Organic Transistors

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***Abstract*—The amalgamation of organic materials in traditionally inorganic devices is a flourishing field of research. Organic transistors are a compelling subset thanks to their economic synthesis and flexibility compared to conventional Silicon-based technology. There have been several improvements in both realization and manufacturing processes since 1986—signified by the first Organic Field Effect Transistor (OFET). This paper provides a sketch of the physical properties and the compounds appropriate for designing such devices. It also describes diverse and fascinating applications of organic transistors in industry and ends with scopes of further improvement in the field.**

***Index Terms*—Biosensors, e-paper, organic, transistors**

I. Introduction

Transistors continue to reign supreme as the fundamental building block in our digital age. From amplifiers and logic gates to sequential components like flip-flops, every elemental device imaginable utilises them. It is, therefore, far-fetched to imagine a world without them. Naturally, we search for plenteous alternatives to Silicon, providing better properties and performance. Given their excellent solubility, low-temperature layering, cheapness, and suitability with sizable printing technology, OFETs have garnered a strong interest in plastic electronics [14]. Although traditional amorphous silicon-based transistors have made real strides—with mobilities of around 1.0 $cm^2V^{-1}s^{-1}$—thin-film layering of regular semiconductors require strong heating processes and contamination free zones, dramatically raising the manufacturing costs. Importantly, because of its inflexibilty, silicon-based materials almost cannot be processed on flexible substrates. On the other hand, organic-based semiconductors can be synthesised on plastic substrates better than silicon-based counterparts [13]. Organic transistors aren't meant to replace traditional ones, because of heavy limitations in their switching speeds. They have potential for new products like flexible displays, smart tags and electronic newspapers to name a few.

This paper briefly provides background information on the device's physics and specifications to equip one with the intuition behind what properties are desirable when designing organic transistors. It then looks at organic semiconductor examples with fetching features and techniques behind the manufacturing of organic transistors. It concludes with a thorough overview of the field's position in the electronic sector and possible prospects for future work.

II. Device Physics and Parameters

We begin by understanding transport of charges in organic materials. A 1D, single e^-, small polaron model developed by Holstein [1] is used. The carrier charge mobility is temperature and field dependent. For the **temperature dependence**, the mobility curve is extended to $E = 0$. On fitting the Monte-Carlo (MC) simulations, the expression is

$$\mu(T) = \mu_0 \exp\left[-\left(\frac{T_0}{T}\right)^2\right] \tag{1}$$

In (1) T_0 represents room temperature, and μ_0 is the corresponding mobility. Although this deviates from an Arrhenius Law, it fits the experimental data. **Electric fields** reduce energy barriers for e^- conduction band transport, and on fitting the MC results, we observe Poole-Frenkel behaviour [2]

$$\mu(E) = \mu_0 \exp\left(\beta\sqrt{E}\right) \tag{2}$$

The measurement techniques used to characterise charge mobility include Time-of-Flight measurement, Field-Effect Transistor configuration measurement and Space-Charge-Limited-Current measurement (TOF, FET, SCLC). For Organic-FET parameters, the current-voltage relations are known from silicon-based MOSFET equations. As one can conclude, the equation in the linear region is

$$I_D = \frac{W}{L}C_i\mu\left((V_G - V_T)V_D - \frac{V_D^2}{2}\right), \qquad V_G - V_T > V_D \tag{3}$$

The characteristics in saturation are

$$I_D = \frac{W}{2L}C_i\mu\left(V_G - V_T\right)^2, \quad \text{if } V_D > V_G - V_T \tag{4}$$

Although the mobility could be extracted from the square root characteristics' slope, it does not remain constant through the channel. Hence, mobility is extracted in the linear region where the charge density is uniform. While extracting mobility and transconductance in the linear region, one must be mindful of contact problems that cause variances from I_D vs V_D linearity [3]. The transconductance in the linear region is given by

$$g_m = \frac{\partial I_D}{\partial V_G} = \frac{W}{L}C_i\mu V_D \tag{5}$$

As (5) neglects $\partial\mu/\partial V_G$, we can obtain mobility from transconductance if and only if there is little variation of μ with V_G. Mobility is one of the most important parameters while designing the device, as it determines switching capabilities and the maximum current given device size. Consequently, efforts have achieved electron mobilities near the benchmark of 10 $cm^2V^{-1}s^{-1}$ and hole mobilities of reaching 20 $cm^2V^{-1}s^{-1}$ [4].

