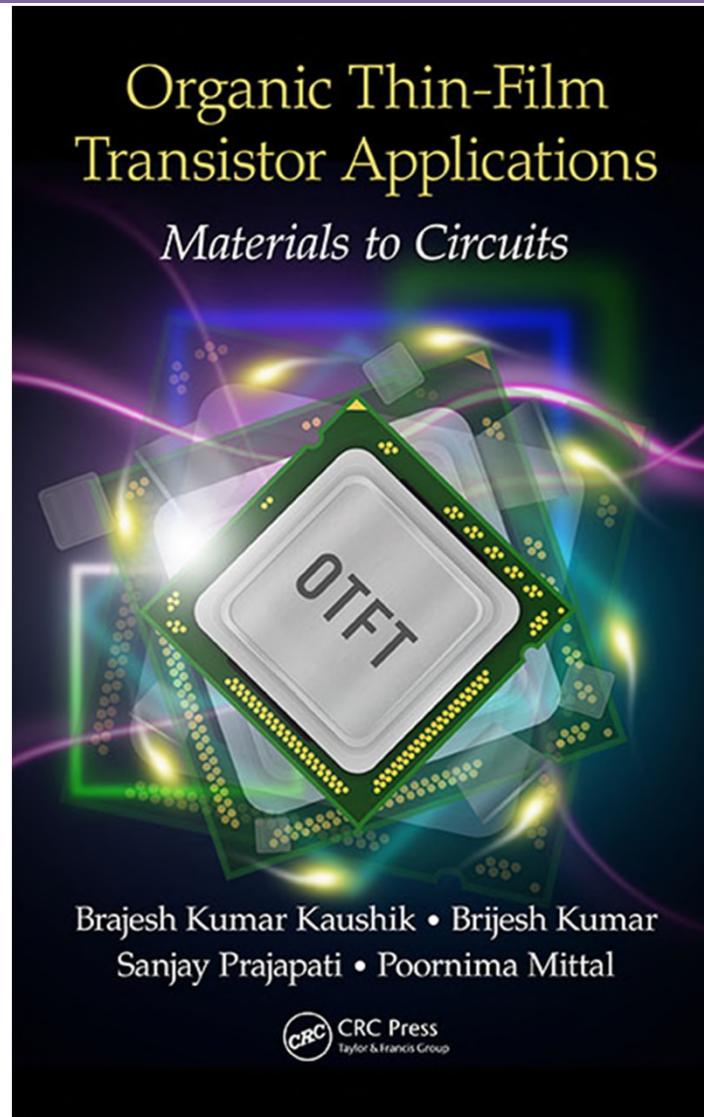


Chapter- 2

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

Organic Thin-Film
Transistor Applications

Materials to Circuits

OTFT

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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+I₂) 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, F₁₆CuPC.
- First Organic / Polymer Thin Film Transistor (OTFT/PTFT) was demonstrated properly – 1986.

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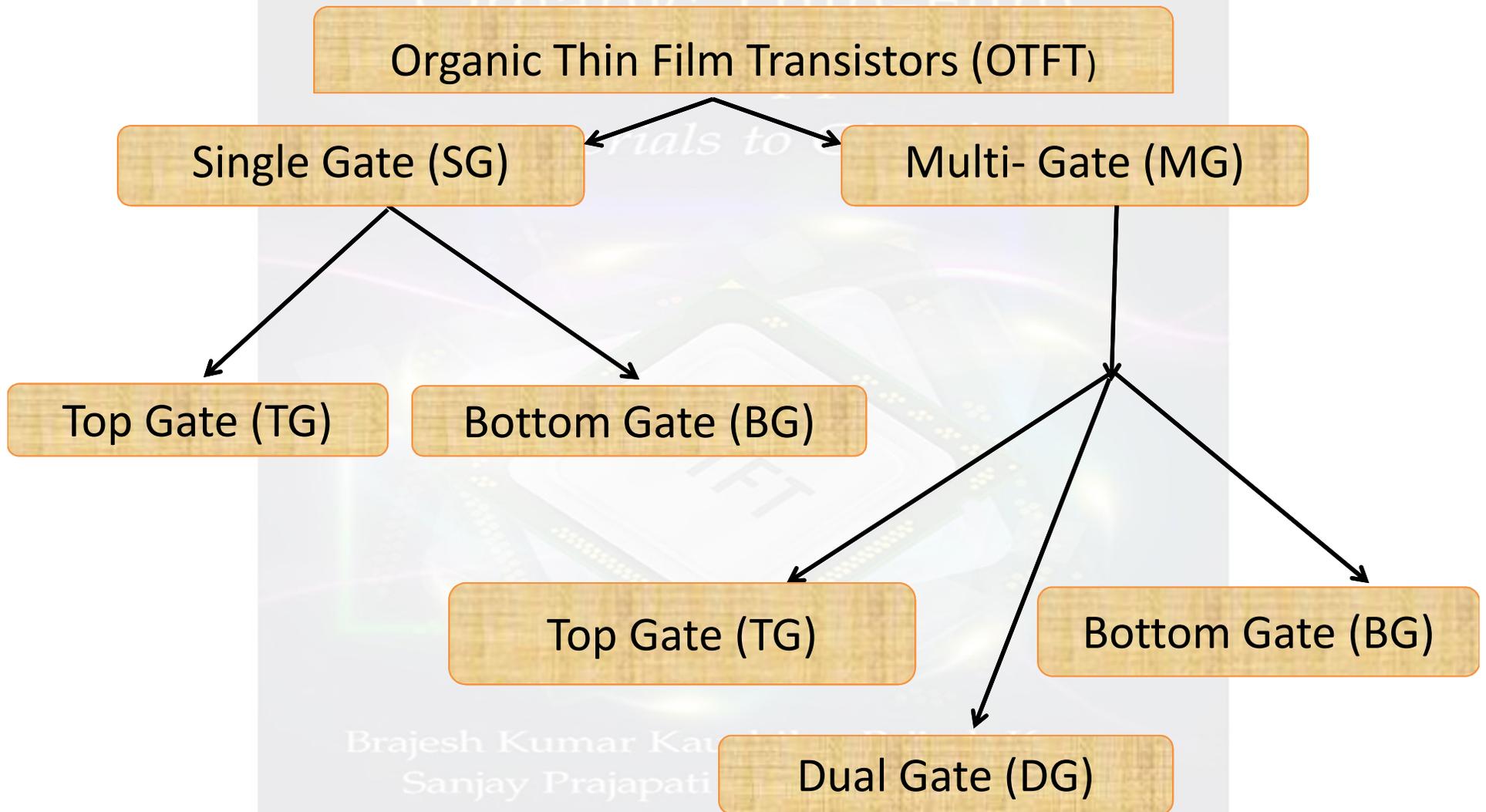


