Solutions for Organic Thin Film Transistor Applications Materials to Circuits 1st Edition by Kaushik

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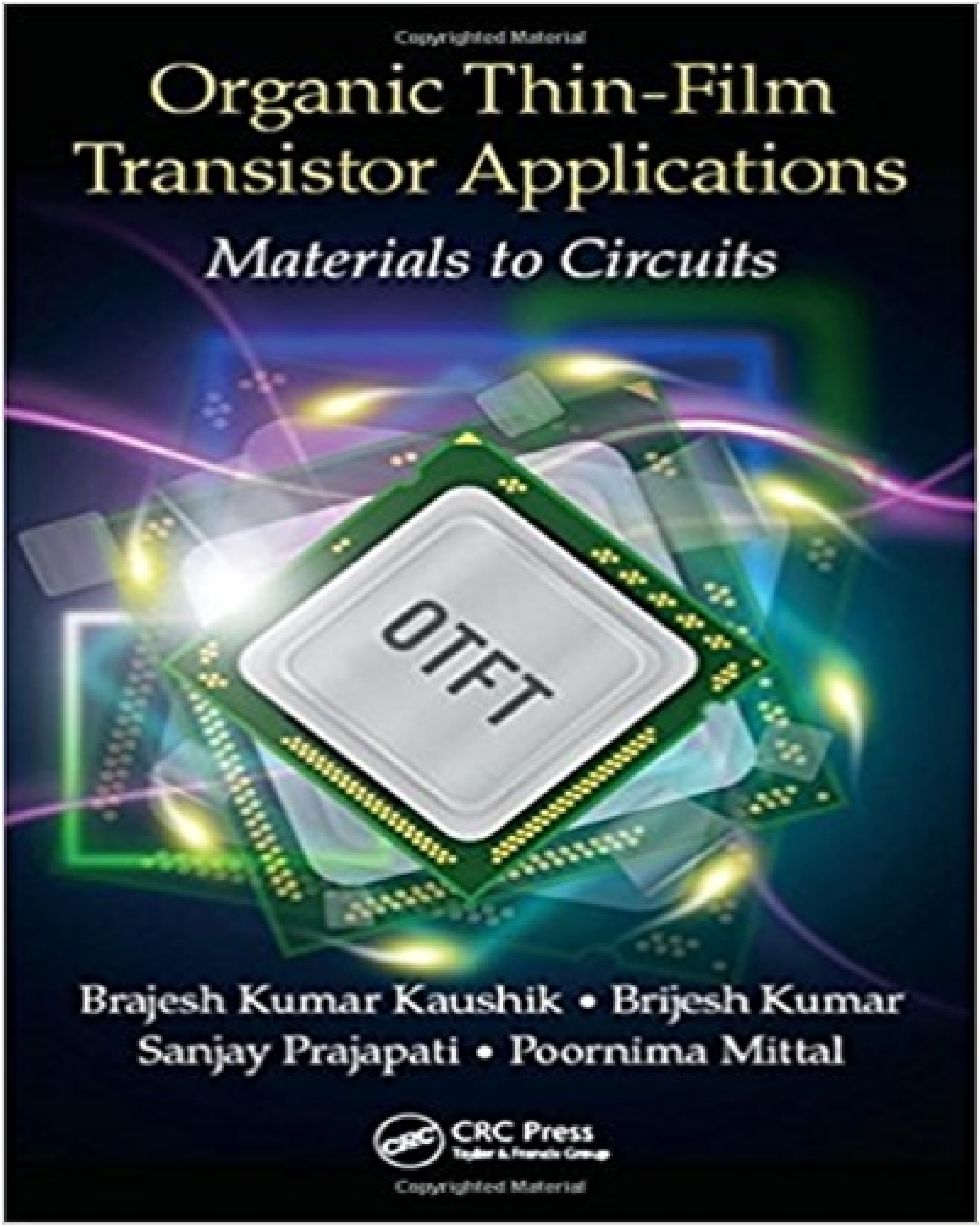


Solutions

Chapter 2

OTFT Parameters, Structures, Models, Materials, Fabrication and Applications - A Review

Solution Manual of Numerical Problems

Q 1. For a *p*-type top gate top contact organic thin film transistor with μ=0.14cm^2/Vs, ε_r=3.9, t_{ox}=200nm, W=1mm, L=30µm and V_t=-3.2V, examine the relationship between the current and the terminal voltages.

Solution:

$$I_{ds} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{gs} - V_t)^2$$

$$C_{ox} = \frac{\varepsilon_0 \varepsilon_r}{t_{ox}} = \frac{3.9 \times 8.85 \times 10^{-12} F/m}{200 \times 10^{-9}}$$

$$C_{ox} = 0.172 \times 10^{-3} F/m^2$$

$$I_{ds} = \frac{1}{2} \times 0.14 \times 10^{-4} \times 0.172 \times 10^{-3} \times \left(\frac{1 \times 10^{-3}}{30 \times 10^{-6}}\right)(V_{gs} - V_t)^2$$

$$I_{ds} = 39.9 \times 10^{-9}(V_{gs} - V_t)^2$$

Q 2. Using field dependent mobility concept in organic thin film transistor, find zero bias mobility (μ_0). The device mobility μ=0.02cm^2/V.s, enhancement factor is 0.2, and source-gate voltage (*Vgs*) are of -14V and threshold voltage (V_t) of -3.2V.

Solution:

$$\mu = \mu_0 (V_{gs} - V_t)^{\alpha}$$

$$0.02 = \mu_0 (-14 - (-3.2))^{0.2}$$

$$0.02 = \mu_0 (10.8)^{0.2}$$

$$\mu_0 = \frac{0.02}{1.609}$$

$$\mu_0 = 0.0124 cm^2 / Vs \, .$$

Q 3. Extract the current On-Off ratio (I_{on}/I_{off}) of an organic thin film transistor with μ=0.015cm^2/Vs, V_{ds}= -10V, V_{gs}= -10V, V_t= -1.3V, C_{ox}=800nF/cm^2, 20nm of OSC thickness (t_{osc}) and σ =1S/cm.

Solution:

$$\frac{I_{on}}{I_{off}} = \frac{C_i \mu (V_{gs} - V_t)^2}{t_{osc} V_{ds} \sigma}$$

$$\frac{I_{on}}{I_{off}} = \frac{800nF/cm^2 \times 0.015 cm^2 / Vs \times (10 - 1.3)^2}{20nm \times 10V \times 1S/cm}$$

$$\frac{I_{on}}{I_{off}} = 454.14 \times 10^{-4} = 0.045$$

Q 4. Find the operating mode and estimate the drive current of an organic thin film transistor for the given parameters: μ=1.64cm^2/Vs, *W*=120μm, *L*=10μm, C_{ox} =800nF/cm^2, *Vgs* =1.6V, *Vds*=2V and V_t =1.2V.

