We will start with an electron-transporting device (n-type).

• This is standard operation (where both $V_D > 0$ and $V_G > 0$).

Unipolar Characteristics

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

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

- Application of drain voltage then leads to a flow of electrons between the source and drain electrodes.
Operating Principles of FETs

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

Operating Principles of FETs

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

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

This region has very high resistance

Operating Principles of FETs

- Pinched-off point moves towards center of channel.
Operating Principles of FETs

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

Operating Principles of FETs

- This is standard behavior (both $V_D$ and $V_G$ same sign).
**Ambipolar TFTs**

- Now consider a device which we can inject and transport both electrons and holes.
- Start with **linear regime**:

\[
V_D > 0, \, V_D < V_G - V_{Te} \quad \text{or} \quad V_D < 0, \, V_D > V_G - V_{Th}
\]

![Diagram of ambipolar TFT with red and blue labels for electrons and holes](image)

**Threshold Voltage**

- We know the injection barrier is not necessarily going to be the same for electrons and holes:

\[
\phi_B(e^-) \neq \phi_B(h^+)
\]
- So the injection properties for holes and electrons are not necessarily going to be the same.
Threshold Voltage

- We also know the trap states are not going to be the same for electrons and holes.
- For these reasons, we cannot assume that the threshold voltage will be equal for holes and electrons.

\[ V_{Te} \neq V_{Th} \]

- Sometimes it is however convenient to say \( V_{Te} = V_{Th} \)

Operating Regimes

\[ V_D = V_G - V_T \]

\[ V_G - V_T \]

To conceptually make this more simple we will set \( V_{Th} = V_{Te} \)
Operating Regimes

- But what happens when the voltages we apply are not the same sign?
  - E.g. if $V_D$ is positive and $V_G - V_T$ is negative.
  - Or if $V_G - V_T$ is positive and $V_D$ is negative.
- For unipolar TFTs there is no situation when you would normally do this.
- However, we cannot understand the behavior of ambipolar TFTs without considering these regimes.

Opposite Voltages

- Consider an ambipolar TFT where we apply the following voltages:
  - $V_G - V_{Te}$ is positive.
  - $V_D$ is negative.
  - $V_G - V_{Th} > V_D$.
- What happens?
- First thing to remember is that voltages are relative.
  - E.g. when we say drain voltage we really mean voltage drop between source and drain.
Voltage Transformation

• Consider the voltage dropped across the terminals.
• Let: \( \Delta V = V_2 - V_1 \).

\[ \Delta V = V_G - V_{Te} \]

\[ \Delta V = V_D \]

\[ \Delta V = V_G - V_{Te} - V_D \]

Voltage Transformation

• This is easier to visualize with a numerical example:
• As before, let: \( \Delta V = V_2 - V_1 \).

\[ \Delta V = +10V \]
Voltage Transformation

• We can equivalently add or remove any voltage to all terminals.

• This will not affect the relative voltages, but can make the situation conceptually easier to visualize.

\[ V_G - V_{Te} > 0 \]
\[ V_D < 0 \]
\[ -10V \]

Subtract \( V_D \)

\[ V_G - V_{Te} - V_D \]
\[ +20V \]

Voltage Transformation

• So, by applying a positive voltage to one terminal, and a negative voltage to another, we are essentially applying a bigger voltage across these terminals.

• Looking at this example, we can identify it as a transistor operating in unipolar (n-type) regime, just with source and drain swapped.

• Current is now flowing the wrong way!
Operating Regimes

\[ V_D = V_G - V_T \]

Voltage Transformation

- Now consider the opposite situation:
  - \( V_G - V_{Th} \) is negative.
  - \( V_D \) is positive.
  - \( V_G - V_{Te} < V_D \).

This ensures we don't inadvertently get electron injection.
**Voltage Transformation**

- So, by applying a negative voltage to one terminal, and a positive voltage to another, we are essentially applying a bigger voltage across these terminals.