Motivation and Why OTFT??

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.

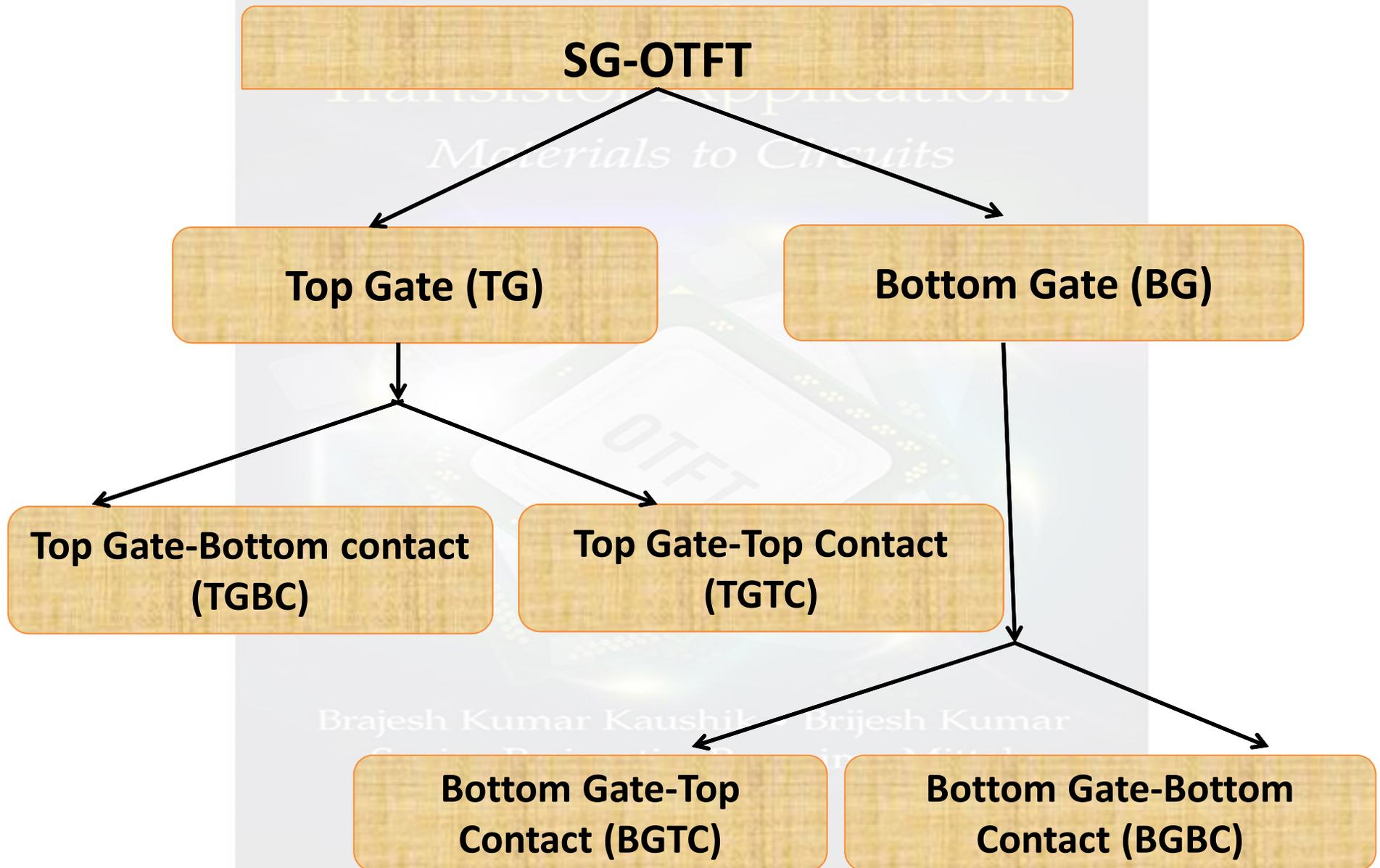
Classification of OTFTs Structures



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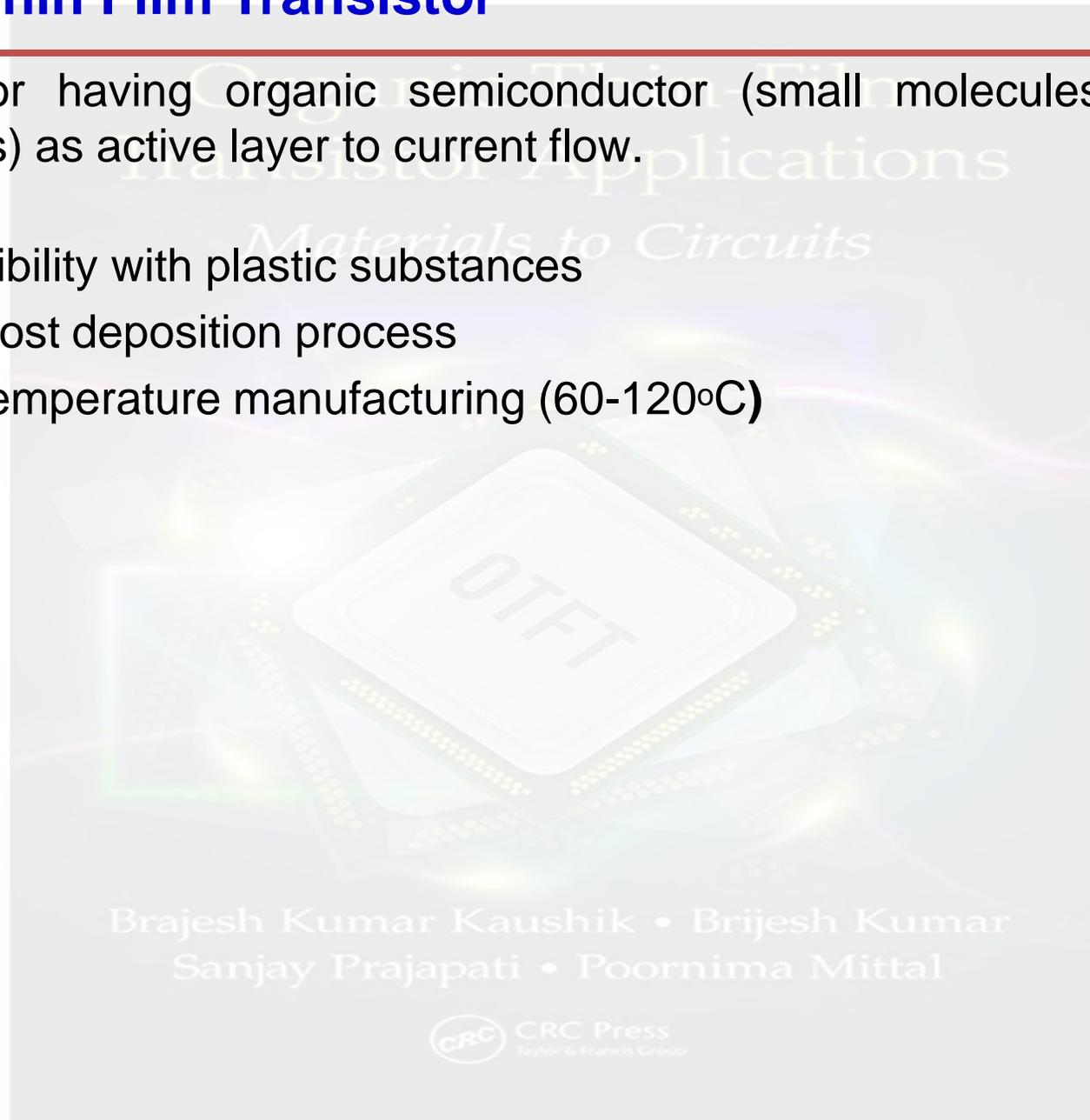
