Journal of Graphic Era University
Vol. 4, Issue 1, 22-31, 2016
ISSN: 0975-1416 (Print)

Characterization and Depth Analysis of Organic Thin Film Transistor

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Abstract
Organic semiconductor technology on polymer and flexible substrate is creating a base for researchers and industrial communities due to their ability to find application as a low cost, flexible and large area electronic device. In this paper an overview of Organic thin film transistor (OTFT) has been done. Different structures of OTFT have been explained on behalf of placement of source, gate and drain electrodes. The working principle of OTFT is enlightened with the help of energy band diagrams. As it is a three terminal device with source, drain and gate electrodes the operation of OTFT is similar to that of a MOSFET with difference in the process of channel formation which is briefly described in this paper. Application of OTFT is their most attractive feature and there are various possible ways of using it which were not possible with the silicon devices. Simulation of Bottom Gate Bottom Contact (BGBC) and Bottom Gate top Contact (BGTC) OTFT structures are carried out using 2-D Simulator ATLAS by Silvaco. The results show a major difference in performance of both the structures, thus highlighting the fact that structure of OTFT plays a very important role.

Key words- Organic Thin Film Transistor (OTFT), Bottom Gate Bottom Contact (BGBC), Bottom Gate Top Contact (BGTC)

1. Introduction

From more than five decades organic material are processed, synthesized and studied regularly. The photoconductivity response and drift management of small molecules were examined in 1950s. These materials showed poor stability and performance and their conductivities ranged from 10-9 -10-5 $Scm^{-1.}$ From the past two decades, because of the major developments in the processing and synthesis of new types of small molecules like conjugated polythiophenes (Kumar, 2014; Marien, 2011), commercially available organic semiconductors can be used in variety of applications such as OLEDs (Organic Light Emitting Diodes) (Liu, 2009), SRAM (Kumar, 2014), Solar cells, OFETs (Organic Thin Film Transistors), RFID tags (Kumar, 2014) and many more. The Sensotec Philishave was the first product that featured an OLED technology based display panel and was introduced by Phillips in 2002. Later, Kodak gave the Kodal Easy Share LS633 digital zoom camera. The commercialization of these devices are only possible because of the lower cost, flexibility and simple manufacturing process. (Mittal, 2015; Atlas User's manual, 2014; Kumar, 2014). OTFT devices are difficult to compete with the silicon devices but due to the advancement and major researches they have attained the Ion/Ioff ratio of 10^6 and mobility in the range of 10^5 -$10^{6.}$ The first OTFT was reported in 1986 which gave the mobility of 10^{-5} cm^2/Vs and was based on polymer polythiophene. Now greater achievements have been attained due to synthesis of new organic semiconductor and insulating materials. In organic semiconductors tunneling or hopping between the localized states are responsible for its low mobility, on the other hand organic semiconductors have higher mobility as the charge carriers move in wide delocalized bands.

In Figure 1.1 a flexible OTFT navigational display can be seen on the hand of a soldier used in locating fellow men and enemy. A mobile phone with transparent display is shown that can only be possible with the organic semiconducting technology.

2. Structure

To achieve greater performance from the semiconducting layer it is necessary to develop smart designs because the device structure is mainly responsible for the electric field effect in a transistor. The different types of device structure that are generally used in organic electronics are mainly inspired from the inorganic the film transistor technology as shown in Figure 2.1. The structure of OTFT is mainly defined by the placement of different electrodes with respect to the semiconducting layer and are classified as staggered and coplanar. In the coplanar category, all the three electrodes are sited on the same side of the OSC layer (structures a and d). In the staggered type devices, the source and drain are separated from the gate electrode by the OSC layer. These structures can be further divided as the top gate and bottom gate OTFTs (Kumar, 2014; Kumar, 2013; Gupta, 2009). Recently novel device structures have also been introduced such as vertical gate (Mittal, 2015), dual gate (Cui, 2005), ditch and elevated electrodes and diagonal channel (Cosseddu, 2007) structure. The dual gate structure finds many advantages with respect to the single gate OTFT structure in terms of better gate transfer control, higher mobility and larger drain current.

The dual gate structure also gives an insight into the device geometry effects; roughness of the surface of organic thin film as well as charge transport characteristics of the device (Wondmagegn, 2009). The modest, yet resourceful advantage of the diagonal and vertical channel arrangements is the regulation of the channel length across thickness of the active layer. Nanometric dimensions are possibly accomplished without embossing, e-beam lithography or other problematical methods. Furthermore, the placement of the source and drain contacts diagonally (crossing through the OSC layer) has a budding potentialin providing a good TFT outcome even if they are combined with semiconductor materials that form stumpy quality films.

