Transport Measurements in Field Effect Transistors

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1 Introduction

Charge transport is a fundamental property of materials that is determined and studied both in academia and industry. It determines how quickly a material's charge carriers move in response to an electric field. The parameter that is most commonly used is called the mobility μ which represents exactly this. When an electric field E is applied to a metal/semiconductor the electrons move with an average velocity v_d known as the drift velocity which is given by $v_d = \mu E$. This relation gives the mobility units $cm^2/(Vs)$. For normal metals we usually only care about conductivity which is the product of mobility and the charge carrier concentration. It doesn't matter so much if a metal has a high mobility with few charge carriers moving or low mobility with many charge carriers, the characteristics of a metal are determined from the conductivity. Whereas mobility plays a big role in semiconductors and especially transistors. Since transistors are a key component in modern electronics there is a lot of motivation to find new materials with high mobility which generally leads to better performance because there is better signal to noise from an on/off state. In this paper we will cover the basic properties of a transistor and the technique of measuring the mobility as well as discuss a newly fabricated organic semiconductor which has been shown to have the highest mobility yet.

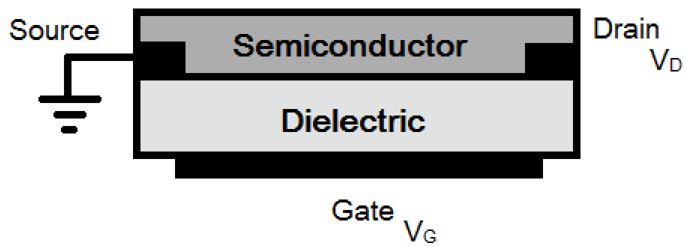

Figure 1: Schematic diagram of field effect transistor where the black bars represent the three different electrodes.

2 Field Effect Transistor

2.1 The Device

The Field Effect Transistor (FET) design acts much like a capacitor where there are two conductive materials sandwiched around a dielectric material. The general scheme of a FET, seen in Figure 1., contains three different electrodes called the source, drain, and gate. The gate electrode acts like the bottom plate of the capacitor, where as the thin layer of the material of interest is like the top plate. The two other electrodes, source and drain, are both placed in contact with the semi-conducting material but separated from the gate electrode in order to apply a voltage across the semiconductor material which is needed for creating a current through the material. Since all these layers and components are generally very thin ($\ll 1\mu m$), they are layered onto an insulating substrate which serves no purpose to the device other than a rigid platform. The electrodes are most commonly layered by conventional lithography techniques and made from gold due to its low resistance properties.

The typical setup is with the source electrode contacted to a ground and the drain and gate electrodes connected to variable voltage supplies. Varying the voltage of the gate layer will draw free charge from the source onto the semi-conducting surface which then acts like the top plate of the capacitor. This extra charge flow to the semi-conductor surface will allow a current to flow when a voltage bias is applied to the drain electrode. The charges from the source electrode accumulate on the interface of the semi-conductor and insulator which allow for a thin conducting channel. By varying the gate voltage one can then vary the current across the semi-conductor's surface.

As the gate voltage V_G becomes greater than a given threshold voltage V_T, an equal amount of charge, but opposite in sign, will accumulate on both sides of the dielectric initiating the conduction channel (*1*). The threshold voltage V_T arises due to there being an excess of holes or electrons in the semiconductor layer when $V_G = 0$ which would need to be filled or removed to create a conducting channel. An excess of charges along the semiconductor would result in a negative threshold whereas a excess of holes would result in a positive threshold. The charge distribution along the surface of the semiconductor is also affected by the gate voltage and the drain voltage. When $V_G = 0$ the charge carrier distribution is constant along the surface but as V_G increases and a drain voltage is applied, the voltage across the surface is no longer constant which means the charge distribution is not constant either. The voltage at the source electrode will always be zero and across the channel it will continuously vary until reaching V_D at the drain electrode. As long as $V_D > V_G - VT$ there will be a charge distribution throughout the entire channel and the current grows linearly with V_D, but as soon as $V_D < V_G - V_T$ there will be no charge carriers at the drain. When this occurs the channel is said to be pinched off and the current saturates (*1*). In this domain a change in V_D only brings a slight change in the current. Equations (1) and (2) model the current through the channel in the linear and saturation regime respectively (*1*)