![Image of a transistor with voltage transformation](image)

- Looking at this example, we can identify it as a transistor operating in unipolar (p-type) regime, just with source and drain swapped.

- Current is again flowing the wrong way.

**Operating Regimes**

![Diagram showing operating regimes](image)
Saturation Regime

- So far we haven’t considered what happens in an ambipolar TFT when it saturates.
- First, remind ourselves how unipolar TFTs behave at saturation:
  \[ V_D > 0, \ V_D > V_G - V_{Te} \quad \text{and} \quad V_D < 0, \ V_D < V_G - V_{Th} \]

Ambipolar TFT

- Now let’s consider an ambipolar TFT.
- Let’s apply the voltages for saturation regime (electron transport).
  - \( V_G - V_{Te} \) is positive.
  - \( V_D \) is positive.
  - \( V_D > V_G - V_{Te} \).
  - We will see electron pinch-off in the channel.
  - We also now have to be aware of hole injection...
Voltage Transformation

• Let’s apply our voltage transformation again, and see what the TFT looks like from the drain’s perspective.

• Now it is important to also know the threshold voltage for holes.

Voltage Transformation

• If the voltage drop between the gate and the drain is able to overcome the threshold voltage for holes then we should also get injection of holes from the drain.

• i.e. if \( V_G - V_{th} - V_D < 0 \)

• For example if:
  • \( V_D = +50V. \)
  • \( V_G = +15V. \)
  • \( V_{Te} = +5V. \)
  • \( V_{Th} = -5V. \)
NP-Junction

- Under the correct biasing conditions, we observe both electrons and holes in the channel simultaneously!
- What happens when electrons and holes meet?

\[ V_G - V_{th} < V_D \]

- Electrons and hole recombine.
- We should expect light emission.

Light Emission

- What is observed experimentally?
- Let’s take a look at this work from Cambridge.
Light Emission

- What is observed experimentally?
- Let’s take a look at this work from Cambridge.
Operating Regimes

\[ V_D = V_G - V_T \]

· Dielectric
· Metal (Gate)

Ambipolar TFT

· For completeness let’s also consider the opposite situation.
· Apply the voltages for saturation hole regime.
  · \( V_G - V_{Th} \) is negative.
  · \( V_D \) is negative.
  · \( V_D < V_G - V_{Th} \).
· In this case we will see hole pinch-off in the channel.
Voltage Transformation

- As usual, apply our voltage transformation to view the biasing conditions relative to the drain.

\[ V_G - V_{Th} > 0 \]

\[ -10V \]

\[ V_G - V_{Th} - V_D \]

\[ +40V \]

Voltage Transformation

- If the voltage drop between the gate and the drain is able to overcome the threshold voltage for electrons then we should also get injection of holes from the drain.

\[ V_G - V_{te} - V_D > 0 \]

- I.e. if \( V_G - V_{te} - V_D > 0 \)

- For example if:
  - \( V_D = -50V \).
  - \( V_G = -15V \).
  - \( V_{Te} = +5V \).
  - \( V_{Th} = -5V \).
Operating Regimes

\[ V_D = V_G - V_T \]

Current-Voltage Characteristics
**IV Characteristics**

- What does this behavior mean for IV characteristics?
- Recall, for a unipolar TFT the behavior is as follows:

  - \( V_D \approx 0V \)
  - \( V_D < V_G - V_{Te} \)
  - \( V_D > V_G - V_{Te} \)

**What happens if increase the drain further?**

  - \( V_D > V_G - V_{Te} \)
  - \( V_D < V_G - V_{Th} \)
  - \( V_D > V_G - V_{Th} \)
  - \( V_D > V_G - V_{Th} \)
IV Characteristics

- So strangely enough ambipolar TFTs will return to being in a linear regime again.

The size of the saturation region depends on the difference between threshold voltages: $V_{Te} - V_{Th}$.