Solution:

$$V_{gs} - V_t = 1.6 - 1.2$$

$V_{gs} - V_t \leq V_{ds}$

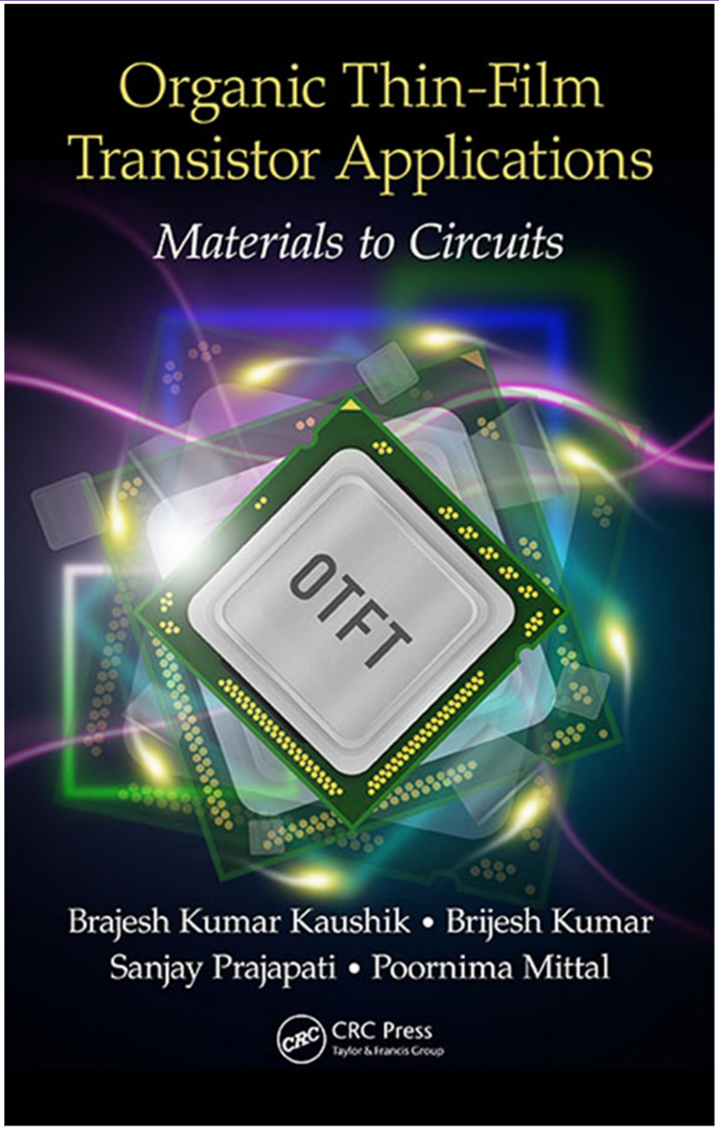
Hence the device is operating in saturation mode.

$$I_d = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{gs} - V_t\right)^2 = \frac{1}{2} \times 1.64cm^2 / Vs \times 800nF / cm^2 \times \left(\frac{120}{10}\right)(1.6 - 1.2)^2 V$$

$I_d = 1.259\mu A$

Chapter- 2

OTFT Parameters, Structures, Models, Materials, Fabrication and Applications - A Review



Outline of the Chapter

- Introduction
- Motivation Behind this Emerging Research Area
- Organic Thin Film Transistor
- OTFT Operating Principle, Its Advantages and Applications
- OTFT Structures
- OTFT Characteristic Parameters
- Organic Semiconductor Materials Basics
- Other Materials Required for OTFTs
- Fabrication
- Summary

Important Landmarks and Introduction

- Researchers realized in 1970 that some applications, like displays, RFID tags, required large array of low cost electronics which was not possible with silicon.

- This marked the advent of amorphous silicon TFTs (a-Si-TFTs).
- Discovery and Development of the conducting polymers (Polyacetylene-pure state is poor conductor+I_2) by Dr. H. Shirakawa, Dr. Alan G. MacDiarmid and Dr. Alan. J. Heeger created a new research field in 1976.

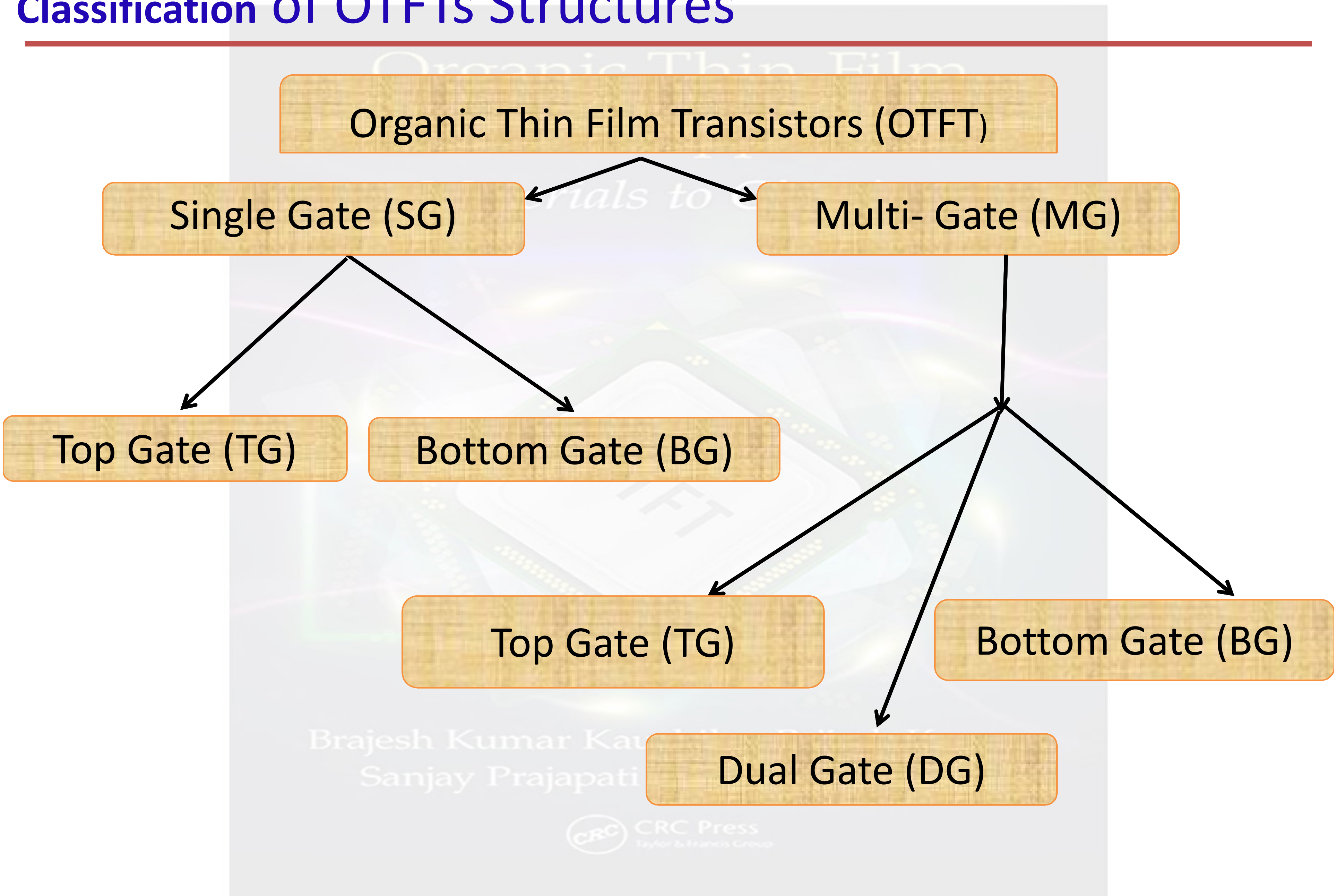
- **Organic Semiconductor Materials:**
- **Conducting Polymers**: Polythiophene group (P3HT, P3OT, P3AT)
- **Small Molecules**: Pentacene, CuPc, PCBM, F_{16}CuPC.
- First Organic / Polymer Thin Film Transistor (OTFT/PTFT) was demonstrated properly – 1986.