$$I_D = \frac{W}{L} C_i \mu (V_G - V_T - \tfrac{1}{2} V_D) V_D, \quad V_D < V_G - V_T, \quad (1)$$
$$I_{Dsat} = \frac{W}{2L} C_i \mu (V_G - V_T)^2, \quad V_D > V_G - V_T, \quad (2)$$

where W is the width of the conduction channel, L is the length and C_i is the capacitance of the system.

2.2 Determining the Mobility

Equations (1) and (2) provide two ways of obtaining the mobility of a material. One way is by taking advantage of the saturation regime and looking at the square root of equation (2) which gives,

$$\sqrt{I_{Dsat}} = (\tfrac{W}{2L} C_i \mu)^{\frac{1}{2}} (V_G - V_T). \quad (3)$$

One can then measure the drain current while varying the gate voltage and plot the square root of the current against the voltage and equation (3) suggests that this would be a straight line with slope proportional to the mobility μ. This method of determining the mobility can be straight forward but it has some caveats. Since we are dealing with the saturation regime, the charge carrier density along the surface is not constant and can change drastically. This means the mobility is not constant throughout the surface either so the measured value is more like an average over the surface. To reduce this problem one can look at the linear regime where the charge density is closer to uniformity and measure the transconductance g_m. The transconductance is given by the derivative of equations (1) with respect to the gate voltage. One then obtains the relation (*1*),

$$g_m = \tfrac{\partial I_D}{\partial V_G} = \tfrac{W}{L} C_i \mu V_D. \quad (4)$$

By measuring measuring the current over different gate voltages one can then take the slope of these values and see that from equation (4) that it should be proportional to the drain voltage and determine the mobility of the material.

3 Organic FETs

The first FET was proposed by J.E. Lilienfeld in 1930 where he showed that current flowing the system could be modulated by just applying different gate voltages (*2*). Since then many variations of the FET have been constructed and have been made smaller and smaller. Within the past few decades the discovery of organic semiconductors has opened a new field of trying to study their properties as well as create 'plastic' electronics by forming transistors with these new materials. Since organic semiconductors have been about, mobilities on the order of 1 cm^2/Vs have been obtained and have been slowly increasing this value through different fabrication methods over the last decade. In 2014, Alan Heeger's group published their finding of a mobility of 23.7 cm^2/Vs in 2014 (*3*). The key component to their fabrication method is carving nano-spaced grooves in the substrate and then applying a thin polymer film by utilizing capillary action along the surface of the substrate (*3*). Once the polymer solution dries, the majority of the polymer chains align with the nano-groove spacing. Polymer chains tend to be very long molecules which leads to a low mobility from an improbable hopping between cites. By using a nano-grooved spacing they have been able to measure a mobility an order of magnitude higher than previously published results.

4 Conclusion

Here we have reviewed some of the basic properties of FETs and the different regimes that they operate in, and how taking advantage of these can lead to a determination of the charge carrier mobility through a semiconducting material. The advent of organic semiconducting materials has opened a new field of 'plastic' electrons by using the organic polymers as thin film transistors and that Heeger's group reports the highest mobility measured in an organic semiconductor with the fabrication on nano-grooved spacings.

References and Notes

1. D. Braga, G. Horowitz, Adv. Materials 2009, 21, 1473.

2. J.E. Lilienfeld (1920-01-28). US 1745175 ”Method and Apparatus for Controlling electrical currents”

3. H. Tseng, et. al. Adv. Materials 2014, 26, 2993