This is what is observed experimentally.
IV Characteristics

- The transfer characteristics typically look like this:
- The easiest way to understand transfer curves is to go back to the output curves and consider how \( I_D \) changes with \( V_G \).

\[ V_D = 10\text{V}. \]
\[ V_D = 40\text{V}. \]

Mobility Evaluation

- So what does this mean for evaluating the mobility of charge carriers?
- At low drain voltages (\( V_D \ll V_G - V_T \)) only one type of carrier is present
- The devices behave like they are unipolar.
GCA

- So we can just use the standard form of the gradual channel approximation, and proceed as usual:

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

- In the linear regime:

\[ |V_D| \ll |V_G - V_T| \quad \Rightarrow \quad (V_G - V_T)V_D \gg \frac{V_D^2}{2} \]

\[ I_D = \frac{W}{L} \mu_{lin} C_{ox} (V_G - V_T)V_D \quad \Rightarrow \quad \mu_{lin} = \frac{L}{W C_{ox} V_D} \frac{dI_D}{dV_G} \]

GCA

\[ I_D = \frac{W}{L} \mu_{lin} C_{ox} (V_G - V_T)V_D \quad \Rightarrow \quad \frac{dI_D}{dV_G} = \frac{W}{L} \mu_{lin} C_{ox} V_D \]

\[ \mu_{lin} = \frac{L}{W C_{ox} V_D} \frac{dI_D}{dV_G} \]

- So as long as we are careful about where we evaluate mobility, we can safely evaluate linear mobility.
GCA

• What about in the saturation regime?
• For a unipolar device we have to assume $I_D$ is not dependent on $V_D$.
  • I.e. the effective voltage is $V_D = V_G - V_T$.

For this assumption to be valid, the channel must be pinched off.

GCA

• For ambipolar TFTs we know that this is not generally true.
• The devices may saturate for a short period, but will return to a second linear regime at higher gate voltages.
• Unfortunately, to accurately model ambipolar TFTs we need a slightly more complex model.
Modelling Ambipolar TFTs

Smits Model

- So we have seen the gradual channel approximation does not encapsulate the behavior of ambipolar TFTs in the saturation regime.
- To accurately model the current-voltage characteristics of an ambipolar TFT we need to use a slightly more complex model.
- We are not going to derive it. We are just going to use the main results.
- I am calling this the Smits Model, as the first author on the relevant paper is Edsger Smits.\(^1\)
- We can consider this GCA+.

Smits Model

- Let’s start by considering this model under unipolar conditions for an **n-type only device**:

\[ I_D = \gamma \frac{W}{L} \frac{T}{2T_0} \frac{T}{2T_0 - T} \left[ (V_G - V_T)^{2T_0/T} - (V_G - V_T - V_D)^{2T_0/T} \right] \]

- \( I_D \): Magnitude of the drain current (no direction).
- \( W \): Channel width.
- \( L \): Channel length.
- \( V_G \): Gate voltage.
- \( V_T \): Threshold voltage.
- \( k_B T_0 \): Width of density of states for this transport state.

\[ \gamma = \frac{\sigma_0}{e} \left( \frac{T_0/T}{(2\alpha)^3 B_c} \right)^{T_0/T} \left( \frac{1}{2k_B T_0 \varepsilon_r \varepsilon_0} \right)^{(T_0/T)^{-1}} \]

- \( \sigma_0 \): Prefactor of conductivity.
- \( e \): Fundamental unit of charge.
- \( \alpha \): Wavefunction overlap parameter.
- \( \varepsilon_0 \): Vacuum permittivity.
- \( \varepsilon_r \): Relative permittivity.
- \( C_i \): Areal capacitance.
- \( k_B \): Boltzmann constant.
- \( B_c \): Critical parameter for percolation.

≈2.8 for amorphous 3-dimensional systems
**Smits Model**

- Because we now need to explicitly consider the sign of voltages, we need a different equation for holes and electrons.

