## Depletion width measurement in an organic Schottky contact using a Metal-

## Semiconductor Field-Effect Transistor

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Although the capacitance measurement is a common method to obtain the depletion width in a Schottky contact, the method is challenging in an organic Schottky junction since the capacitance is a combination of the capacitances associated to the trapped charges, bulk semiconductor and the depletion region. We have implemented a metal-semiconductor field-effect transistor structure in order to estimate the depletion width in an organic Schottky contact. In the transistor the depletion width is calculated from the drain current at a small drain-source voltage. The result suggests that the depletion width is exponentially dependent on the bias voltage.

Schottky contacts have been extensively used in organics to build various electronic devices including organic light emitting diodes (OLEDs)<sup>1</sup> and organic solar cells.<sup>2</sup> Also, organic Schottky diodes are used as rectifying elements in prototype organic circuits.<sup>3</sup> The AC characteristic of a Schottky contact is dependent on the depletion width at a given bias voltage.<sup>4</sup> Also, the subthreshold regime in organic field-effect transistors is studied on basis of the depletion width in a Schottky contact.<sup>5</sup> Furthermore, in a short channel transistors the device characteristic is dependent on the depletion width.<sup>6</sup> Therefore, the study of the depletion width and its variation with the bias voltage is useful to develop more accurate models for various organic devices and enhance their performances.

The depletion width in a Schottky contact between a crystalline semiconductor and a metal can be determined analytically using Poisson's equation.<sup>4</sup> In the full depletion approximation the magnitude of the net charge density in the depletion region is equal to the product of the unit charge, q, and the dopant density, N. For a uniformly doped semiconductor this product is constant which leads to an electric field linearly dependent on the distance from the junction and a quadratic potential profile in the depletion region. Consequently, the width of the depletion region, W, is expressed by: <sup>4</sup>

$$W = \sqrt{\frac{2\varepsilon_s}{qN}(V_{bi} - V_A)} \tag{1}$$

where  $V_{bi}$  is the built-in voltage in the Schottky contact,  $\varepsilon_S$  is the permittivity of the semiconductor, and  $V_A$  is the applied voltage across the junction in the forward bias. Knowing the depletion width, the junction capacitance (per unit area),  $C_J$ , is obtained from  $\varepsilon_S/W$ .<sup>4</sup> In a simple small signal model, applied for crystalline semiconductors, a Schottky diode behaves like a parallel RC circuit which R is the inverse of the conductance at a given bias voltage and C is the product of the junction area and the junction capacitance.<sup>4</sup> The capacitance across the diode is usually measured in different biases to obtain the depletion width. Plotting C<sup>-2</sup> versus V results a linear curve which the voltage intercept and the slope of the curve give the built-in voltage and the doping density, respectively.<sup>7</sup>

Unfortunately the depletion width can not in general be analytically determined in organic semiconductors. The net charge density in the depletion region is the summation of the densities of ionized dopants and the density of trapped charges in the localized states.<sup>7</sup> Since the density of the trapped charges is not constant in the depletion region and it changes with the bias voltage, the Poisson's equation generally has to be solved numerically to obtain the depletion width. To do so, the density of states in the organic is required, which is strongly dependent on the molecular order in the semiconductor. Usually the density of states is not known, in which case depletion width is estimated from the measured capacitance. In some organic Schottky diodes the capacitance measurement technique is applied to measure the depletion width and from that equation 1 is

applied to determine the built in voltage and the carrier density.<sup>8-10</sup> However, the AC model of an organic Schottky diode consists of three sources of capacitance, associated to the depletion width, the localized states in the organic semiconductor, and the bulk semiconductor, respectively.<sup>10</sup> Therefore, a simple capacitance measurement method across a Schottky diode, which gives the overall capacitance, is not appropriate for finding  $C_J$  and W in organic diodes, unless the junction capacitance is dominant. In this paper we are proposing a metal-semiconductor field-effect transistor (MESFET) structure to measure the depletion width in an organic Schottky contact. Although the method is useful to measure the depletion width independent from other capacitances, the dopant density and the built-in voltage are not determined from the depletion width as equation 1 is not valid in organic Schottky contacts.