Motivation and Why OTFT??

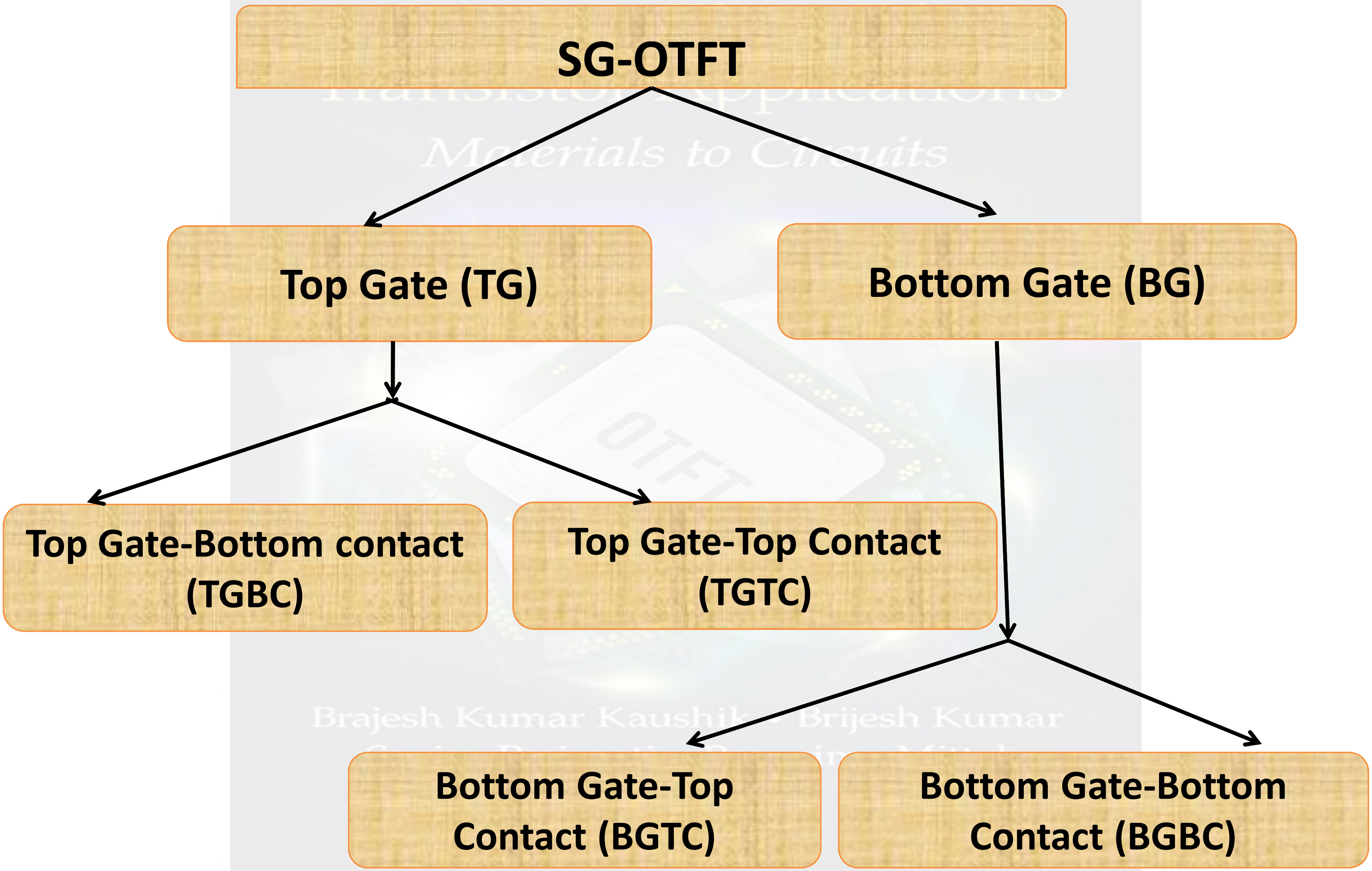
OTFTs provide various important benefits over TFTs and MOSFET/CMOS based on inorganic semiconductor materials:

- ✓ Mechanical flexibility: Foldable, Bendable, Lightweight
- ✓ Compatibility with plastic substances
- ✓ Organic displays are relatively cheap.
- ✓ Polymer based TFTs with electrical characteristics comparable to or better than (a-Si-H) TFTs devices have been demonstrated.
- ✓ Does not require a glass substrate as amorphous silicon does.
- ✓ Chemical tunability of conducting polymers.
- ✓ Easy integration in different device applications.
- ✓ Ecological and economic benefits.

Classification of OTFTs Structures



Classification of Single Gate OTFT Structures



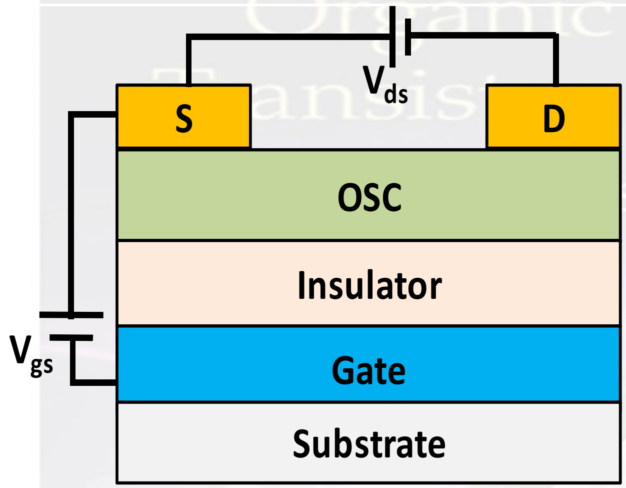
Organic Thin Film Transistor

- Transistor having organic semiconductor (small molecules/ conducting polymers) as active layer to current flow.