- For electrons we have:
  \[ I_D = \gamma \frac{W}{L} \frac{T}{2T_0} \frac{T}{2T_0 - T} \left[ (V_G - V_T)^{2T_0/T} - (V_G - V_T - V_D)^{2T_0/T} \right] \]

- For holes we have:
  \[ I_D = \gamma \frac{W}{L} \frac{T}{2T_0} \frac{T}{2T_0 - T} \left[ (V_T - V_G)^{2T_0/T} - (V_T - V_G + V_D)^{2T_0/T} \right] \]

- For this model we have to assume \( V_{Te} = V_{Th} \equiv V_T \).

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**Smits Model**

- Even though we know, conceptually, that \( V_{Te} \) and \( V_{Th} \) should be distinct, we do need to enforce they are equal \( (V_T) \) for this model.

- Since \( T_0, \sigma_0, \alpha, \) and \( \mu \) are all properties of a semiconductor band, they are specific to each carrier type. And they are treated this way in the model.

  \[ I_D = \gamma_e \frac{W}{L} \frac{T}{2T_{0e}} \frac{T}{2T_{0e} - T} \left[ (V_G - V_T)^{2T_{0e}/T} - (V_G - V_T - V_D)^{2T_{0e}/T} \right] \]

  \[ I_D = \gamma_h \frac{W}{L} \frac{T}{2T_{0h}} \frac{T}{2T_{0h} - T} \left[ (V_T - V_G)^{2T_{0h}/T} - (V_T - V_G + V_D)^{2T_{0h}/T} \right] \]
Ambipolar Operation

- The purpose of studying this model is to quantify the behavior of ambipolar TFTs when both holes and electrons are present in the device simultaneously.

- How do we use the equations from the previous slide to quantify behavior under these conditions?

Ambipolar Operation

- When both carriers are present, the channel will not saturate, but the position of the interface will move in the channel.

- We can consider this a pn-junction in our transistor channel.
Ambipolar Operation

- If we assume the recombination rate at the interface between the p-channel and n-channel is infinite, we can just equate source-drain currents.

\[
I_D = \gamma_e \frac{W}{L} \frac{T}{2T_{0e}} \frac{T}{2T_{0e}} - \frac{T}{T} \left[ (V_G - V_T)^{2T_{0e}/T} - (V_G - V_T - V_D)^{2T_{0e}/T} \right]
\]

\[
= \gamma_h \frac{W}{L} \frac{T}{2T_{0h}} \frac{T}{2T_{0h}} - \frac{T}{T} \left[ (V_T - V_G)^{2T_{0h}/T} - (V_T - V_G + V_D)^{2T_{0h}/T} \right]
\]

Majority & Minority Carriers

- The result of setting these currents equal depends on which way we bias the device however.
- I.e. which carrier is the majority carrier.

- So the majority carrier is the one we would expect to flow in a unipolar device, under these biases.
Majority & Minority Carriers

- We say the carrier that flows conventionally (i.e. from the source to the drain) is the **majority carrier**.
- We say the carrier that flows the opposite direction (i.e. from the drain to the source) is the **minority carrier**.

\[ e^- \quad V_D > 0 \]

\[ V_G - V_T > 0 \]

\[ V_D > 0 \]

\[ V_G - V_T > 0 \]

Smits Model

- It is easy to evaluate the following relationships by setting \( I_D = I_D \):
- For electron majority carriers (i.e. positive \( V_D \) and \( V_G - V_T \)):
\[
I_D = \frac{W}{L} \left[ \gamma_e \frac{T}{2T_{0e}} \frac{T}{2T_{0e} - T} (V_G - V_T)^{2T_{0e}/T} + \gamma_h \frac{T}{2T_{0h}} \frac{T}{2T_{0h} - T} (V_D - V_G + V_T)^{2T_{0h}/T} \right]
\]
- For hole majority carriers (i.e. positive \( V_D \) and \( V_G - V_T \)):
\[
I_D = \frac{W}{L} \left[ \gamma_h \frac{T}{2T_{0h}} \frac{T}{2T_{0h} - T} (V_T - V_G)^{2T_{0h}/T} + \gamma_e \frac{T}{2T_{0e}} \frac{T}{2T_{0e} - T} (V_T - V_G + V_D)^{2T_{0e}/T} \right]
\]
Experimental Results

- This model has had success in modelling the properties of ambipolar TFTs.