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Classification of Single Gate OTFT Structures



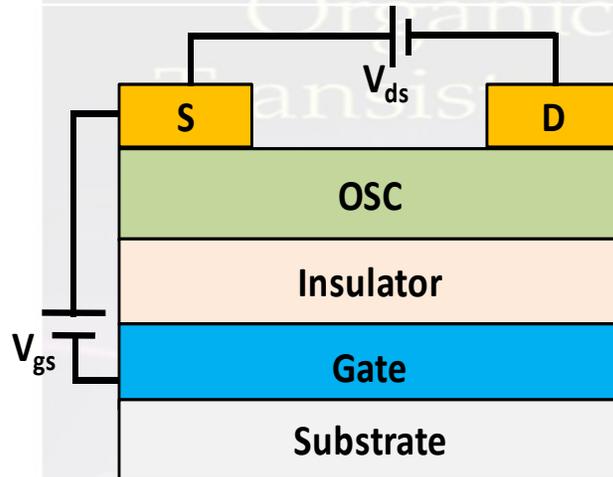
Organic Thin Film Transistor

- 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°C)



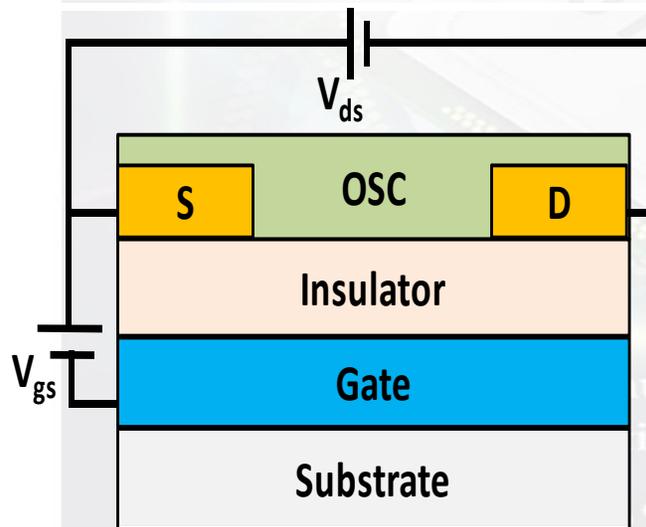
Comparison of BGTC and BGBCOTFTs Structures