- Compatibility with plastic substances
- Lower-cost deposition process
- Lower temperature manufacturing (60-120^{o}C)

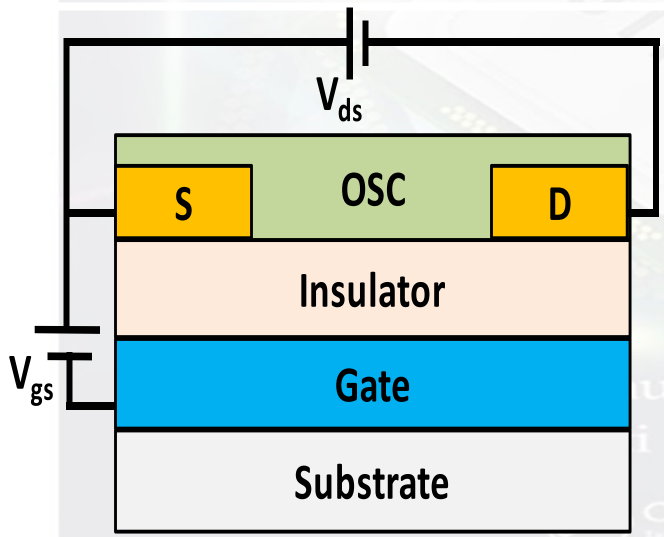
Comparison of BGTC and BGBCOTFTs Structures

BGTC



- Low Contact Resistance.
- High Mobility.
- High Current
- Larger Channel Length

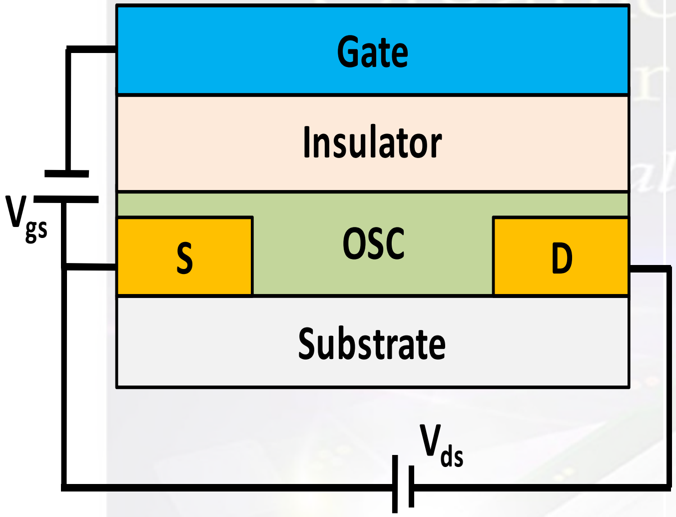
BGBC



- High Contact Resistance
- Low Mobility.
- Low Current.
- Easy to Fabricate.

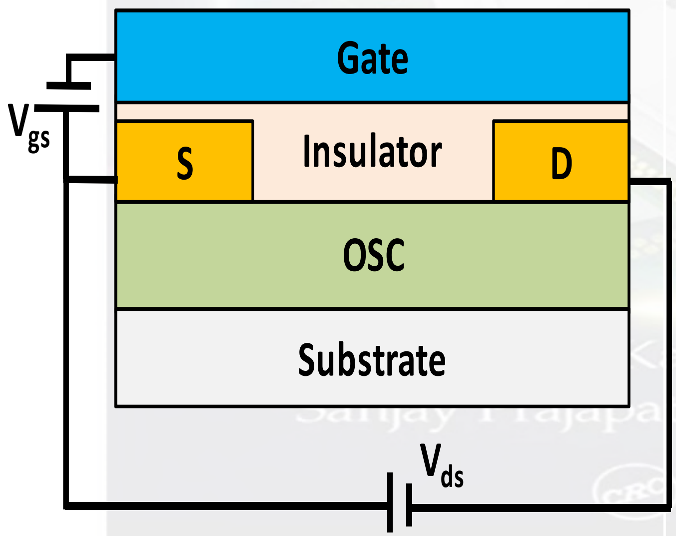
Comparison of TGBC and TGTC OTFTs Structures

TGBC



- Tough Fabrication.
- Low Contact Resistance

TGBC



- Easy to Fabricate.
- High Contact Resistance.
- Similar to MOSFET.

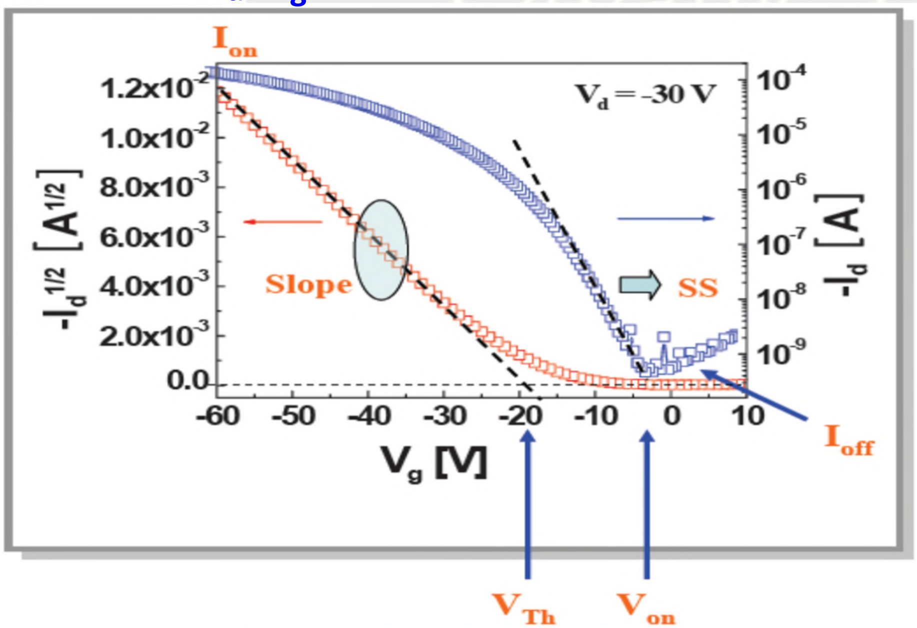
Difference Between Organic and Inorganic Material

S.N.	ORGANIC MATERIAL	INORGANIC MATERIAL
1. OSC	Polymer/Small molecule based organic material	Silicon based inorganic material
2. Charge carriers:	Polarons and Excitons	Charge carriers through electrons, holes and ions.
3. Charge Transport:	Hopping	Energy band gap
4. Mobility:	10^{-6} -5 $cm^2/V.s$	10^{-2} - 10^{-4} $cm^2/V.s$
5. Bonding:	Ionic, Covalent and Van-der waal force	Ionic, Covalent, metallic
6. Cost:	\$ 5/ft^2	\$ 100/ft^2
7. Fabrication Cost:	Low capital	\$1 - \$ 10 billion
8.Temperature Range:	Low temp (30 – 120^0 C)	Greater than 1050^0 C
9. Device Size:	10ft X Roll to Roll	Less than $1m^2$
10.Substrate	Flexible Plastic Substrate	Rigid Glass or Metal

S. N.	ORGANIC MATERIAL	INORGANIC MATERIAL
11.Process Conditions:	Ambient processing	Ultra Clean Room
12. Process:	Continuous direct printing	Multi–step photo lithography
13. Biodegradability:	Biodegradable being made from carbon	Non biodegradable
14. Compatibility:	With flexible or plastic substrates	Non compatible with plastic or flexible substrate
15. Free Carriers:	Do not support free electrons and holes instead have Polarons and excitons	Free carriers in form of electrons and holes.
16. Effective Mass:	Huge	Less