While determining the anticipated transistor structure architecture, one must keep in thought the probable damages it can cause to the OSC because of the chemical collaboration with the succeeding organic layers (e.g. a polymer gate dielectric) or because of the dissemination of metallic atoms from the top electrodes (Kumar, 2013). Usually, the deposition of metal contacts takes place by thermal evaporation, due to this fact top gate devices are usually constrained to the fabrication of polymer based TFTs, as small molecules are easily degraded by the successive deposition of the gate electrode and insulator.

Additional fact that is worth considering is that organic devices that use metal electrodes evaporated on top of semiconducting films portray the disadvantage of low resolution through the shadow masking. But the chemical flimsiness of the OSCs prohibits the use of other conventional approaches, such as electron beam lithography and photolithography. Furthermore, the degree of metal penetration into the semiconductor is difficult to control. The reliability and quality of top-contact transistors are limited by all these aspects. However, solutions are constantly intensifying; one such was described by Noh et al. (Cui, 2005), who efficaciously fabricated by using a self-aligned all-printed technique a top-gate OTFT with 100-nm-long channel.

3. Device Operation

An OTFT device comprises of an organic semiconductor layer (OSC) also identified as an active layer, three electrodes namely drain, source and gate and an insulating layer. Analogous to the conventional MOSFET structure, the source terminal permits to inject carriers, the drain to excerpt carriers, and the gate to govern the conductivity of the channel formed between source and drain (Kumar, 2014).

When a voltage is applied to a gate electrode of an OTFT, a three terminal device, it controls the current flow between the source and drain electrodes by means of an imposed bias. A basic method is shown in Figure 3 where V_{ds} and V_g are the applied source-drain and gate voltages, respectively. Fundamentally, the organic thin film transistor functions like a capacitor. When a voltage is applied between Gate and Source, a charge is stimulated at the insulator semiconductor boundary. This charge creates a conducting channel whose conductance is directly proportional to Vg.

According to the Ohm's law, the current increases linearly with drain voltage, at low drain voltages. When the drain voltage comes close to the gate voltage, the voltage drop at the drain contact descends to zero, and the conducting channel formed is pinched off. This corresponds to the so-called *saturation region,* and the current happen to be independent of the drain voltage.

Organic FETs operates in the *accumulation mode* in a different way from the inorganic devices that operate in the *inversion mode*. The conduction process mainly takes place in the on-state, because of the layer of charge carriers which are formed in the semiconductor region within few angstroms from the insulator-semiconductor interface, and after the application of an appropriate Vg. These charges are of the equivalent to the majority charge carriers responsible for the current flow in the off state. A small portion of the total drain current is thus determined by the free carriers in the semiconductor region, which can be produced by unintentional doping or can be thermally generated. Regardless of this fundamental dissimilarity, the characteristic equations of the inorganic MOSFET transistors (Kumar, 2013) can be applied, as a first approximation, to an Organic FET.

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Where, L is the channel length of the transistor in the direction of the current flow from source to drain, Ci is the capacitance per unit area of the insulating layer, W is the channel width of the transistor, and μ is the field effect mobility of the transistor. The quality and nature of the organic semiconductor is crucial for obtaining high OFET performances that are mainly determined by the charge carrier mobility which symbolizes a measure of the charge carrier drift velocity per unit of the electric field. The mobility is also unswervingly related to the switching time of the device. Other imperative parameters are the On/Off ratio, which is the ratio between the current in the accumulation mode to the current in the depletion mode, and the threshold voltage (V), that is the voltage applied at the gate electrode corresponding to the formation of the conduction channel. The On/Off ratio is analytical of the switching performance of OTFTs, ratios as high as 106, suitable for most applications, can be achieved by current generation OTFTs (Kumar, 2013).

4. Working Principle

The operating principle of FETs relied on p-type organic semiconductors can be showed by the simplified energy level diagram of Figure 4.1.

