Announcements

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 18

• Flexible Electronics.
• Device Development.
• Device Flexibility.
• Plastic Electronics.
• Applications.

Additional Sources

• This is a subject the course textbook (Brotherton) does cover.
• Chapter 11.
• The textbook goes into quite a lot of depth on the subject.
• This is an active area of research so some of the content is out of date.
Additional Information

- This is also a very good review on oxide TFTs, with a focus on flexible applications

Applied Physics Reviews A 021303 (2016)

Metal oxide semiconductor thin-film transistors for flexible electronics

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Giuseppe Cantarella,3 Francesca Bottacchi,3 Thomas D. Anthopoulos,3
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2Sensor Technology Research Centre, University of Sussex, Falmer, United Kingdom
3Department of Physics and Centre for Plastic Electronics, Imperial College London, London,
United Kingdom


Additional Information

- There are journals dedicated to the subject of flexible electronics:

https://www.nature.com/npjflexelectron
Flexible Electronics

TFT Backplanes

- We have previously talked about TFT’s main commercial application at present: display backplanes.

https://www.youtube.com/watch?v=yuU105p09s
Flexible Electronics

• But we hope that one day we can create electronic products that are mechanically flexible.

Samsung Infinity Flex

• A couple years ago saw the release of the first flexible phone / tablet prototype from Samsung.

https://www.youtube.com/watch?v=t0NbSPmIo20
Flexible Electronics

- We have learnt a lot about TFTs generally, but what do we need to consider when we move from rigid, planar, devices to flexible and conformal electronics?

Device Development
Materials

• Before we talk about device behavior, we first need to address how to make mechanically flexible TFTs?
• We know we cannot use glass as a substrate.

• So we need to identify substrates and semiconductors which are mechanically flexible.

Young’s Modulus

• The best way to quantify a material’s ability to withstand mechanical deformations is via it’s Young’s Modulus.
• We will not spend too long on what exactly Young’s modulus is. We will treat it as a way to quantify the stiffness of a material.
• The Young’s modulus ($Y$) is ratio of stress to strain:
  \[ Y = \frac{\sigma}{\varepsilon} \]
• $\sigma$: Stress.
• $\varepsilon$: Strain.
Strain

- Strain ($\varepsilon$) is defined as the change in length divided by original length.

\[ \varepsilon = \frac{L_n - L_0}{L_0} \]

- I.e. strain is dimensionless.

Stress

- Stress is just the force per unit area applied to create the deformation.

\[ \sigma = \frac{F}{A} \]

- Stress has units of pressure (e.g. Pascals).
Young’s Modulus

- The Young’s modulus \( (Y) \) is ratio of stress to strain:
  \[
  Y = \frac{\sigma}{\varepsilon}
  \]

- Systems with high \( Y \) have high stiffness:

- Systems with low \( Y \) have low stiffness:

For anisotropic materials \( Y \) will depend on directions.
- In this case, \( Y \) will be a tensor.
- We will assume materials have isotropic \( Y \).

Most materials we are interested in have Youngs Moduli in the GPa regime:

<table>
<thead>
<tr>
<th>Material</th>
<th>( Y ) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>71</td>
</tr>
<tr>
<td>Kapton</td>
<td>2.5</td>
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<tr>
<td>PAR</td>
<td>2.9</td>
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<tr>
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<tbody>
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<td>PET</td>
<td>5.3</td>
</tr>
<tr>
<td>Steel</td>
<td>200</td>
</tr>
<tr>
<td>SiN</td>
<td>210</td>
</tr>
<tr>
<td>SiO₂</td>
<td>70</td>
</tr>
<tr>
<td>Si</td>
<td>130</td>
</tr>
</tbody>
</table>

Table 11.1 Brotherton
Maximum Temperature

• We are interested in substrate materials which have a low stiffness (i.e. a low Young’s modulus).

• These are materials which also have low melting points (or glass transition temperatures).

• We cannot exceed these temperatures at any stage in the development process.

<table>
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Table 11.1 Brotherton

Maximum Temperature

• These maximum temperatures are extremely prohibitive.

• While materials such as Kapton (poly-oxydiphenylene-pyromellitimide) are stable up to close to 400°C, we would prefer to use cheaper plastics such as PEN (Polyethylene naphthalate) or PET (Polyethylene terephthalate).

  • For these systems we really need to aim for process temperatures < 200°C.