OTFTs Performance Parameters

Transfer (I_d-V_g) Curve at saturation region



❖ Performance of an OTFT is characterized in terms of several conventional parameters, including

- ✓ Field effect mobility,
- ✓ Threshold voltage,
- ✓ On/off current ratio
- ✓ Sub-threshold slope
- ✓ Transconductance

Performance Parameters

Field Effect Mobility (μ) [cm²/V.s]

$$slope=\left(\frac{W\mu C_i}{2L}\right)^{1/2} \qquad \mu_{lin}=\frac{Lg_m}{WC_iV_D}$$

$$\mu_{sat}=\frac{2L}{WC_i}\left(\frac{\partial\sqrt{I_{Dsat}}}{\partial V_G}\right)^2$$

Threshold Voltage (V_{Th})

On/Off Current Ratio (I_{on}/I_{off})

Sub-threshold Slope (SS)

$$SS=\frac{\partial[V_G]}{\partial[\log_{10} I_D]}$$

Transconductance (g_m)

$$g_m=\frac{\partial I_{Dlin}}{\partial V_G}$$

Factors Influencing OTFTs Performance

Performance Parameters	Dominant Factors
Mobility (High)	Fabrication Technique, Impurity, Gate Biasing, Material for Semiconductor
On – Current (High)	W/L , Mobility, Contact Resistance, Channel Length
Off - Current (Low)	W/L, Gate Insulator, Contact Resistance
Threshold Voltage (Low)	Channel Length, Thickness of Semiconductor Layer
Sub-Threshold Slope (Steep Slope)	Capacitance & Thickness of Insulator Drain /Source and Gate Biasing
Contact Resistance (Low)	Structure of PTFT Channel Width

Material Requirements for OTFTs

- Target: > 1 cm^2/Vs on/off ratio >10^6 for n type or p/n type Organic Semiconductors
- Conjugated π-Electron System, High Electron Affinity (for n type) or ambipolar Characteristics (for p/n type)
- Good Intermolecular Electronic Overlap
- Good Film Forming Properties
- Chemical Purity
- Stability

Organic and Inorganic Device Materials

Materials	Organic (PTFTs / OTFTS/OFETs)	Inorganic (MOSFETs/TFTs)
Substrate	PET-Polyethylene Terephthlate, PEN –Polyethylene Naphthalate, Klauk et al. 2003etc.(High Toughness & thermal resistance, Flexibility, Light weight)	Silicon wafer (High Melting Point, good flatness, Low Diffusivity of chemical)
Contact Electrodes	Gold,Platinum,Al,Mg,Pd source/drain metal with large work function matched with either HOMO or LUMO. Polymer contact-PEDOT:PSS	Metals (**Au, Cu)**
Semiconducting Layer (Channel/ Thin Film)	Organic Semiconducting material with electrical characteristics P3HT- Poly(-3-hexylthiophene), P3AT-Poly (3-alkylthiophene) P3OT- poly (3-octylthiophene) Pentacene: good electrical Propt.)	a-Si:H, Si
Dielectric layer	Gate insulating layer with high dielectric constant and high resistivity (PMMA-Polymethyle methacrylate)	Insulating Materials SiO_2, TiO_2, Al_2O_3

Organic Semiconductors

- ❖Organic semiconductors are classified as the conducting polymers and small molecules.
- ❖Mobility of polymers is found lower than small molecules due to higher molecular weight.
- ❖To obtain it higher; the grains of semiconductor should be larger in size.
- ❖Performance of Polymer transistor (PTFTs/OTFTs) critically depends on the chemical and structural ordering of the chains at interface of OSC-insulator.

▪Important Influencing Factors

- ❖Interface of metal and dielectric with semiconductor
- ❖Ordered molecular structure of the active layer
- ❖Efficient injection at contacts and stability.

Organic Semiconductor Material Basics

- ✓ An **organic semiconductor** is an organic material with semiconductor properties.
- ✓ **Molecular conjugation** :The fundamental property that allows organic molecules to conduct electronic charge.
- ✓ Conjugation causes **Delocalization** and allow charge transport.
- ✓ Organic Semiconductor materials categories as:
- ✓ Polycyclic aromatic compounds(e.g. Pentacene, anthracene, etc)
- ✓ Polymeric organic semiconductors(e.g. Poly(3-hexylthiophene, etc)

Electronic structure of Organic semiconductor

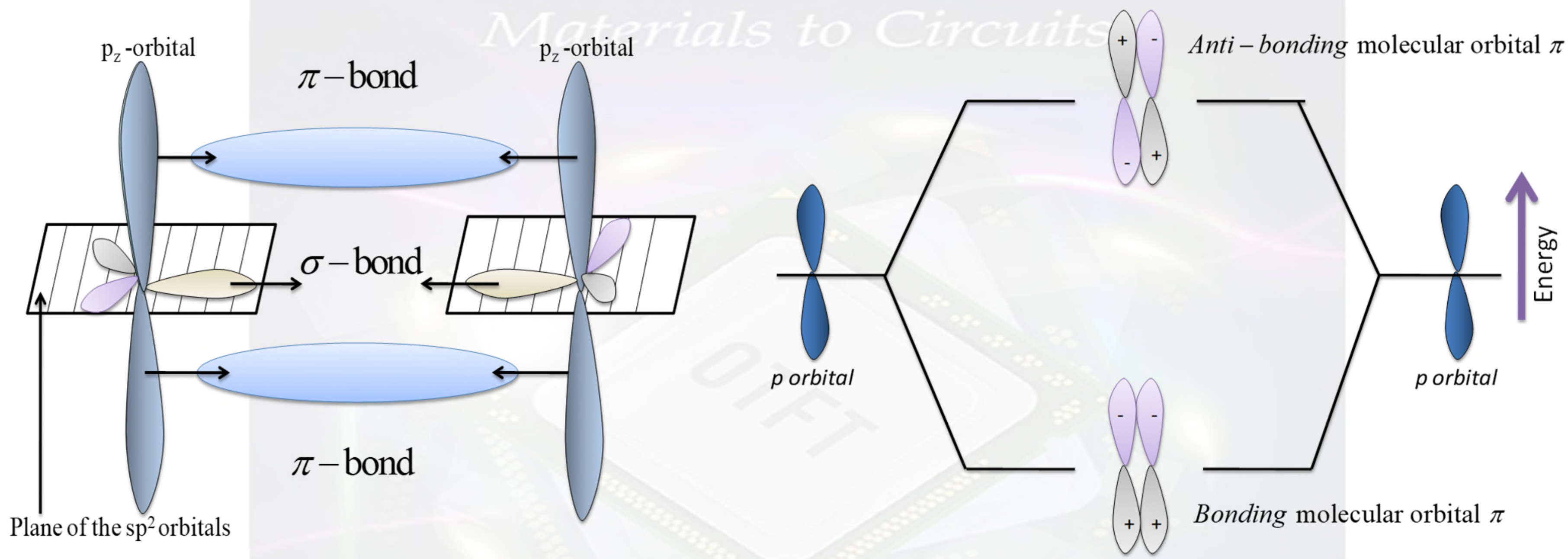
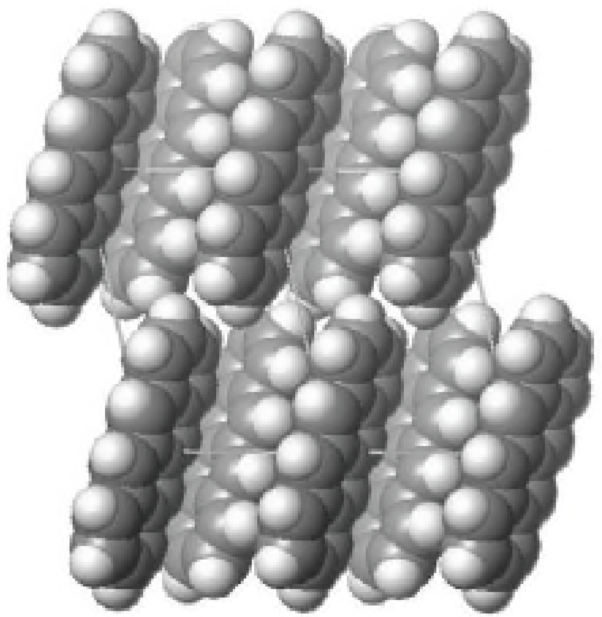