When there is no Gate voltage applied (Figure 4.1b), the intrinsically undoped organic semiconductor, will not show any current formation. The only way to create current flow in the organic semiconductor is the direct injection from the Source/Drain electrodes. This current will be comparatively small because of the high resistance of the organic semiconductors and huge distance between Source and Drain electrodes. When a negative or positive voltage is applied at the gate electrode (Figure 4.1a), positive or negative charges are induced at the organic semiconductors interface with the Gate dielectric and a p-type conducting channel formation takes place. If the Fermi level of the Drain or Source metal is close to the LUMO or HUMO level of the organic semiconductor, then negative or positive charges can be removed by the electrodes through the application of a voltage V_{ds}, among the source and drain. Organic semiconductors that have the capability to conduct only negative or positive charge carriers are named as n-type or p-type semiconductors. In some organic semiconductors both holes and electrons may be inserted and accountable of charge transport realizing ambipolar transistors. Moreover, n-type organic semiconductors are not as much common due to the struggle of producing materials with a huge electron affinity that permits the addition of electrons from constant electrodes in air (Wondmagegn, 2009). Altogether along with the intrinsic properties of the electrodes and semiconductor, also the device configuration impacts its electronic properties (Tiwari, 2007; Mittal, 2016).

5. Simulation Setup

Characteristic behavior and different parameters of bottom gate and top gate structures are analyzed using industry traditional organic module tool Atlas by Silvaco, a 2-D numerical simulator (Atlas User’s manual, 2014). Both the structures are simulated with the iindistinguishable parameters. Fundamentally developed for inorganic and silicon devices, the Atlas simulator consents user-defined semiconductor material and has proved to be one of the most indispensablele tool for studying the device physics of OTFT and other organic devices (Wondmagegn, 2009). The Atlas simulation process usually consists of three parts (a) material parameters and operational bias conditions (b) physical modeling (c) structural dimensions and mesh specifications (Mittal, 2015).

The performance of top gate and bottom gate are analyzed keeping the material properties, dimensions and operating conditions unaltered . The devices simulated are all organic device i.e all the layers and electrodes of the device are made up of organic material. The dimensions of different layers and electrodes for the simulated structure are defined in the Table 1 and the simulated structures are shown in Figure 5.1.

Poole-Frenkel mobility model for holes is amended to visualize the results under proper boundary conditions and it is given by

$$\mu(E) = \mu_0 \exp\left[-\frac{\Delta}{kT} + \left(\frac{\beta}{kT} - \gamma\right)\right] \tag{1}$$

where, E is the electric field, Δ is the zero field activation energy with a value of 1.792 x 10^{-2} eV, k is the value of Boltzman constant , β is the Poole-Frenkel (PF) factor given as 7.758 x 10^{-5}eV (cm/V) $^{0.5}$, μ is the field dependent mobility, μ_0 is the zero field mobility ,γ is the fitting parameter and T is the temperature (Kumar, 2013).

6. Results and Discussions

The output characteristics of BGTC and BGBC are plotted with respect to different $V_{GS.}$ The output characteristics of BGBC are shown in the Figure 6.1. The output curves are plotted against the drain voltage and drain current. Maximum drain current achieved through the simulation of BGBC structure is 7.98 µA with threshold voltage 32.58 volts.

The output characteristics of BGTC structure is shown in the Figure 6.2. The current obtains by simulating this device is 30.63 µA which is much higher than the current obtained through the BGBC structure.

The simulated results of all the structures are given in the following Table 2. The main reason for a higher current value in the BGTC structure is due to the higher injection area for the holes in the top contact structure which is responsible for higher current flow inside the structure.

7. Conclusion

Thus we can conclude that organic electronics is the emerging field of electronics that have promising effects in the generation to come. Due to their flexibility and low cost, organic devices are finding various applications in today’s world. The structure of OTFT have gate

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electrode either at the top or at the bottom of the device with both having their own merits and demerits. The working of OTFT is similar to that of the MOSFET with majority charge carriers being holes and channel region formed due to the accumulation of charge carriers. ATLAS by Silvaco tool was used to simulate the structure of OTFT and output characteristics were obtained for both top contact structure and bottom contact structure of OTFT. The bottom gate top contact structure showed much better performance than the bottom gate bottom contact structure due to the higher injection area present for the BGBC structure.