  • This can be a challenge for certain material systems.
Metal Oxide Semiconductors

- For example, in Lecture 7 we saw that the conversion temperature for solution-processed metal oxide semiconductors can be above this.


Coefficient of Thermal Expansion

- In addition to the maximum temperature of the substrate, we also need to be aware of how much the substrate is going to deform during processing.

- Why is this important?

- It can potentially cause cracking / deformations

![Diagram](image-url)
Coefficient of Thermal Expansion

- We quantify this through the coefficient of thermal expansion (CTE):
  \[ \alpha = \frac{1}{L} \frac{\partial L}{\partial T} \]

- \( \alpha \): coefficient of thermal expansion (CTE)
- \( L \) length of material.
- \( T \) Temperature.
- The CTE is normally quoted in ppm/K.

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Table 11.1 Brotherton

Thermal Strain

- Say we heat our sample to some temperature that is \( \Delta T \) above room temperature to deposit the film.
- If our substrate (\( \alpha_s \)) and film (\( \alpha_f \)) have different values of coefficient of thermal expansion, we can expect to induce strain (\( \varepsilon_f \)) into the TFT:
  \[ \varepsilon_f = \left( \frac{\alpha_f - \alpha_s}{Y_f d_f} \right) \frac{\Delta T}{Y_s d_s + 1} \]

- \( Y_f \): Young’s modulus of film.
- \( Y_s \): Young’s modulus of substrate.
- \( d_f \): Film thickness.
- \( d_s \): Substrate thickness.
Thermal Strain

\[ \varepsilon_f = \left( \frac{(\alpha_f - \alpha_s)\Delta T}{Y_f d_f / Y_s d_s + 1} \right) \]

- For thick substrates we will normally find that \( Y_s d_s \gg Y_f d_f \).
- Under these circumstances we see that the thermal strain of reduces to:
  \[ \varepsilon_f = (\alpha_f - \alpha_s)\Delta T \]
- I.e. the higher the processing temperature, the higher the strain on the film.

Cracking

- What happens if \( \varepsilon_F \) is too large?
- The main problem is cracking.

- As a rule of thumb we should aim for \( \varepsilon_F < 0.3\% \)

Figure 11.1 Brotherton

ECE 617 – Thin Film Electronics
Fall 2020 - John Labram
Bending

• In addition to cracking, thermal stress can also lead to bending and buckling.

\[ R = \frac{d_s}{6(1 + \nu)e_M k \eta} \left[ \frac{(1 - \kappa \eta^2)^2 + 4 \kappa \eta (1 - \eta)^2}{1 + \eta} \right] \]

• Where:
  • \( d_s \): Substrate thickness.
  • \( e_M \): Differential thermal strain of substrate and film:
    \[ e_M = (\alpha_f - \alpha_s) \Delta T \]
  • \( \alpha_f \): coefficient of thermal expansion of film.
  • \( \alpha_s \): coefficient of thermal expansion of substrate.
Bending

- The radius of curvature ($R$) is given by:

$$R = \frac{d_s}{6(1 + v)\epsilon_M \kappa \eta} \left[ \frac{(1 - \kappa \eta)^2 + 4\kappa \eta (1 - \eta)^2}{1 + \eta} \right]$$

- Where:
  - $\kappa$: Ratio of Young’s moduli:
    $$\kappa = \frac{Y_f}{Y_s}$$
  - $\eta$: Ratio of film thicknesses:
    $$\eta = \frac{d_f}{d_s}$$
  - $v$: Poisson’s Ratio:
    $$v = -\frac{d\epsilon_{\text{trans}}}{d\epsilon_{\text{axial}}}$$
  - $\epsilon_{\text{trans}}$: Transverse strain.
  - $\epsilon_{\text{axial}}$: Axial strain.
Poisson’s Ratio

• Poisson’s Ratio just quantifies the deformation of a material due to stretching or compression.

• Axial strain ($\varepsilon_{\text{axial}}$) will be positive for tension and negative for compression.

• Transverse strain ($\varepsilon_{\text{trans}}$) will be positive for axial compression and negative for axial tension.