BGTC



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

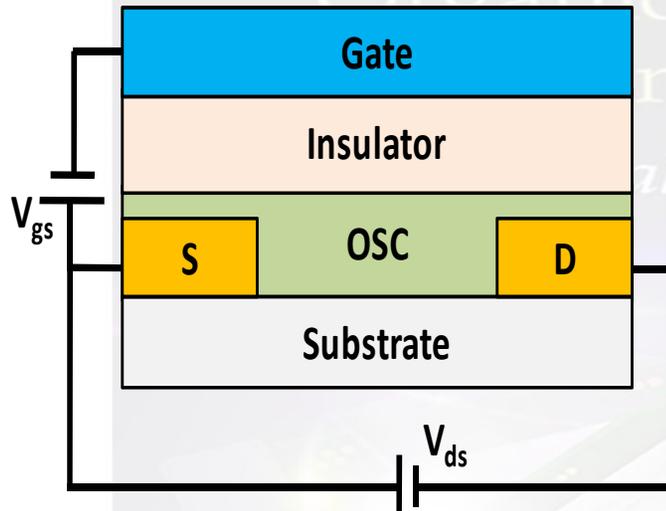
BGBC



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

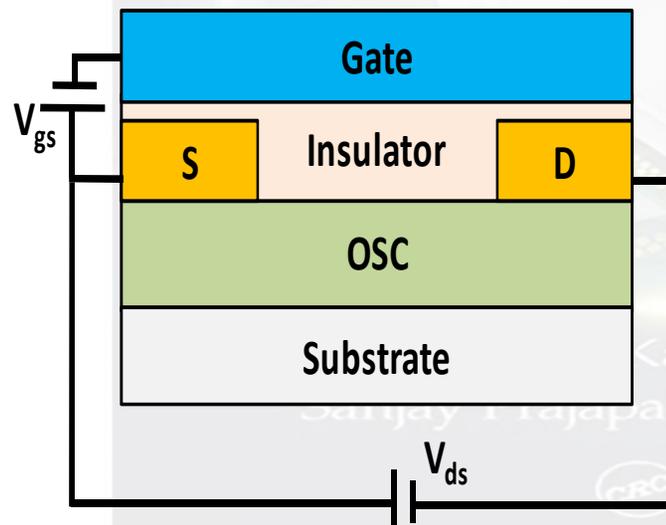
Comparison of TGBC and TGTC OTFTs Structures

TGBC



- Tough Fabrication.
- Low Contact Resistance

TGTC



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

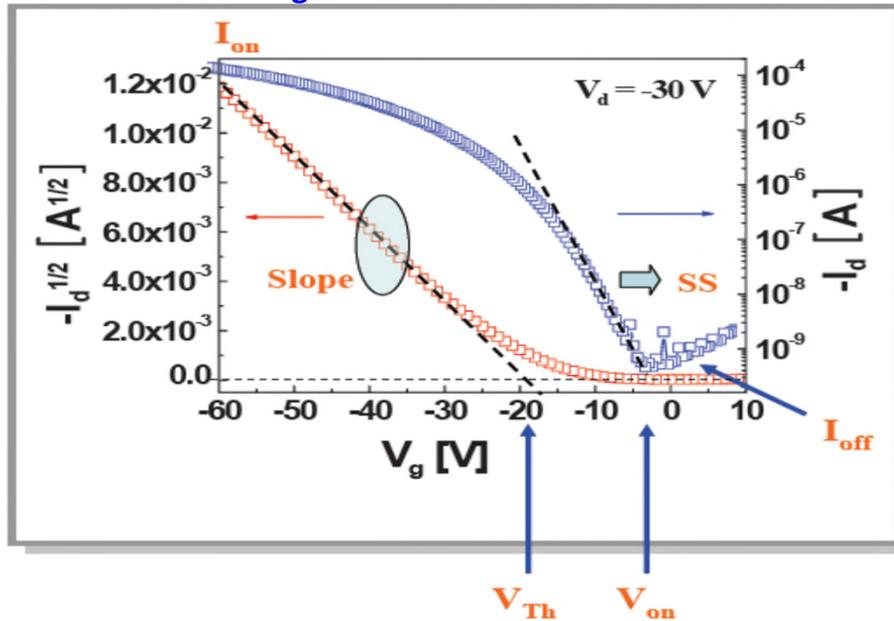
Difference Between Organic and Inorganic Material

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} - $5 \text{ cm}^2/\text{V.s}$	10^{-2} - $10^{-4} \text{ cm}^2/\text{V.s}$
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) [$\text{cm}^2/\text{V}\cdot\text{s}$]

$$\text{slope} = \left(\frac{W\mu C_i}{2L} \right)^{1/2} \quad \mu_{lin} = \frac{Lg_m}{WC_i V_D}$$

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

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: $> 1 \text{ cm}^2/\text{Vs}$ 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

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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 ₂ O 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)

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Electronic structure of Organic semiconductor