![Graphs showing experimental results]

Parameter | $T_0$ (K) | $\sigma_0$ (10$^6$ S/m) | $\sigma$ (Å) | $\mu$ [cm$^2$/Vs]
--- | --- | --- | --- | ---
NiDT holes 600 | 1.9 | 2.1 | $2.5 \times 10^{-4}$
NiDT electrons 460 | 0.78 | 0.9 | $2.0 \times 10^{-5}$


Routes to Ambipolarity
Ambipolar TFTs

• So how do we actually make an ambipolar TFT?
• We have already described the most obvious way: use a low-band gap semiconductor.
• We just need both injection barriers ($\phi_B (e^-)$ and $\phi_B (h^+)$) to be low enough for good injection.
• There are some materials which this is the case.

There are plenty of organic semiconductors which have small enough band gaps (< 1eV).
• With gold source and drain electrodes we can access both the HOMO (~valence band) and LUMO (~conduction band).
Ambipolar TFTs

- There are other systems which can be used for ambipolar TFTs.
- We briefly talked about metal halide perovskites before (Lecture 9).
- They are a new class of materials studied mainly for solar cells.

Ambipolar TFTs

- They have been used in p-type, and n-type transistors

Labram et. al. JPCL 18 (2015) 3565
Ambipolar TFTs

- They have also been used in ambipolar TFTs:

Multiple Electrodes

- Bilayer electrodes is one strategy to inject into both the conduction band and valence band.

  - Another is to use asymmetric electrodes.
  - I.e. source and drain are not the same metal.
Asymmetric Electrodes

- For this structure, we use one electrode to inject holes into the VB and one to inject electrons into the CB.

Kanagasekaran et. al. Nature Comms. 8 (2017) 999

Asymmetric Electrodes

- Since electrons flow downhill and holes flow uphill, extraction is not a problem.
- We can only use this device in one direction.
  - n-type from left to right.
  - p-type from right to left.

Chin et. al. Nature Comms. 6 (2015) 7383

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Multiple-Semiconductor TFTs

• Instead of using multiple electrodes, we could adopt the analogous approach by using a single electrode and two semiconductors.

• The first examples of this involved bilayer (evaporated) organic semiconductors.

For these first examples the mobility was quite low ($\sim 10^{-3} \text{ cm}^2/\text{Vs}$)
**Bilayer Semiconductor TFTs**

- There are a few important subtleties that need to be considered with bilayer TFT.
- We now have a separate channel for each type of charge.
- We essentially have two unipolar TFTs in parallel.
- It should be possible for the TFTs to saturate now.

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**Bilayer Semiconductor TFTs**

- This is generally what is observed: normal saturation.

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Bilayer Semiconductor TFTs

- We also need to be careful in analysis.
- The effective dielectric for each channel is now different.
- From Lecture 11 we saw the areal capacitance is:
  \[ C_{ox} = C_i = \frac{\varepsilon_0 \kappa}{d} \]
  - Hence for different carrier type we need to use a different value of \( C_{ox} \).

Bilayer Semiconductor TFTs

- Contact resistance depends on interfacial area between the semiconductor and electrodes.
  \[ R_c = \frac{\rho_i}{A} \]
  - Aside from injection barriers \( (\phi_B) \), we can also expect the contact resistance to depend on relative position of electrodes.
Blend TFTs

- Another option is to create a random, interpenetrating network of two semiconductors.
- This has been done for solution-processed organic semiconductors.

Blend TFTs

- This system exhibited ambipolarity.
  - Distinctive output characteristics.
    - Evidence of both carriers present in the channel at once.

Next Time...

- Integrated Circuits

\[ V_{DD} \]

\[ V_{in} \quad V_{out} \]

P-Type

N-Type

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97/97