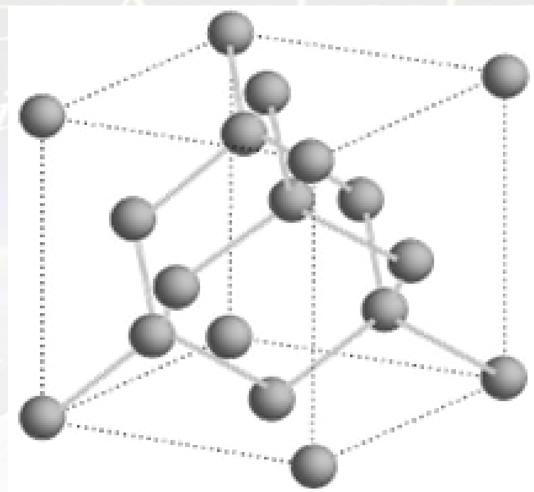
Fig. (a) sp^2 hybridization of two carbon atoms and (b) Bonding of p_z orbitals.

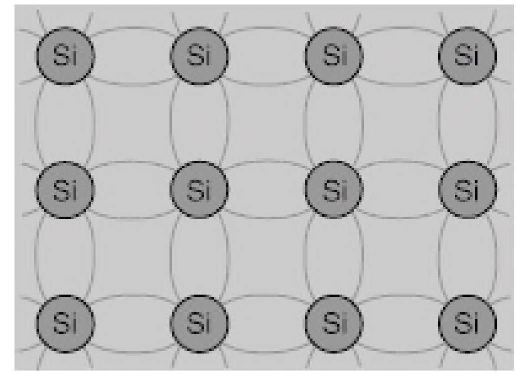
Organic and Inorganic Semiconductors

Organic Semiconductor



Inorganic Semiconductor





- Weak Van der Waals interaction forces
- π-bond overlapping
- Molecular gas property (molecule's identity)
- Hopping type charge transport dominant
- Low mobility and small mean free path

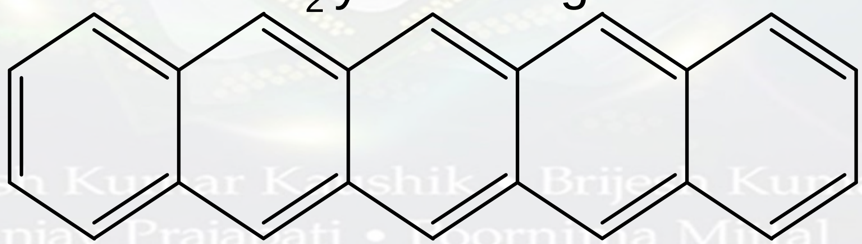
- Strong covalent bonds
- σ-bond
- Only crystal property
- Band type charge transport dominant
- High mobility and large mean free path

P-type Organic Semiconductors

Small Molecules

Most extensively used *p*-type Small molecule OSCs are

- ❖Pentacene
- ❖6,13-bis_triisopropyl-silylethynyl (TIPS) pentacene
- ❖Tetracene
- ❖Pentacene and its derivatives are the most promising and extensively used materials due to highest mobility.
- ❖Its deposition on dielectric SiO_2 yielded higher carrier mobility.



Pentacene

Chemical Structure of Pentacene small molecule Semiconductor

P-type Organic Semiconductors

Conducting Polymers

Most extensively used *p*-type conducting polymers are

✓PA - Polyacetylene

✓Polythiophene

✓Polyfluorene

✓P3AT - Poly (3-alkylthiophene)

✓P3HT - Poly(-3-hexylthiophene)

✓ P3OT - poly (3-octylthiophene)

✓PQT-12 - Poly 3, 3′′-dialkylquarterthiophene

✓F8T2 - Poly-9, 9’ dioctyl-fluorene-co-bithiophene

N-type Organic Semiconductors

- ✓ p and n-type OSCs are required to design the complementary inverters that are beneficial for low power consumption, higher noise margin and better stability.
- ✓ Therefore, the development of *n*-type semiconductors is equally important.
- ✓ There is an optimum thermodynamic stability window in *n*-type doped materials.
- ✓ It strongly depends on the free energy of activation that is associated with the chemical process/reaction with either water or oxygen.
- ✓ While designing these devices, the semiconductor must be utilized which, can allow the injection of electrons into its LUMO.

Ambipolar Materials OSCs

- ✓In the literature, the majority of OTFTs is demonstrated either by *p* or *n*-type semiconductors.

- ✓To achieve the organic complementary technology either *n* and *p*-type transistors can be incorporated by electrical connection or ambipolar charge transport can be realized in a single transistor.

- ✓Researchers reported high gain inverter with a natural pigment-Indigo, which contains the balanced electron and hole mobility and good stability against the degradation in air.

Source and Drain Electrode Materials

- ✓ Electrodes can be fabricated using either inorganic or organic materials.
- ✓ Contact metal for source (S) and drain (D) should contain low interface barrier with active layer to inject a large number of carriers.
- ✓ Contacts must possess a small resistance.
- ✓ Contact Electrode can be fabricated by thermal evaporation method.
- ✓ Adding Ni on Au improves the adhesion of gold on oxide, whereas, Pt electrodes are inferior comparatively.

Work Function of S/D Contact Electrodes

Electrode Materials	Work function (eV)
Au (Gold)	5.1
Cu (Copper)	4.7
Ag (Silver)	4.0
Cr (Chromium)	4.5
Al (Aluminum)	4.0 - 4.28
Ni (Nickel)	5.0 - 5.22
Ti (Titanium)	3.84
Pt (Platinum)	5.65
Ca (Calcium)	2.87
Co (Cobalt)	5.0
Fe (Iron)	5.0

Gate Electrode Materials

- ❖Selection of material for gate (*G*) electrode should be based on good adhesion and patterning capabilities to the substrate and gate dielectric.