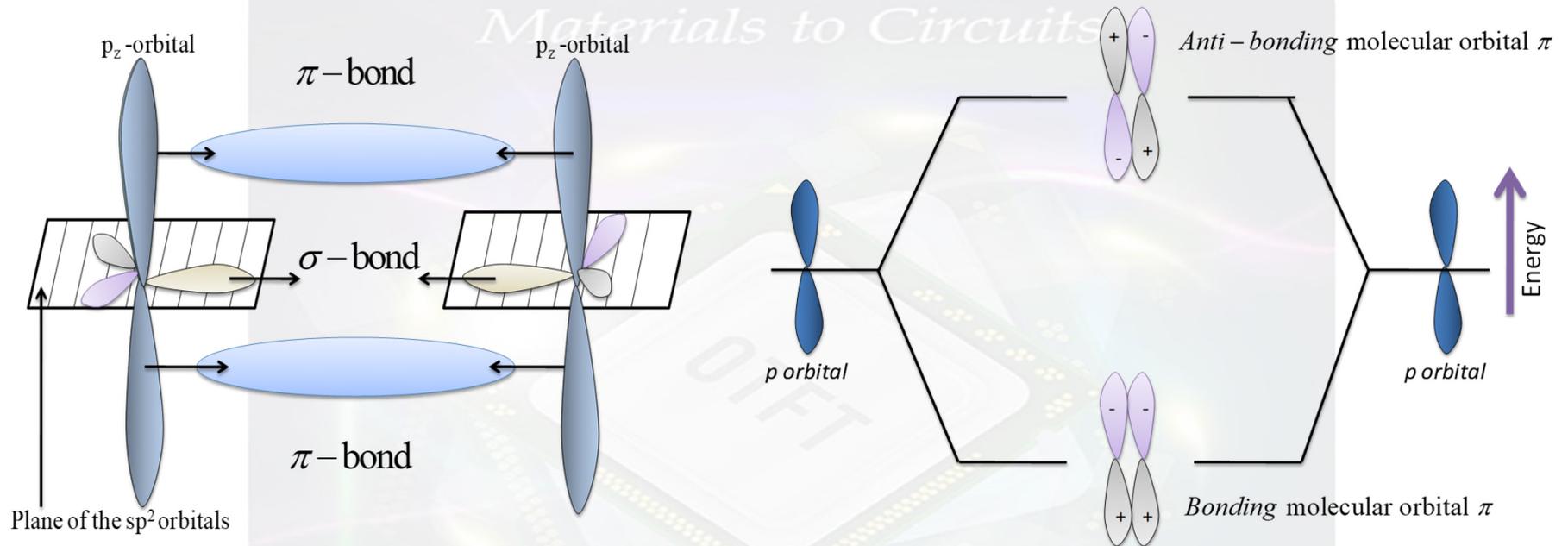


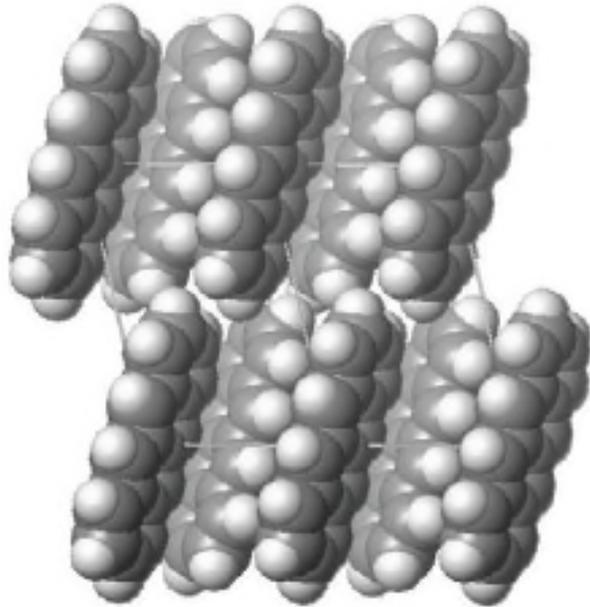
Fig. (a) sp^2 hybridization of two carbon atoms and (b) Bonding of p_z orbitals.

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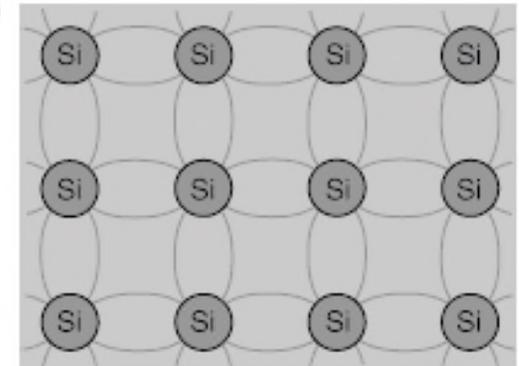
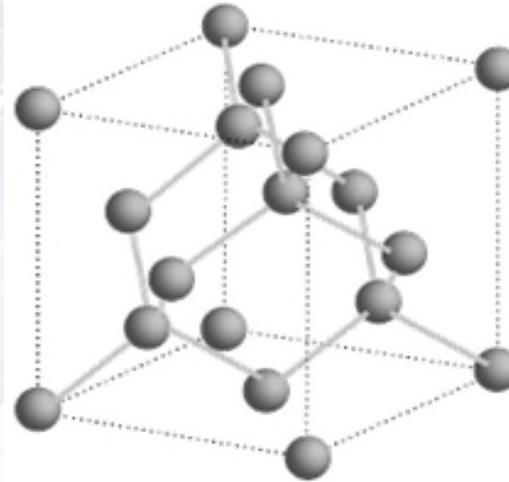
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Organic and Inorganic Semiconductors

Organic Semiconductor



Inorganic Semiconductor



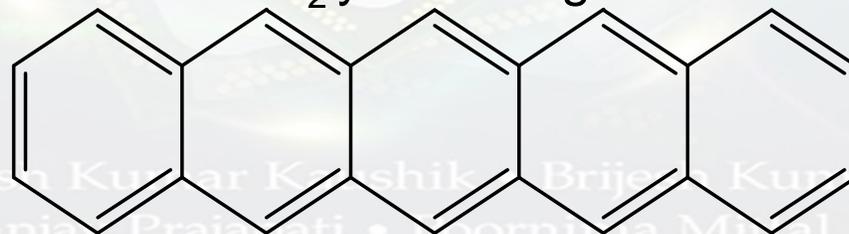
- Weak Van der Waals interaction forces
- π -bond overlapping
- Molecular gas property (molecule's identity)
- Hopping type charge transport dominant
- Low mobility and small mean free path
- Strong covalent bonds
- σ -bond
- Only crystal property
- Band type charge transport dominant
- High mobility and large mean free path

P-type Organic Semiconductors

Organic Thin-Film Transistors 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 SiO₂ yielded higher carrier mobility.