Usage	**Material**	**Thickness**
Substrate	Plastic or any flexible material	
Gate insulator	Poly-3, 4-ethylenedioxythiophene: styrene sulphonic acid (PEDOT:PSS)	20 nm
Dielectric	Polyethylene-therephthalate (PET)	1.8 μm
Organic semiconductor	Pentacene	50nm
Source/ Drain	PEDOT:PSS	40nm

Table 1. Dimensions and materials for tg, bg and novel structures [cosseddu, p., 2007]

Structure	I_D**(μA)**	V_{th}**(V)**	μ**(cm²/Vs)**
BGBC	7.98	32.58	0.039
BGTC	30.63	32.76	0.13

Table 2. Extracted parameters of different structures

Figure 1.1 OTFT flexible screen used for navigational display and as a transparent display for mobile

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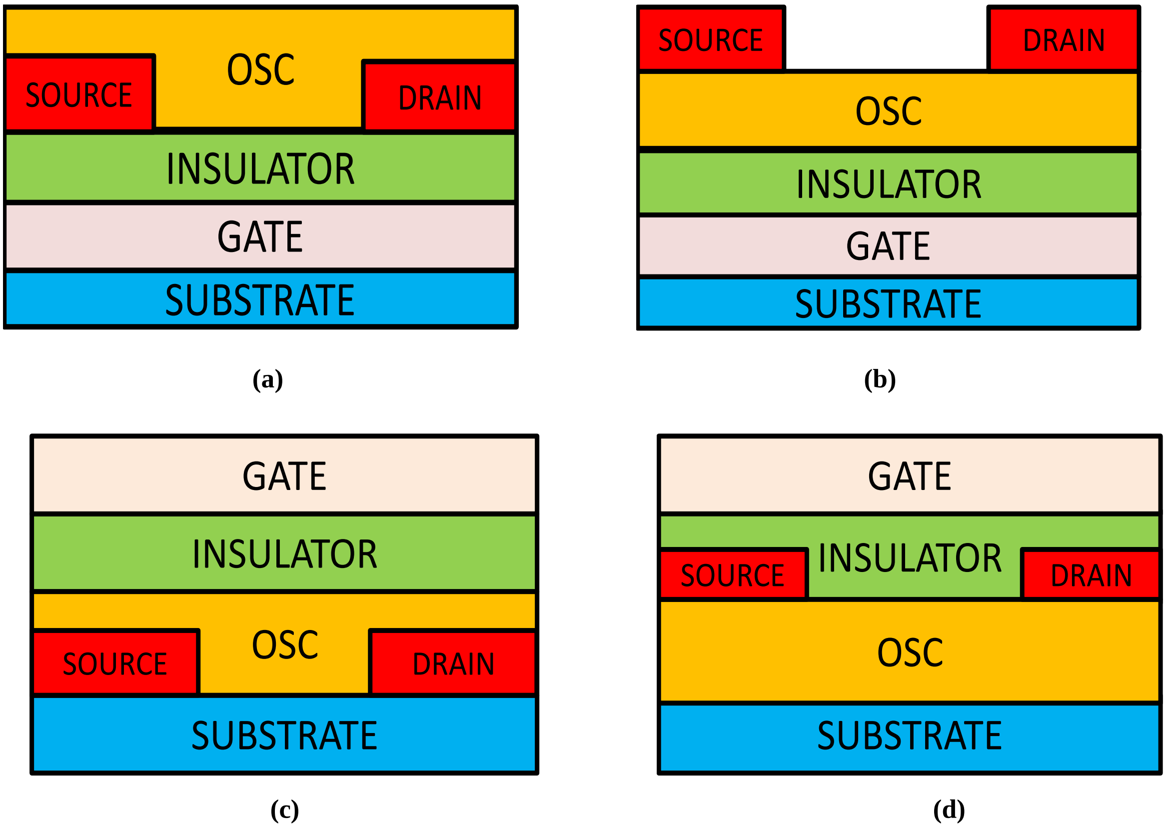