Substrate Bending

• The figure below shows the normalized radius of curvature.

$$R = \frac{d_s}{6(1 + \nu)E_M\kappa \eta} \left[ \frac{(1 - \kappa \eta^2)^2 + 4\kappa \eta(1 - \eta)^2}{1 + \eta} \right]$$

Figure 11.2 Brotherton
Implication for Applications

- Brotherton tend to discuss flexible electronics in the context of a-Si:H.
- To deposit a-Si:H reliably we require process temperatures > 300°C.
- At these temperatures, the effects of cracking and bending are significant.
- By using solution-processable organic semiconductors for example, we could get closer to room-temperature.
- Clearly this would be beneficial for developing commercial products.

Device Flexibility
Flexible Electronics

- So far we have only looked at the mechanical requirements of our materials to be able to form TFTs using flexible materials.
- We also need to consider another question: what sort of deformation can the devices tolerate?
- We often quantify deformations in terms of bending radius ($R$):

$$
\varepsilon_f = \left[ \frac{d_f + d_s}{2R} \right] \left[ \frac{1 + 2\eta + \kappa \eta^2}{(1 + \eta)(1 + \kappa \eta)} \right]
$$

- Where:
  - $\kappa$: Ratio of Young’s moduli:
    $$
    \kappa = \frac{Y_f}{Y_s}
    $$
  - $\eta$: Ratio of film thicknesses:
    $$
    \eta = \frac{d_f}{d_s}
    $$
  - Young’s modulus of film
  - Young’s modulus of substrate
  - Thickness of films
  - Thickness of substrate
Flexible Electronics

- For hydrogenated amorphous silicon, there is a reasonably limited range of acceptable value of $\varepsilon_f$:

  ![Figure 11.2 Brotherton](image)

  - Under tensile strain the failures is due to crack propagation.
  - Under compressive strain the failures is due to buckling and delamination.

Example

- Lets consider some examples.

  $$\varepsilon_f = \left[ \frac{d_f + d_s}{2R} \right] \frac{1 + 2\eta + \kappa \eta^2}{(1 + \eta)(1 + \kappa \eta)}$$

- We will consider the structure below

  ![Structure Diagram](image)

  $$\eta = \frac{d_f}{d_s} = \frac{100}{10} = 0.1$$

  $$R = 1000 \mu m$$
Example

• Let’s start by looking at silicon as our semiconductor.

\[
\kappa = \frac{Y_f}{Y_s} = \frac{130}{5.3} = 24.5
\]

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Table 11.1 Brotherton

Example

• Enter these values:

\[
\varepsilon_f = \left[ \frac{d_f + d_s}{2R} \right] \left[ \frac{1 + 2\eta + \kappa \eta^2}{(1 + \eta)(1 + \kappa \eta)} \right]
\]

\[
\kappa = 24.5 \quad \eta = 0.01 \quad R = 1000 \mu m \quad d_f = 0.1 \mu m \quad d_s = 10 \mu m
\]

• Let’s work in \(\mu m\):

\[
\varepsilon_f = \left[ \frac{0.1 + 10}{2 \times 1000} \right] \left[ \frac{1 + 2 \times 0.01 + 24.5 \times 10^{-4}}{(1 + 0.01)(1 + 24.5 \times 0.01)} \right]
\]

\[
\varepsilon_f = 5.05 \times 10^{-3} \times 0.813
\]

\[
\boxed{\varepsilon_f = 0.41\%}
\]
Flexible Electronics

- Even if we don’t irreversibly damage our device, we can expect the performance of devices to change as we adjust strain.
- This is normalized mobility data for a-Si:H:

\[
\frac{\mu}{\mu_0} = 1 + 26\varepsilon
\]

![Figure 11.22 Brotherton](image.png)

Flexible Electronics

- Even if we don’t irreversibly damage our device, we can expect the performance of devices to change as we adjust strain.
- Similar data for poly-crystalline silicon.

![Figure 11.30 Brotherton](image.png)
Flexible Electronics

- A lot of these studies are empirical, but intuitive results are obtained.
- Consider this data for example.
- IGZO is amorphous.
- ZnO is polycrystalline.
- It is believed that grain boundaries can act as nucleation centers for cracks.

![Normalized TFT Mobilities vs Tensile Bending Radius](image)


Flexible IGZO

- For electronics based on inorganic semiconductors, IGZO is a good choice.
  - It is amorphous.
  - High electron mobility.
  - Optically Transparent.
- However the Young’s modulus is a lot higher than plastics:

![Young's modulus vs Indentation depth](image)

Yoshikawa et al., App. Phys. Exp. 6, (2013) 021101
Flexible IGZO TFTs

- IGZO TFTs with impressive bending radii have been demonstrated.