Pentacene

Chemical Structure of Pentacene small molecule Semiconductor

P-type Organic Semiconductors

Organic Thin-Film Transistor Applications 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.

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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

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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

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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.

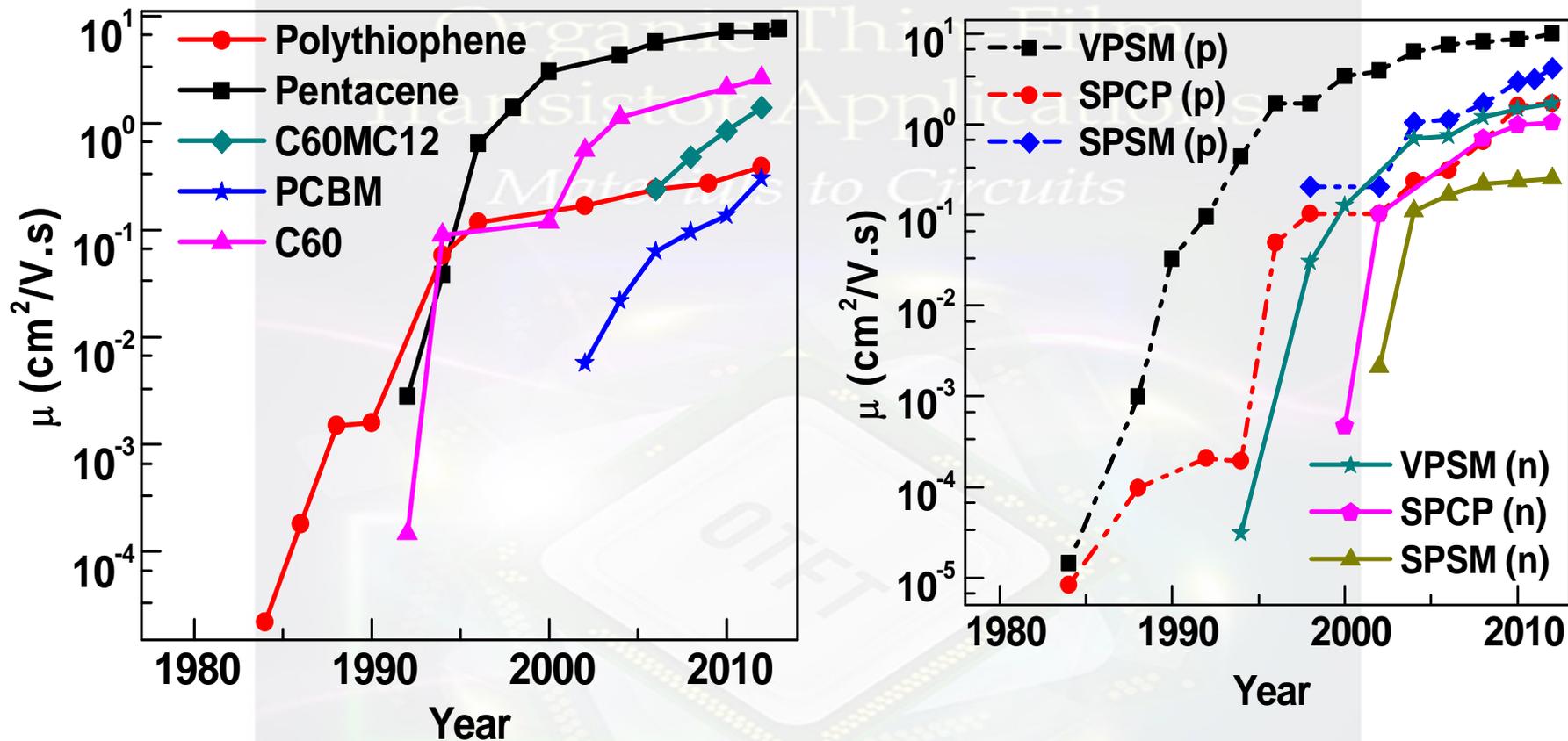
Limitations of Organic Material

- ❖ 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.