Figure 2.1 Structure of OTFT (a) BGBC (b) BGTC (c) TGBC (d) TGBC

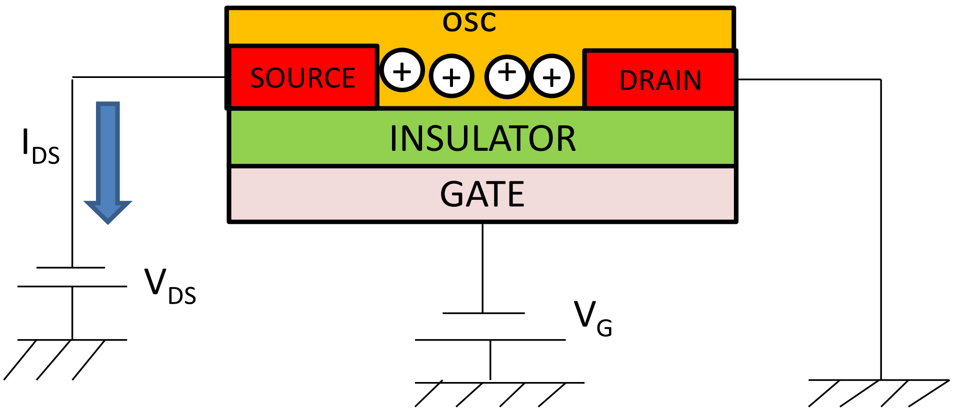

Figure 3.1 Schematic of biased OTFT device

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Vol. 4, Issue 1, 22-31, 2016
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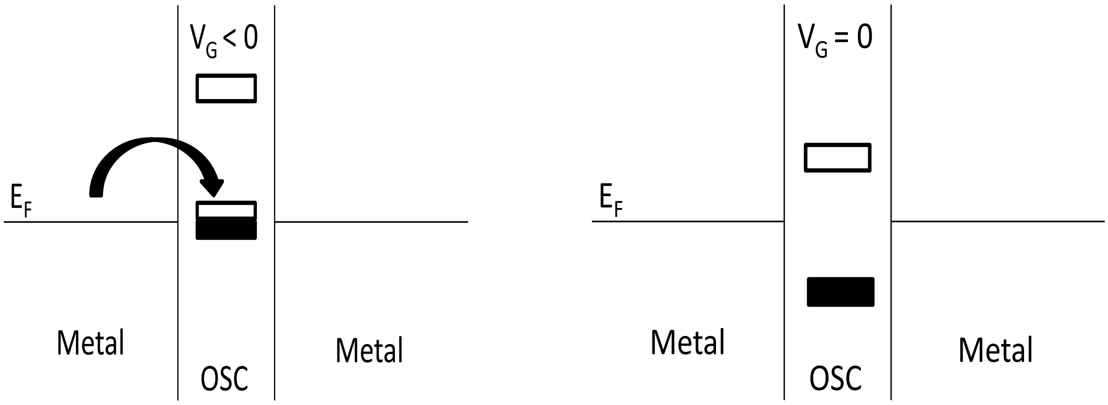
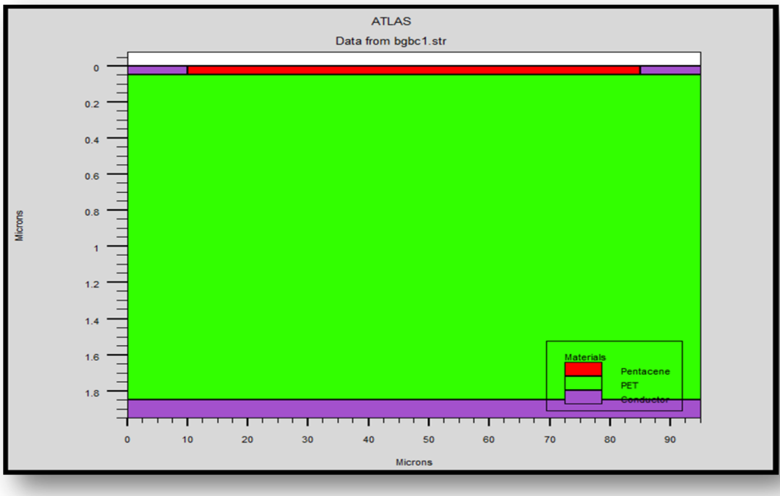
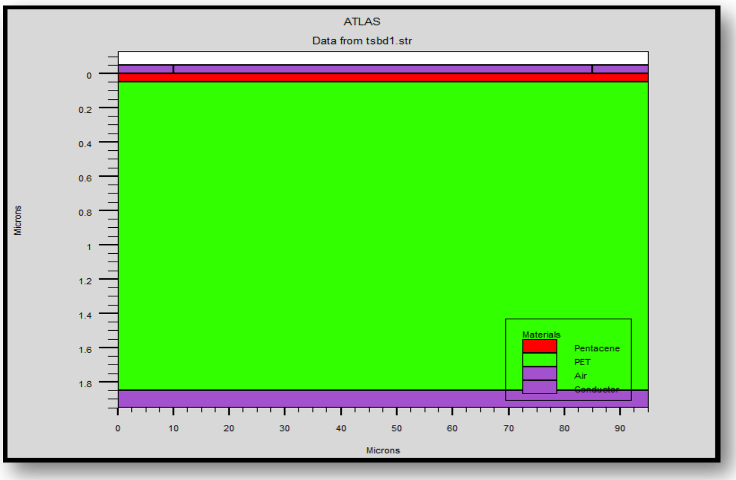


(a) (b)

Figure 4.1 Energy level diagram



(a)



(b)