- ❖Gate metal work function should be comparable to the active semiconductor layer to attain lower threshold voltage (V_t).

- ❖Such materials include heavily doped silicon, Al, Au, indium tin oxide (ITO) etc.

Gate Dielectric Materials

- Insulator material needs to have very high resistance to prevent the leakage between gate and channel.
- High dielectric constant to achieve enough capacitance (C_i) for channel current flow.
- High dielectric constant insulators result in lower switching voltage and elevated current capabilities.
- **Organic polymers**

✓PMMA

✓PVP

✓PI

✓PVA

- Demonstrate good process ability and dielectric properties

Inorganic Gate Dielectric Materials

- Currently, the researchers are focusing to enhance the properties of dielectric materials, since it is extremely crucial to achieve the reliability and high-performance.

- Dielectric materials should have the compatibility with OSCs, these materials should exhibit high insulation also.

- High resistivity reduces the interface trap density between OSC and gate dielectric which, in turn prevents the leakage

Substrate Materials

- Most of the OTFTs are fabricated on a heavily doped silicon substrate to achieve the film of SiO_2 dielectric with ease of oxidation.

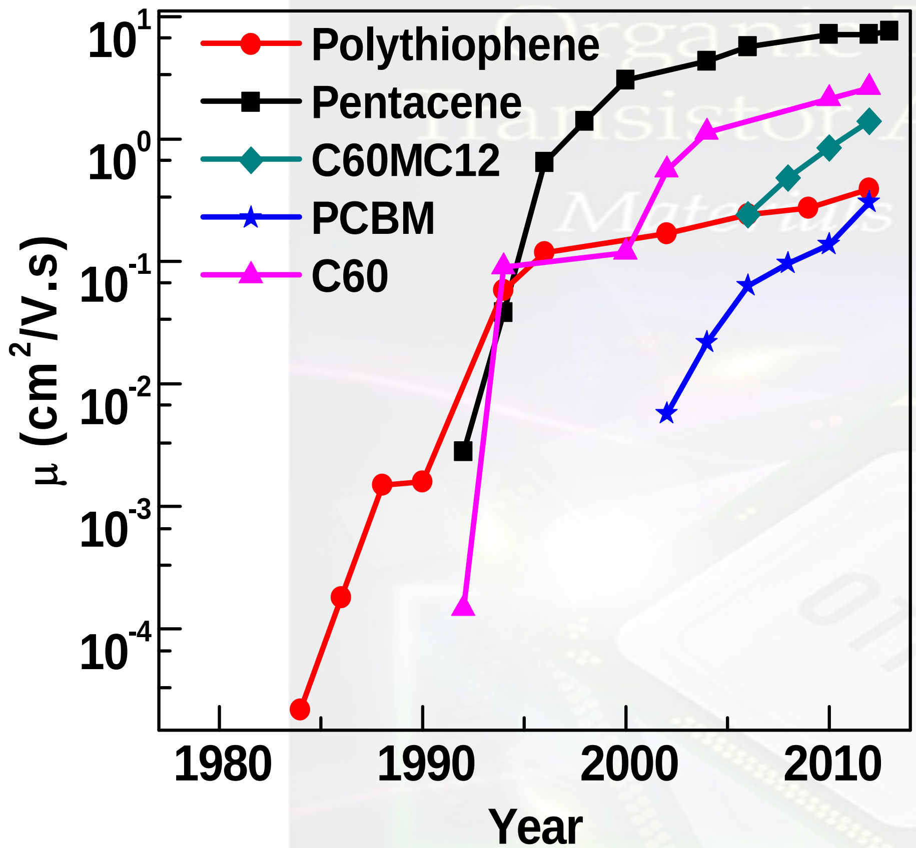
- Si is often used in electronics not only for its intrinsic properties but also for its good interface with thermally grown oxide.

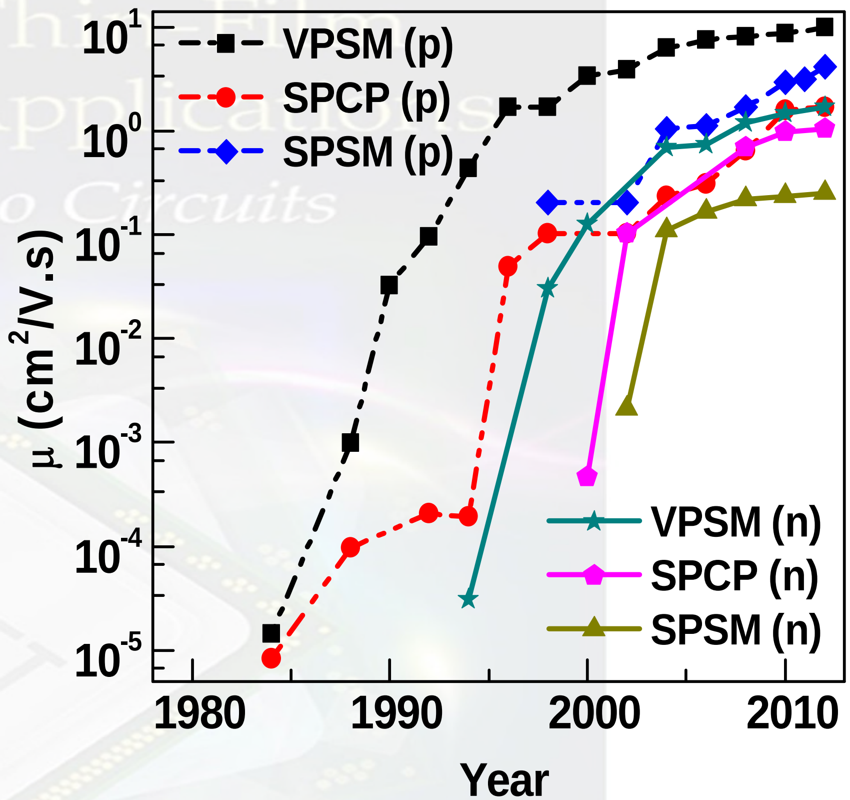
- Organic substrates like poly ethylene-naphthalate have shown remarkable performance in term of flexibility that motivates the researchers for its utilization in flexible electronic devices and circuits.

Limitations of Organic Material

- Organic semiconductors are **very soft and sophisticated**.
- Organic Materials **degrade** and can break easily .
- Characteristics of **organic materials changes** with environmental conditions after long duration.
- Most of **instability comes from chemical structure** of compounds.
- **Lower mobility** and **switching speed** compared to silicon based devices
- Due to low mobility, it is limited to low speed applications.

Performance of *p* and *n*-type OSC Materials in terms of Mobility





Comparative plot of mobility growth for *p*- and *n*-type OSCs

Comparative plot for growth in mobility of p- and n-type transistors w. r. t. fabrication processes.