Apart from mobility, we also desire a large on to off current ratio. The on-current again depends on the mobility and the gate dielectric capacitance. I_{off}, which is undesirable, results from gate leakage-current. Bulk conductivity of the semiconductor and conduction routes at the interface influence off-current. Minimising unintentional doping in the transistor is effective in reducing off-current.

Threshold Voltage in organic transistors depends strongly on the organic materials used. There are many more dependencies of Threshold Voltage due to which it varies even in the same device. Organic FETs show bias-stress behaviour under which the threshold voltage increases as the device is used for extended periods. This, of course, heavily affects the usability of organic FETs and is a field of intense research [5].

III. MATERIALS USED IN MANUFACTURING

Organic transistors, like their inorganic counterparts, consist of four major parts. The substrate, electrodes, the semiconducting layer and the dielectric layer.

Minerals like quartz, glass and Silicon wafers or amorphous thermoplastic polymers like polycarbonate, polyimide may be used to construct the **substrate**. Inorganic materials provide higher melting points, smoother surfaces and minimal diffusion with chemicals and air. In contrast, polymer-based substrates have higher toughness, flexibility and light-weight. Irrespective of the substrate material chosen, all contaminants and impurities must be cleaned before use.

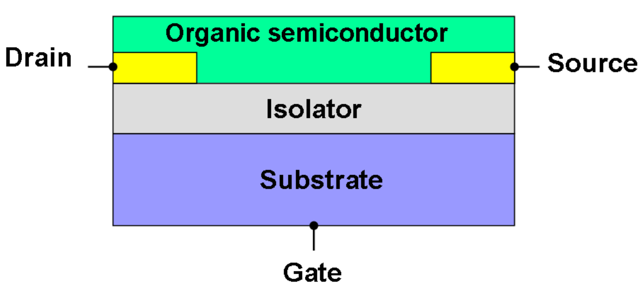

Fig. 1. Basic OFET structure [15]

Electrodes are popularly made of metals like gold, platinum, aluminium and magnesium. Non-metal counterparts such as graphite and camphorsulphonic acid doped polyaniline is also used. Work functions of the contacts influence the performance of these transistors and consequently influence the choice of electrodes. Lower work function metals such as magnesium and aluminium give slightly higher electron mobilities.

The **semiconducting layer** makes up the organic part of organic transistors. Organic semiconductors pass current by majority carriers, unlike their inorganic complements. This is due to the charge transport nature in them. In well-ordered inorganics, the delocalisation of electrons results in charge carriers moving in a continuous band. In organic materials, the charge carriers hop between individual, localised states of discrete molecules. This makes them particularly sensitive to impurities and inconsistencies in the structure. The resulting traps in energy levels caused by irregularities may inhibit the flow of charge carriers. Along the molecular π-orbitals, charge transport occurs. Therefore, overlap with neighbouring π-orbitals is very important. These complexities make the selection of organic semiconducting layers a formidable challenge. Next, we introduce some compounds that may be used to construct the semiconducting layer.

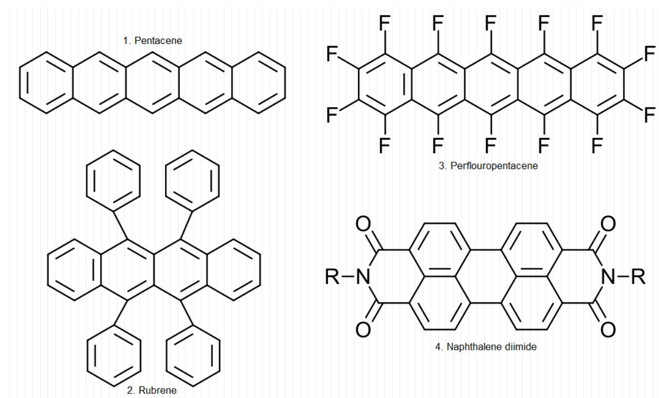

Fig. 2. Examples of Organic Semiconductors

P-type organic semiconductors: Acene and its derivatives compose the majority of these semiconductors. Polycyclic aromatic compounds are the popular choice. The oldest organic semiconductor—Pentacene, reported in the 1970s, is the standard for P-type organic semiconductor performance. For best carrier mobility, a tetracene derivative—rubrene shows 20 $cm^2V^{-1}s^{-1}$which is the highest mobility for monolithic devices in FET configuration.