Salvatore et al., Nat. Comms. 5, (2014) 2982
Mechanical Properties of IGZO

- IGZO will crack under extreme deformations.

Plastic Electronics

- Because organic semiconductors are plastics, they are the obvious choice for flexible electronics.
- They have similar mechanical properties to plastic substrate (e.g. Young’s modulus and coefficient of thermal expansion).
- Low thermal budget (generally).
- Some systems do require thermal energy to arrange into optimal morphology.

Shahid et al., Chem. Sci. 3 (2012) 181
Plastic Electronics

- But if we want to do something like this:

  ![Image](https://www.youtube.com/watch?v=3_JUHHMyLQw)
  ![Image](https://www.youtube.com/watch?v=zPhDUN5IBZ8)

- Plastic electronics is the most likely way it will happen.

Organic Flexible Electronics

- There have been demonstrations of extremely flexible electronics using organics.

  ![Image](https://halik.et.al.nature.431(2004)963)

  ![Image](https://sekitani.et.al.nature.materials.9,(2010)1015)
Organic Flexible Electronics

• There have been demonstrations of extremely flexible electronics using organics.


Organic Flexible Electronics

• Complementary inverters have been demonstrated:

Organic Flexible Electronics

• And ring oscillators.


Applications
Applications

- So why do we want flexible electronics?
- Some potential applications are novel and clearly have commercial value:

  ![Flexible electronics application](https://www.youtube.com/watch?v=3_JUHHMyLQw)

- Many applications are imagination limited.

Communications

- The most simple application are **passive**.
  - I.e. those not requiring power.

  ![RFID diagram](https://i.imgur.com/2oJ5z5y.png)


- Energy provided by incoming signal is processed, then a different signal is returned.
- This is radio-frequency identification (RFID).
RFID Tags

- These are very common.

- They typically operate over very short distances only.
  - < 10cm.

RFID Tags

- Traditionally an antenna is combined with a standard silicon-based integrated circuit.

- This is something where flexible electronics can take over (and probably will).
Electronic Whisky Bottle

- Prototype by Thin Film Electronics (Norwegian Company).

![Electronic Whisky Bottle Image]

https://www.youtube.com/watch?v=5h6m6CESS14

Longer Range Communication

- But what about communicating over longer distances?

- This typically requires an active device and a higher frequency.
- E.g. Bluetooth is 2.45 GHz.
  - This is much higher than RFID (13.56 MHz).
Longer Range Communication

- Longer distances open up more applications.

![Diagram showing different ranges and frequencies for communication systems](image)


- Is this possible for flexible electronics?

High Mobility Systems

- High charge carrier mobilities are required.
- Mobilities and frequencies obtained on flexible substrates:

![Graph showing mobility and frequency relationships](image)

Electronics on Paper

- This is a very challenging topic.


Electronics on Paper

- The surface roughness is incredibly large for paper.
- The surface must be passivated before semiconductors can be deposited.

Electronics on Paper

- Display arrays have been demonstrated on paper:

![Diagram of a display array on paper](image)


Electronic Bank Notes

- Some research groups have deposited operation TFTs onto 5 Euro bank notes.

![Images of TFTs on a 5 Euro bank note](image)

Electronic Bank Notes

• There is significant device-to-device variation.


• But some devices do work.

Electronic Bank Notes

• Working circuits can be demonstrated:


• This is the first step to electronic / traceable physical currency.
3D Printed Electronics

- Recent developments had led to the 3D printing of flexible electronics components.

- While not as fast as roll-to-roll printing, 3D printing enables the development of multilayer systems.

3D Printed Electronics

- In particular, high-density capacitors.
Biodegradable Electronics

• Another potential benefit of using organic materials for flexible electronics is the fact that we use organic compounds routinely.


Biodegradable Electronics

• Researchers have demonstrated “edible” electronics deposited onto the surface of a capsule.

Biodegradable Electronics

• For the same reason, we should be able to manufacture electronics which are biodegradable.

Lei et al., PNAS. 114, (2017) 5107.

Biodegradable Electronics

• For the same reason, we should be able to manufacture electronics which are biodegradable.

• The main challenge is to do with electrodes.
• A certain amount of metal is ok, but ideally we would seek biodegradable electrodes as well.

Lei et al., PNAS. 114, (2017) 5107.
Next Time...

- Bio-electronics.