Announcements

Homework 8/10:
- Is due now.

Homework 9/10:
- Is online now.
- Due **Monday November 30th at the start of the lecture (2:00pm)**.
- I will return it one week later (December 7th).
- Homework 9 consists of content covered in Lectures 16 and 17.
Lecture 17

• Phototransistors.
• Phototransistor Operation.
• Characterizing Phototransistors.
• Designing Phototransistors.

Additional Information

• Unfortunately, there is not much information out there on phototransistors – it is very much an emerging area.
• The below is a review is probably the best source of information but is not complete.

Organic Light Detectors: Photodiodes and Phototransistors
Kong-Jun Baeg, Maddalena Binda, Dario Natoli, Mario Cairoli,* and Yong-Young Noh*

Phototransistors

• If transistors are capable of emitting light, they should also be capable of detecting light.
• We call these devices either light-sensing thin film transistors (LSTFTs), or phototransistors.
• Unlike light-emitting transistors, phototransistors do not need to be ambipolar to work.
  • Although many are ambipolar it turns out.
Photodiodes

- Before we consider phototransistors, let's briefly talk about the incumbent technology: photodiodes.
- The most common large-area detectors at present are X-Ray Detectors.

- They need to image a large area with parallel beams.

Optical Photodiodes

- Most optical detectors are based on charge-coupled device (CCD) sensors.

- Lenses are used to focus light from wide image onto the small CCD.
Optical Photodiodes

- However groups are interested in flexible image sensor arrays.

- These devices require large-area image sensor arrays.
- The traditional approach is to use photodiodes.

The normal signal detection method is to detect light using a photodiode, then use a TFT to amplify the signal → process information.

Something like this is common:

- Interconnects
- Blocking layers
- Substrate
- Dielectric
- Source / Drain Electrodes
- Transparent conductor
- Passivation
- Gate Electrode
- Semiconductor
- Photodiode
- TFT
Optical Photodiodes

- Why are photodiodes used?

- They are have a current density \( \propto \) optical power density.

- They are easy to understand.

This sort of structure required multiple deposition and masking steps.

Often with different semiconductors.
Phototransistors

- The motivation for phototransistors is to combine detection and amplification into a single circuit element.

- This could reduce number of masking steps.
- Significantly reduce cost.

Phototransistor Operation
Phototransistors

- How do we make a phototransistor?
- Most transistors will respond to light in some way.
- Often this is unwanted or unpredictable.

![Phototransistor Diagram]

IGZO:

![IGZO Diagram]

Phototransistors

- Most TFTs are phototransistors by accident.
- It is hence important to be able to understand and control the photo-response of TFTs.
- I.e. we need to know how the drain current \( I_D \) changes as we change illumination conditions.
- It turns out that the applied voltages (both \( V_G \) and \( V_D \)) strongly effect measured \( I_D \).
- This is unlike photodiodes, which are broadly insensitive to biasing conditions.
Photoconductive Effect

• There are three mechanisms which result in changes in drain current.
• The first is generally referred to as the photoconductive effect.
• Direct generation of charge carriers in channel contribute to $I_D$.

![Diagram of a transistor with labeled components and an applied voltage $V_D > 0$.]

Photoconductive Effect

• This is essentially the same mechanism by which solar cells generate usable power from light.

![Diagram of a solar cell with labeled energy levels $E_{CBM}$, $E_{VBM}$, and $E_G$.]
**Photoconductive Effect**

- So what happens in a TFT under the photoconductive effect?
- Start with no applied gate voltage ($V_G = 0V$).

\[ V_D > 0 \]

- Photogenerated current will directly contribute to $I_D$.
- Off-current will increase.

\[ V_D \approx 0 \]

**Photoconductive Effect**

- What about applied gate voltages (assume n-type)?

\[ V_D > 0 \]

\[ V_G > 0 \]

- We now have a perpendicular field component.
- In this example, photo-generated electrons will be pulled into the channel, and holes will be repelled out of the channel.
Photoconductive Effect

- Electrons directly contribute to current.
- Holes are repelled out of the channel.
- The may end up filling trap states, being swept out of the device, or making it to the source terminal.

Photoconductive Effect

- What happens at high carrier density?
- When current is high, a lot of electrons are present.
- Photo-generated electrons just add to current.
- Photo-generated holes are more likely to recombine as current increases. **Charge generation rate drops.**
Current Voltage Characteristics

- So what does this mean for current-voltage behavior?
- At low gate voltages, generated carriers directly contribute to $I_D$.
- I.e. light increases off current.
- When current is high, recombination is high. Current generation rate is reduced.

Response Times

- An important question for any type of light-sensor is how fast does the device respond to light?
- The process of a photon converting to an electron-hole pair is extremely fast ($<\text{ps}$).
- So in theory we could go from incident light to detectable current very quickly.
Response Times

• In a TFT structure we are limited by:
  • Carrier transit time, \( v = \mu E \),

  which depends on mobility (\( \mu \)) and applied fields (\( E \)).

  • TFTs are also implicit parallel-plate capacitors (as we have seen previously) in series with a resistor.

  • So they have an RC time constant:

\[
\tau = RC
\]

Response Times

• At present, the response times of photo-TFTs under the photoconductive effect are modest.

• Reducing capacitance and/or shortening channels can improve response times.
Photovoltaic Effect

• The second process is called the **photovoltaic effect**.
  • Although it has nothing to do with how photovoltaic cells (solar cells) work.
  • It is an unfortunate name.
  • This process is due to photo-induced trapping and de-trapping.
  • It is an effect that will shift the threshold voltage of TFTs under illumination.
  • We also do not need photons with $h\nu > E_g$ necessarily.