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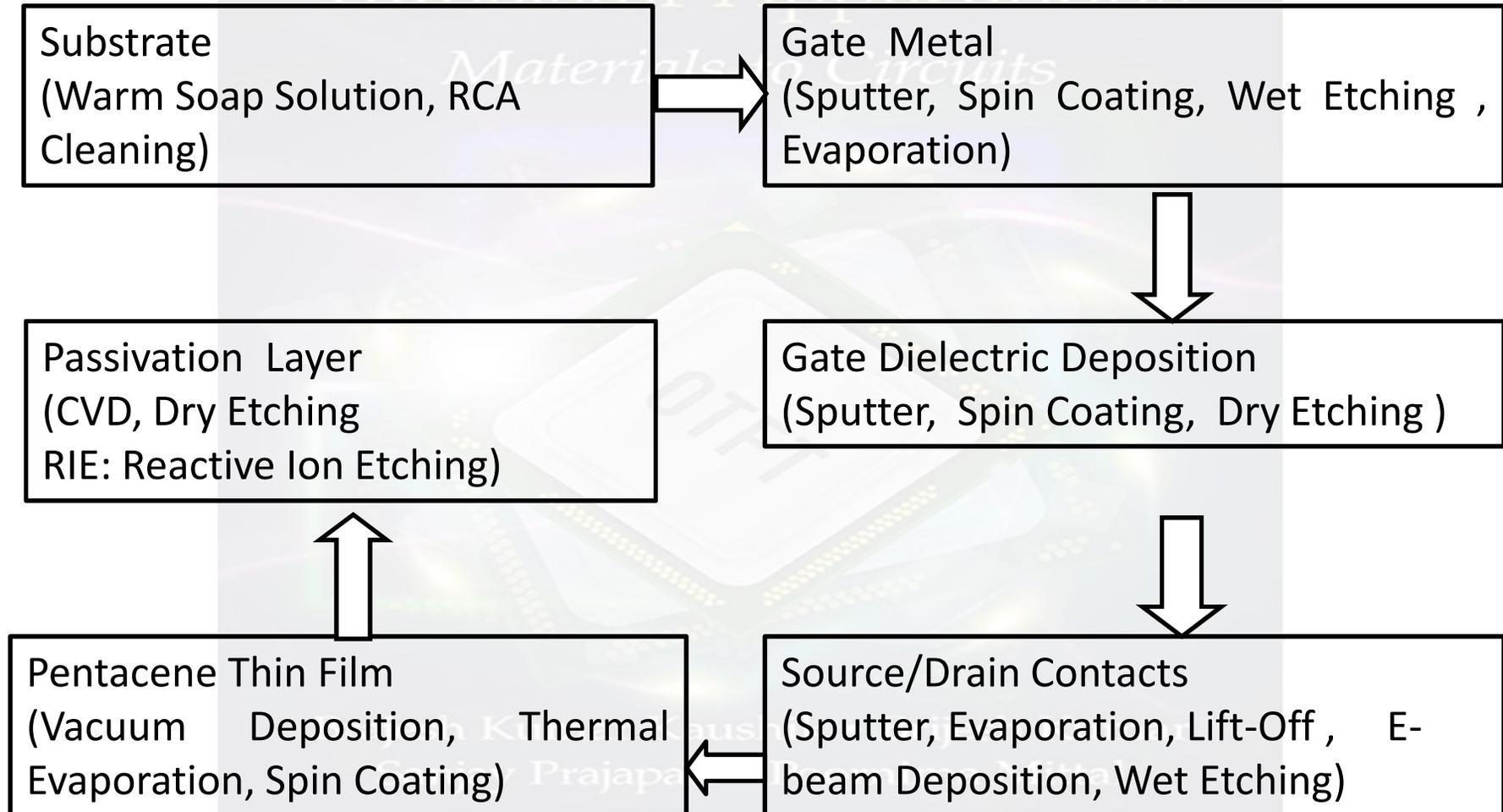
Performance of p and n -type OSC Materials in terms of Mobility



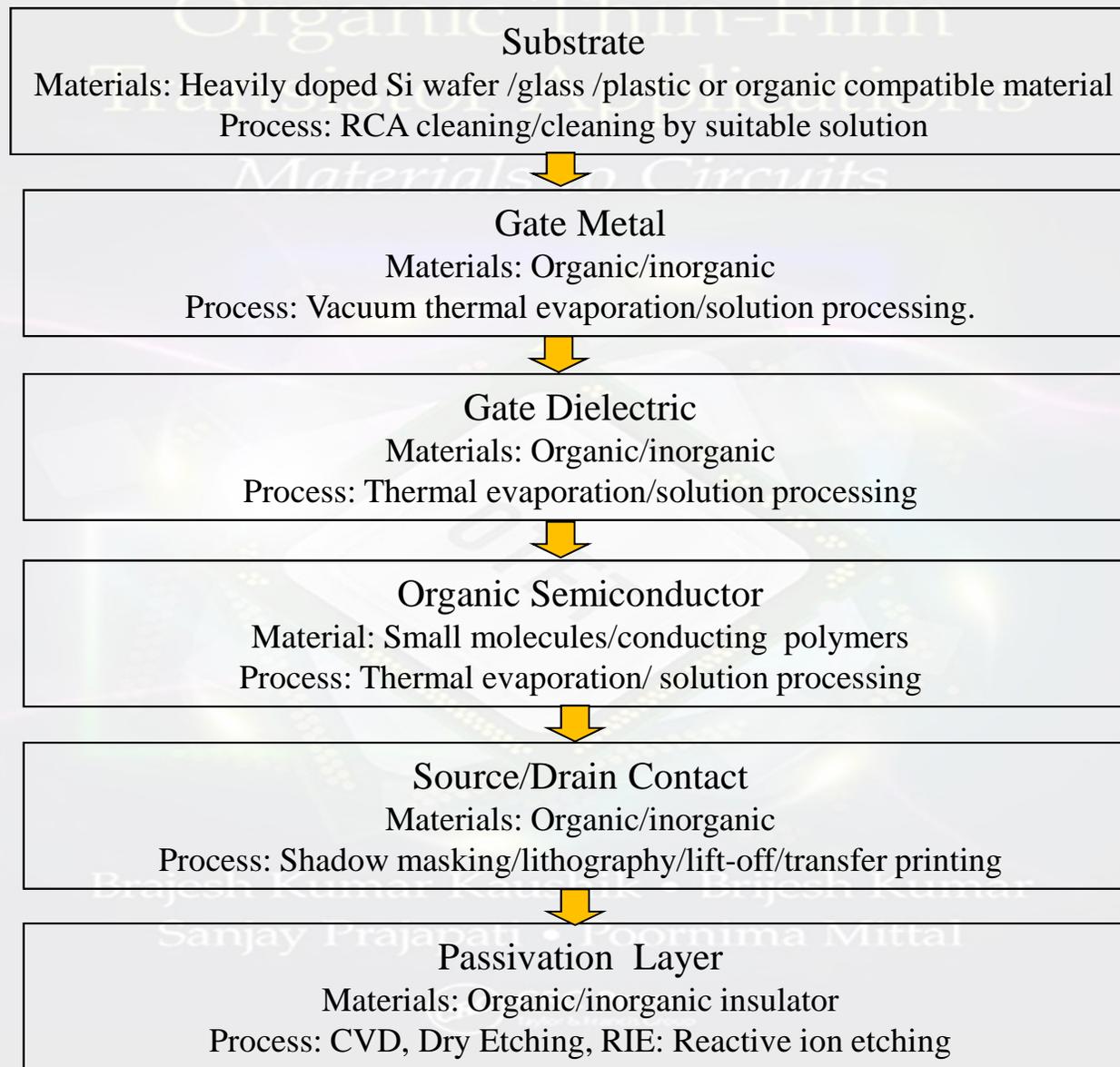
Comparative plot of mobility growth for p - and n -type OSCs