N-type organic semiconductors: They lag behind their positive correspondents, due to their complex synthesis requirements, ambient instability in environments and low device performance—especially the significant limitations in carrier mobilities. Since they are necessary to develop any organic electronic device, we witness the need for stable N-type organic semiconductors with up-to-par carrier mobilities. These semiconductors are unstable in air owing to their high lowest unoccupied molecular orbital (LUMO) levels. The LUMO energy must be below -3.97 eV to prevent redox reactions. The first important N-type organic semiconductor—perfluoropentacene— reported by Sakamoto et al. [6]. It shows high μ value of 0.11 $cm^2V^{-1}s^{-1}$. However, its LUMO energy is not below the requirement to be stable in natural environments. Consequently, different materials needed to be tested out. Aromatic diimide materials show an N-type character on account of imide functionalisation. On substitution with cyano and halo groups, the air stability of the resulting compounds also improves significantly. Naphthalene-diimide with cyanides at core positions also show μ values as high as 0.11 cm^2/Vs and better stability as far as N-type organic semiconductors are concerned. Organic N-type small molecules are much sparser than their P-type counterparts. Correspondingly, good quality N-type polymers are much rare than P-type. However, complementary circuits require both. Currently, the most assuring N-type polymer is a naphthalene-based polymer called ($P(NDI_2OD\text{-}T_2)$), which exhibits high performance: μ values > 0.1 cm^2/Vs (up to 0.85 cm^2/Vs), excellent stability and $I_{on}/I_{off} = 10^6$ [7].

Finally, we come to the **dielectric layer**. The dielectric layer is characterised by high resistivity and a very high dielectric constant. The high resistivity ensures minimal current leakage between the active components. A high dielectric constant enables enough capacitance for current to flow through the channel and low switching voltage. Accordingly, inorganic insulators such as Ta_2O_5 or barium zirconate titanate (BZT) with high dielectric constants are used. Polymethyl methacrylate (PMMA) adheres well to pentacene and boosts its mobility up to ten times compared to a SiO_2 gate insulator. Since the dielectric interface with the active layer heavily determines the transistor characteristics, a smooth and defect-less interface is required.

IV. Fabrication Techniques

This section discusses some essential techniques commonly used in OFET fabrication.

Solution Deposition: Liquid deposition involves, as one may guess, deposition of the Organic-FET semiconductor material through various techniques. The organic materials are designed to be soluble. Insoluble compounds are dispersed to form colloids. This solution is then deposited via various techniques such as solution casting and spin coating. Solution casting provides better mobility to charge carriers than spin coating because slow evaporation accounts for better ordering. Because of issues with film thickness and compositional uniformity, it is not as perfect as vacuum deposition. However, it is an attractive method, thanks to its cost-effectiveness. This method is used for regioregular P3HT and other such soluble oligomers [8].

Thin Film Alignment: Aligned organic films have higher carrier mobilities thanks to the π-orbital interactions between adjacent molecules. Therefore, many deposition techniques have been investigated to align organic semiconductors. The techniques are broadly set apart by (1) mechanical force based alignment methods like friction-transfer and nanoimprinting; (2) depositing the material directly on the alignment layers via rubbing and photoirradiation; (3) using solution-processed techniques to align; (4) using field-induced alignment; (5) growing them in single inorganic crystals [9].

Patterning: Patterning is the act of confining the semiconductor in the channel region. This minimises cross talk and parasitic leakage. Different techniques may be used to carry out the patterning. Some examples include optical lithography, soft lithography and screen printing. Optical lithography is used to pattern larger features in microelectronics and photonics. Next, we have soft lithography, which encompasses various techniques of patterning. In general, Silicon is used as a base to fabricate a master structure. Then elastomeric replicas are made in a material such as polydimethylsiloxane (PDMS).

V. Current Status in Industry

Organics are attractive in the electronic industry—attributable to their lightweight, flexibility and low cost. Recent progress in performance has broadened the horizons of applications as well. Despite this, the OTFT backplane technology developed by FlexEnable is one of the only products used today. popSLATE—also developed by FlexEnable [10], in Germany—is an iPhone cover which consists of OTFT-driven flexible e-paper display.