Photovoltaic Effect

• This process simply changes the background charge density.
  • And hence the threshold voltage.
Photovoltaic Effect

- We have seen this already for metal oxide transistors in Lecture 7.

\[ V_{GS} = 10V \]

![Graph showing dark and illuminated conditions](image)

- At certain gate voltages, the response can be enormous. Essentially we are photo-gating the TFT.

- Here we are getting gain in our measurement.
  - I.e. we can get quantum efficiencies > 100%.

\[ I_{DS} = 1.0 \times 10^{-10} A \]

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


Response Times

- Unlike the photoconductive effect, in this effect (photovoltaic) we are not directly generating carriers.
- We are relying on the filling and emptying of trap states.
- This can be an extremely slow process.

![Graph showing response times](image)

Photo-Assisted Injection

- The third process is photo-excitation of carrier from source / drain electrodes into the semiconductor.
- While the energy is not enough to ionize the metal, it can reduce an injection barrier.
  - Improve injection / reduce contact resistance.

![Diagram showing photo-assisted injection](image)
Photo-Assisted Injection

• Groups have studied the effect of selectively illuminating source and drain electrodes.

• This effect shifts threshold voltage, so can be considered analogous to the “photovoltaic” effect.

Characterizing Phototransistors
Responsivity

- How do we quantify the response of TFTs to light?
- The parameter we most often see is responsivity ($R$).
- It is simply the ratio of photo-generated current ($I_{PH}$) to incident optical power ($P$). It has units A/W.

$$R = \frac{I_{PH}}{P} = \frac{I_{D,ill} - I_{D,dark}}{P_iLW}$$

- $I_{D,ill}$: drain current under illumination
- $I_{D,dark}$: drain current in dark.
- $L, W$: TFT Channel length and width, respectively.
- $P_i$: Optical power density (e.g. mW/cm$^2$)

External Quantum Efficiency

- Alternatively, we can quantify behavior via $\eta$

$$\eta = \frac{(I_{D,ill} - I_{D,dark})hc}{eP_iLW}$$

- $\eta$: External quantum efficiency (EQE) $\in [0,1]$.
- $h$: Planck constant.
- $c$: Speed of light in vacuum.
- $e$: Magnitude of fundamental unit of charge.
- These are equivalent variables, $\eta \propto R$. 
**EQE / Responsivity**

- The interesting thing about phototransistors is illustrated below:

- The increase in $I_D$ **depends on the applied gate voltage**.
- Hence the responsivity and EQE also depend on $V_G$.

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**EQE / Responsivity**

- So this is a very interesting feature.
- We are able to modify the responsivity of our device by changing the applied $V_G$.
- Hence we can define how sensitive our sensor is through user-defined electrical signals.
- There is no analog for this property in photodiodes.
Photocurrent

- The photocurrent is modeled according to the dominant mechanism:
- **Photoconductive Effect:**
  \[ I_{PH} = e \mu n E W d \]
  - \( I_{PH} \): Photocurrent.
  - \( \mu \): Charge carrier mobility.
  - \( n \):Carrier density in the channel.
  - \( E \): Magnitude of the electric field in the channel.
  - \( W \): Channel width.
  - \( d \): The channel thickness.

- **Photovoltaic Effect:**
  \[ I_{PH} = g_M \Delta V_T \]
  - \( I_{PH} \): Photocurrent.
  - \( g_M \): Transconductance at applied gate voltage.
  - \( \Delta V_T \): Change in threshold voltage.
Transconductance

- We implicitly evaluate transconductance when we carry out mobility extraction.
- It is the conductance of the transfer curve:

\[ g_m = \frac{\partial I_D}{\partial V_G} \]

- We can write our equation for linear mobility (as derived from the gradual channel approximation) as:

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

Photocurrent

- Photovoltaic Effect:

\[ I_{PH} = g_M \Delta V_T = \frac{\alpha k_B T}{e} \ln \left( 1 + \frac{\eta \lambda P}{I_{D,\text{dark}} hc} \right) \]

- \( \alpha \): Constant.
- \( k_B \): Boltzmann Constant
- \( T \): Temperature.
- \( e \): Magnitude of fundamental unit of charge.
- \( I_{D,\text{dark}} \): drain current in dark.
- \( \eta \): EQE.
- \( \lambda \): Wavelength.
- \( P \): Optical Power.
- \( h \): Planck Constant.
- \( c \): Speed of light.
Designing Phototransistors

Phototransistors

- To make a phototransistor we normally just need to make a transistor.
  - Most TFTs will exhibit some photoresponse.
  - So the more important question is how do we make a good **phototransistor**?
    - High responsivity.
    - High wavelength selectivity.
    - Fast response time.
Phototransistors

- To achieve fast response we need an effective means to separate holes from electrons.

- The applied gate field is effective in separating charge.
- Can enhance separation with two semiconductors.

Bilayer TFTs

- We can spatially separate the semiconductors using bilayer ambipolar TFTs:
Bulk Heterojunctions

- In organic solar cells, two interpenetrating networks of p-type and n-type semiconductors are used.

- The interface between these two semiconductors is used to separate the charges.

Bulk Heterojunctions

- The same approach can be applied to phototransistors.
Oxide Phototransistors

- Traditionally metal oxides don’t make very good phototransistors.
- One of their main attractions is they are optically transparent.

\[ E_C \approx 3.25 \text{ eV} \]

Dye-Sensitized TFTs

- However we can modify them with organic dyes.
- The dye is designed to absorb only green light.
- Charges are transferred from dye to ZnO.
Perovskites

- We have seen that metal halide perovskites have excellent absorption properties.
- So they are natural candidates for phototransistors.
- They have low exciton binding energy.
- This means you don’t necessarily need two materials to separate charges.

Next Time...

- We will study some of the specific problems of flexible electronics.