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

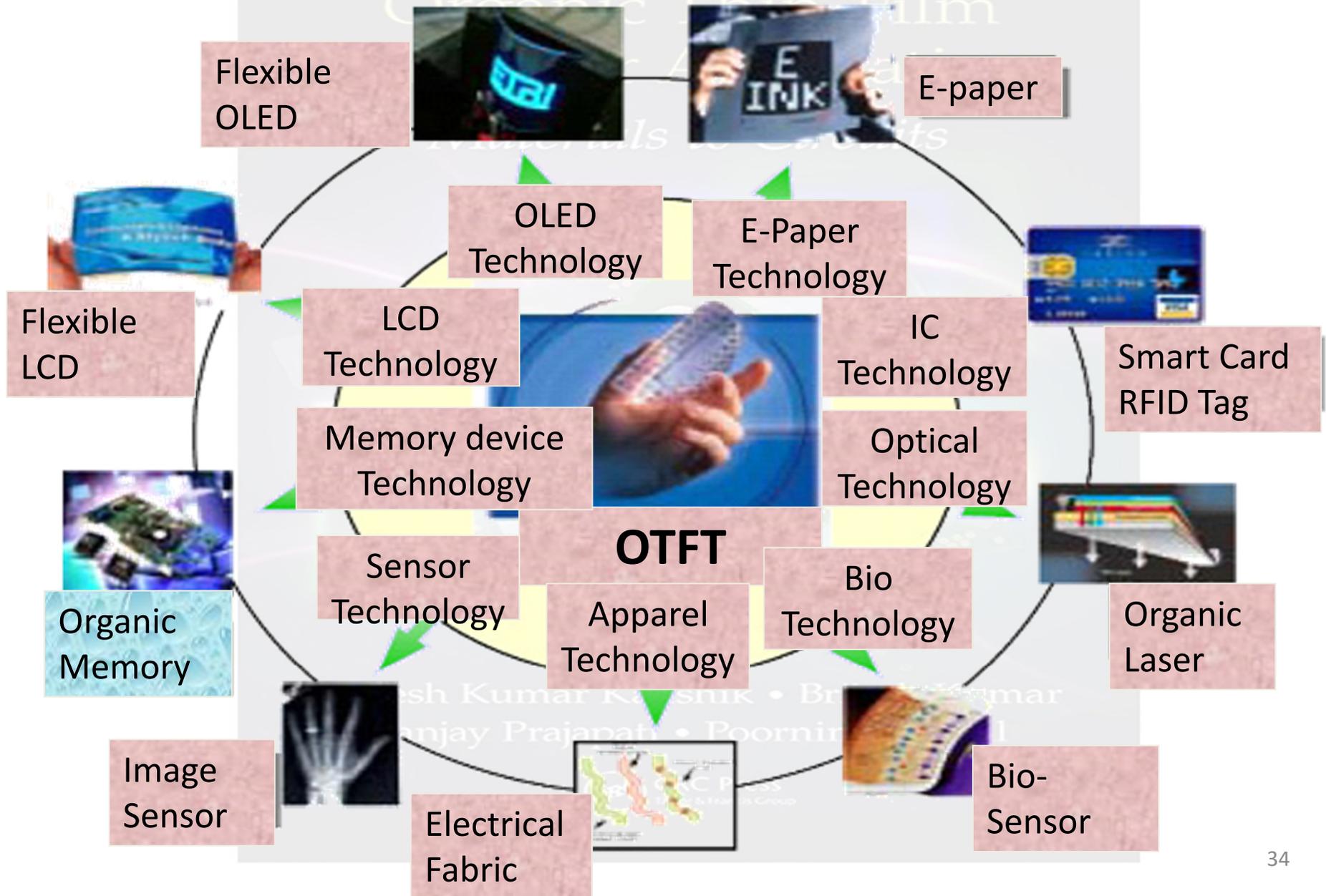
Basic Fabrication Steps SG-OTFT (BGBC)



Basic Fabrication Steps SG-OTFT (BGTC)



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

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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.

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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.