Organic displays are furnished as OTFT switches to turn on singular pixels. With Gyricon Media, Plastic Logic has demonstrated a bistable reflective display which is driven by a printed active-matrix backplane. The prototype they demonstrated featured a 3024 bit display on glass, at 50 dots per inch (dpi). To take the name of a more well-known company—Philips, with E-Ink, has demonstrated a larger display with 85 dpi resolution and a bending radius of 2 cm [11].

Apart from e-paper displays, OTFTs also find applications in biosensor applications. Most biosensor applications involving organic transistors are potentiometric transducers. Slight changes in gate voltage will amplify the driven current, making them an ideal candidate for biological sensing—marked by feeble voltage fluctuations. Blood glucose measurement, which currently involves finger stick analysis, is painful. Organic transistors can provide noninvasive glucose detection [12]. Although these sensors are not yet commercialised, they are expected to find a big market in the future once they overcome mass production limitations and biocompatible devices are synthesised.

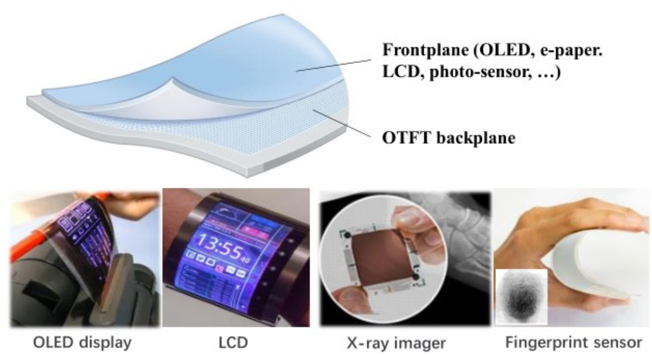

Fig. 3. Illustration of the structure followed by photographs of the developed applications based on the OTFT backplane technology from FlexEnable. [10]

Aside from these, organic transistors are also finding promise in CMOS technology. They may be used for lower power applications like RFID cards to identify, track, and verify their holders. Organic transistors may also find uses in lower-complexity applications incorporating logic operations, such as smart cards and disposable sensors.

VI. Conclusion and Future Direction of Work

In conclusion, organic materials' physical properties and comparatively simpler manufacturing allow for affordable, flexible and large-area devices. The applications described earlier herald a growing potential as well. That being said, we note that organic transistors currently find deficiencies in both performance and industrialisation abilities. Since it is imperative to improve on performance to expand the applications possible, efforts are being carried out to improve on each of the following material selection aspects such as:

- The selection of active semiconducting materials such as polymers, oligomers, or small molecules such that our selection maximises carrier mobility.
- Compatible gate dielectrics with high resistivity and dielectric-constant to provide minimal losses.
- Good ohmic contact providing metal electrodes.
- Building on device structure, dimensioning and spacing various components such as the thickness of the active and dielectric layers and accurate fabrication of the interface between the two.

Research is being executed on the association of device performance and molecular structure of the organic semiconductor. As mentioned before, maximising device matching improves mobility. Hence errorless fabrication techniques need to be developed. More attention is currently on discovering air-stable, solution-processable, high-performance organic n-type semiconductors to minimise the P-N organic semiconductor performance disparity. There is still a long way to go as far as industrialisation is concerned. The critical challenges concerning the industrial deployment of organic transistor devices are summarised below.

Lack of material stacks to produce high performance, stable and uniform Organic Transistors: Too much emphasis has been put on carrier mobility. There is a need to shift focus to commercial performance metrics such as uniformity, stability and manufacturability. These figures of merit should be handed over from the academic to the electronics manufacture and design community, since they are the ones fabricating the deliverables to users. **Lack of standardisation of material, device integration and manufacturing methods:** Although providing a versatile platform for experimentation, the lack of standardisation brings challenges for the whole community to work together. This is why the industry still lags behind the silicon industry in building an industry chain toward commercialisation. Efforts also need to be taken to reduce the entry barrier for the design community. **Trade-offs between large scale low-cost processing and performance:** With a suitable combination of mass-scale production and performance surety, opportunities can be opened for organic transistors. These goals come with their trade-offs. Mass-scale production inhibits critical feature monitoring, thus limiting performance. **Defining focused applications:** If there are more fabricators with consistent yield and regularity, faith in the OTFT technology will grow. However, currently, few concrete applications are found. Investments are hard to come by as a consequence.

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