Figure 5.1 Simulated Structures of (a) BGBC (b) BGTC

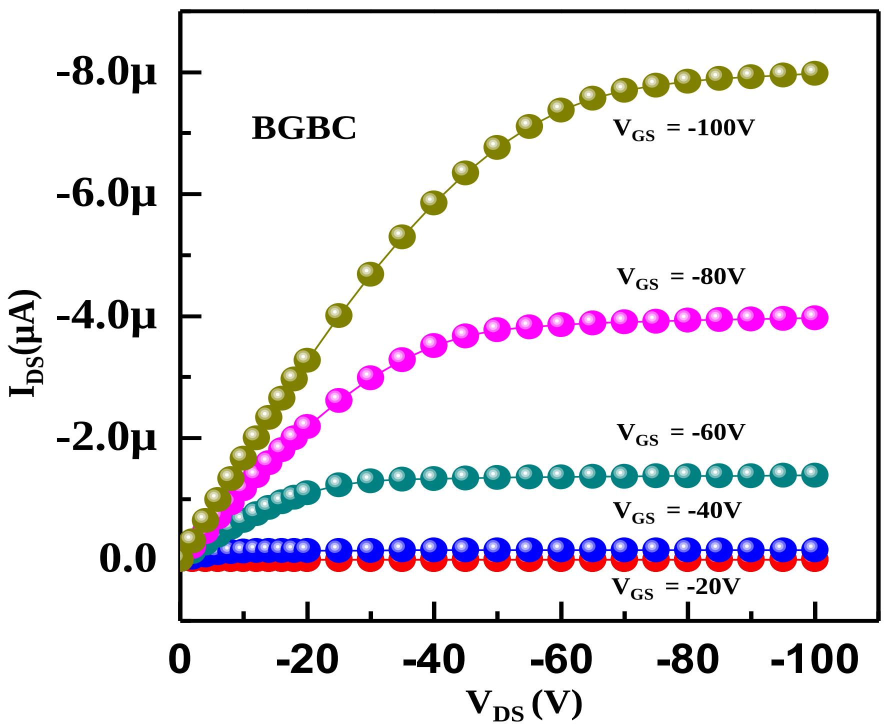


Figure 6.1 Output characteristics of bottom gate bottom contact structure

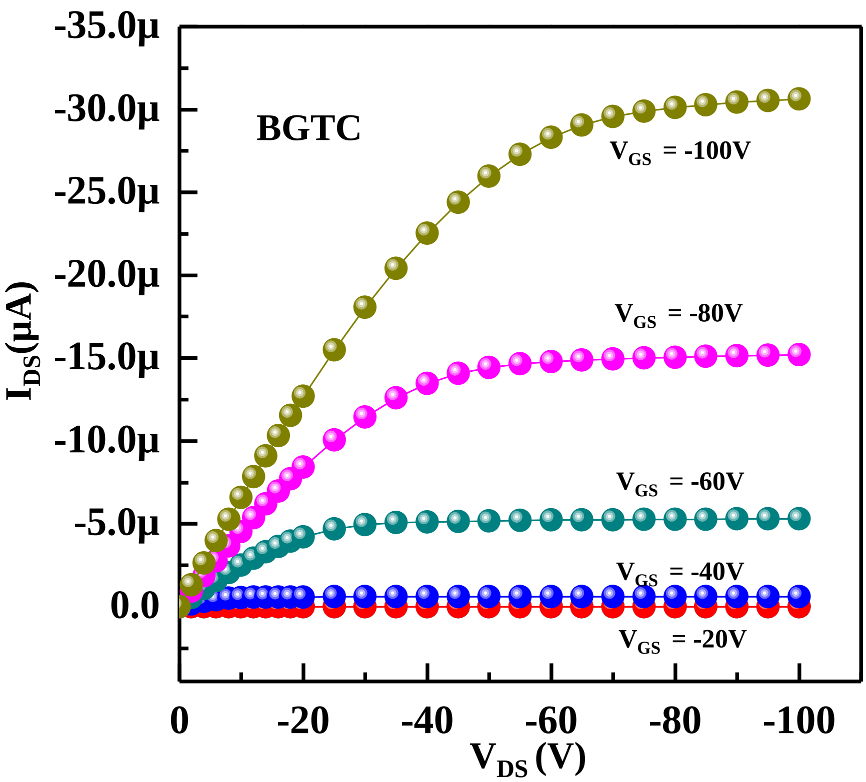


Figure 6.2 Output characteristics of bottom gate top contact structure

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