Basic Fabrication Steps SG-OTFT (BGBC)

Substrate
(Warm Soap Solution, RCA Cleaning)

Gate Metal
(Sputter, Spin Coating, Wet Etching , Evaporation)

Gate Dielectric Deposition
(Sputter, Spin Coating, Dry Etching)

Source/Drain Contacts
(Sputter, Evaporation, Lift-Off , E-beam Deposition, Wet Etching)

Pentacene Thin Film
(Vacuum Deposition, Thermal Evaporation, Spin Coating)

Passivation Layer
(CVD, Dry Etching
RIE: Reactive Ion Etching)

Basic Fabrication Steps SG-OTFT (BGTC)

Substrate
Materials: Heavily doped Si wafer /glass /plastic or organic compatible material
Process: RCA cleaning/cleaning by suitable solution

↓

Gate Metal
Materials: Organic/inorganic
Process: Vacuum thermal evaporation/solution processing.

↓

Gate Dielectric
Materials: Organic/inorganic
Process: Thermal evaporation/solution processing

↓

Organic Semiconductor
Material: Small molecules/conducting polymers
Process: Thermal evaporation/ solution processing

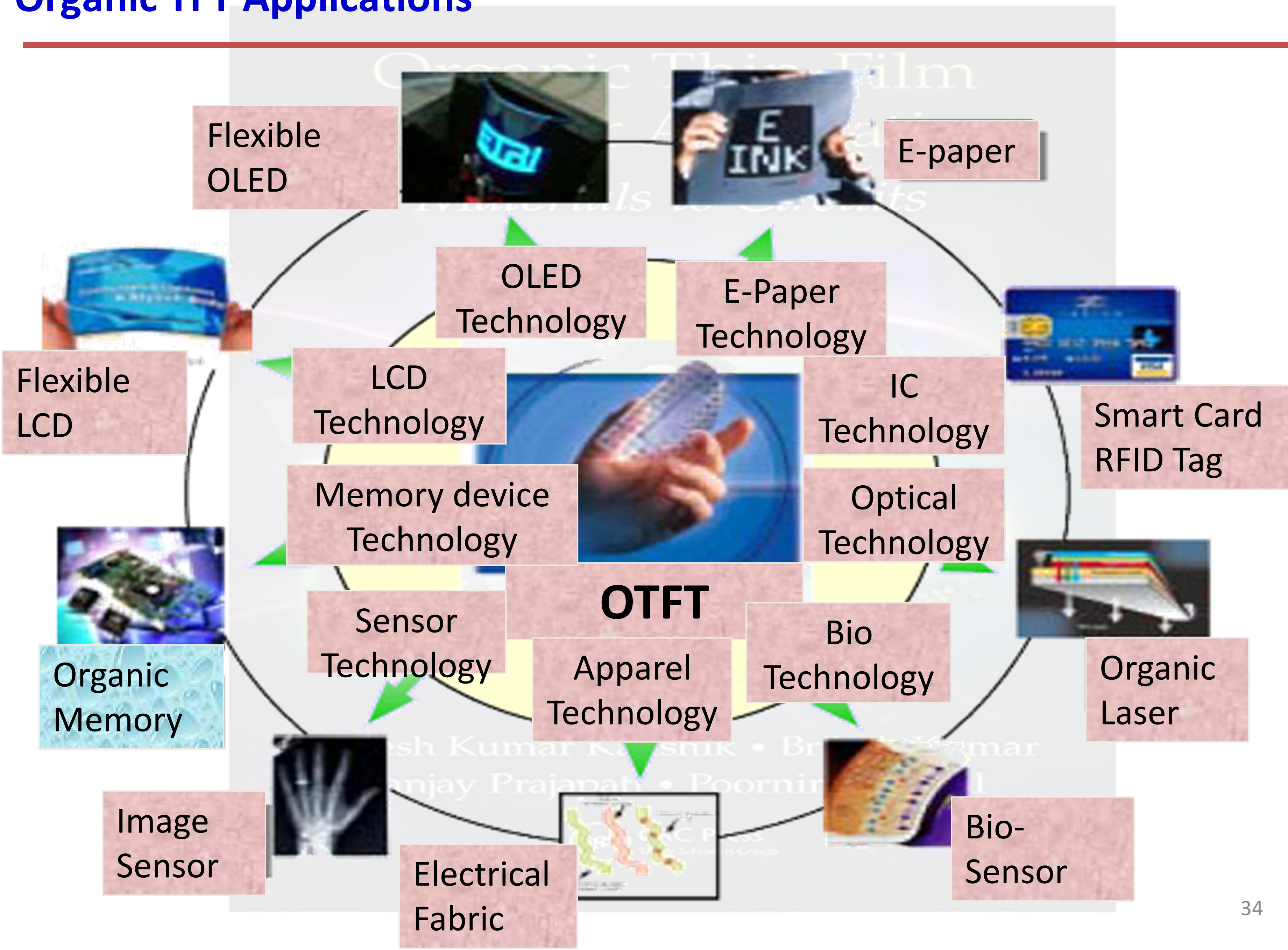
↓

Source/Drain Contact
Materials: Organic/inorganic
Process: Shadow masking/lithography/lift-off/transfer printing

↓

Passivation Layer
Materials: Organic/inorganic insulator
Process: CVD, Dry Etching, RIE: Reactive ion etching

Organic TFT Applications



Effect of Scaling on OTFT Parameters and Performance

- Scaling is not very much effective in OTFT due to their lower drive current
- Effect of scaling is almost similar in both OTFT and MOSFET devices
- Current in OTFT reduces by the scaling factor in full scaling that in turn degrades the switching behavior
- Constant voltage scaling increases the drain current and power density too
- OTFTs are strongly affected by the contact resistance that becomes increasingly evident as the channel length is scaled down

Lifetime and Durability of Organic Semiconductors

- Characteristics of OSCs alters with time and ecological environment due to their susceptibility to water and oxygen under ambient conditions
- Several *n*-channel TFTs processed and tested under inert condition only
- Numerous issues are still open ended, specifically those associated with the stability and performance variation from roll to roll and device to device
- Optimization of fabrication methodology and synthesis of novel materials, the lifetime/durability can be undoubtedly increased
- Through encapsulation of the devices, longer functioning lifetime can be achieved
- Due care must be taken against exposure of devices to moisture and oxygen, which can be achieved by depositing a film of inorganic oxides and special protective coatings.

Steps Needed for OTFTs to be Commercialized on a Larger Scale

- Improvement in Stability, lifetime and durability
- Cost economy, temperature dependency, operating bias and power dissipation
- Miniaturization
- Look for high performance OSCs, electrode, dielectric and substrate materials and novel OTFT structures
- Surface treatment and self-assembled monolayer of the dielectric
- High doping region near the contacts and additional OSC layer between contact and OSC.

Summary

- Organic transistor boasts of a bright future **with a wide spectrum of applications.**

- It is required to **develop suitable models** to adequately understand the OTFTs behavior..

- To investigate the **impact of active and dielectric layers thickness on the performance of both top and bottom contact structures** individually

- It is strongly required to **develop techniques** that can substantially improve the performance of organic digital circuits.