The schematic of the device is shown in Figure 1. In a MESFET the drain and the source are making ohmic contacts with the semiconductor and the gate contact is a Schottky contact. The depletion region produced by the gate contact reduces the effective cross section of the semiconductor between the drain and the source. Therefore, the drain current is controlled by the depletion width. Application of a voltage between the gate and the source ( $V_{GS}$ ) changes the depletion width which changes the drain current. The Schottky contact in a MESFET is either at the reverse bias or at low voltage forward bias so that the gate current is much smaller than the drain current. The depletion width is a function of the voltage profile in the space between the drain and the source, known as the channel. For relatively large voltages across the drain and source ( $V_{DS}$ ) the depletion width is developed deeper into the semiconductor close to the drain contact. At a high enough voltage the channel is pinched off and the drain current saturates. However, for a small  $V_{DS}$  the variation of the depletion width along the channel is insignificant and the channel pinches off when the depletion region covers the entire thickness of the semiconductor by application of a large enough voltage across the Schottky contact. For a small  $V_{DS}$  the channel is modeled as a resistor<sup>4</sup> and the drain current,  $I_D$ , is expressed by:

$$I_D = \sigma \frac{Z(a-W)}{L} V_{DS}$$
(2)

where  $\sigma$  is the conductivity of the semiconductor, *a* is the semiconductor thickness, and *W* is the depletion width. *Z* and *L* are the channel width and length, respectively. Rearranging equation 2, the depletion width is:

$$W = -\frac{L}{\sigma \cdot Z \cdot V_{DS}} I_D + a \tag{3}$$

To study the depletion width in an organic Schottky contact, regioregular poly (3-hexylthiophene) (rr-P3HT), a well characterized and relatively stable p-type organic semiconductor,<sup>11</sup> is chosen as the semiconductor. To measure the

conductivity two gold electrodes with a thickness of 60 nm were deposited on a piece of Si/SiO<sub>2</sub> using a photolithography process. The spacing between the electrodes, *L*, is 4  $\mu$ m and each electrode has a length of 500  $\mu$ m (*Z*). A solution of 0.8% (weight) of rr-P3HT, supplied by ADS (www.adsdyes.com), in chloroform is used to make a 200 nm (±5 nm) thick polymer layer by dipping the gold electrodes into the solution and pulling it out slowly. The film is then cured by heating it at 120 °C for 30 min on a hot plate. The thickness of the film is measured by an atomic force microscope (AFM) after all electrical measurements are complete. Since gold is making ohmic contacts with rr-P3HT <sup>12</sup>, a linear I-V curve is obtained when the voltage is scanned from -3V to +3V (Figure 2). The slope of the curve shows a resistance of 52 MΩ which corresponds to a conductivity of 7.7×10<sup>-6</sup> S/cm for the given dimensions. The electrical measurement is done by a Keithley 6430 unit. To avoid any oxygen contamination<sup>13</sup> the film deposition and electrical measurement are done in a glove box filled with nitrogen. To deposit the gate electrode the sample is transferred to the chamber of a thermal evaporator embedded in the glove box. Since aluminum makes a Schottky contact with rr-P3HT,<sup>12</sup> Al is chosen as the gate electrode. A 120 nm thick layer of aluminum is then deposited all over the polymer to form a MESFET transistor. The Schottky contact between the aluminum and the polymer is first tested by measuring the I-V characteristic of the diodes formed between the drain/source and the gate. The results are presented in Figure 3, indicating a turn on voltage of about 1.1 V. Rectification ratios of about 800 are achieved at ±2 V in the both diodes.

In order to determine the depletion width, the drain electrode is biased at -0.3 V by a Keithley 2400 unit while the gate voltage is scanned from +3 V to -1 V using the Keithley 6430 unit. The drain current is plotted versus  $V_{GS}$  (Figure 4). Using equation 3 the depletion width is obtained versus the gate voltage, which is plotted in Figure 5. Since the polarity of  $V_{GS}$  is chosen to reverse bias the Schottky contact, the plot represents the variation of the depletion width versus the reverse voltage. At  $V_{GS}$  =3 V the depletion width is almost as thick as the semiconductor thickness (pinch off). The depletion width is about 172 nm at  $V_{GS}$  =0 V.

In order to check whether the depletion width is proportional to the root square of the voltage (as equation 1 predicts),  $W^2$  is plotted in the same chart (right hand axis). The nonlinearity between the voltage and  $W^2$  indicates that the equation 1 is not applicable in this organic Schottky contact. Using the least squares method, an exponential is fit to the width data. The equation which describes the fit curve is found to be:

$$W = 200 \times (1 - 0.1363 \exp(-0.6471 \cdot V_{GS}))$$
<sup>(4)</sup>

where W has units of nm. The fit is within 0.2% error at every measured point. Therefore, the relationship between the depletion width and the voltage is more exponential than quadratic, as it has been observed by others in non-crystalline

semiconductors.<sup>7</sup> The exponential variation of the depletion width is due to the distribution of localized states in the organic semiconductor.

The MESFET approach is suitable for measuring the depletion width both in crystalline and non-crystalline semiconductors, including organics. As an advantage the MESFET method allows to measuring the depletion width at DC bias, whereas in the capacitance measurement the measured depletion width is dependent on the applied frequency.<sup>8,14</sup> However the method does require the fabrication of a three electrode device, and only works at a junction under reverse and at low voltage forward biases. At a high voltage forward bias where the gate current is comparable to the channel current equation 3 is not valid. In conclusion, we have applied a MESFET structure to measure the depletion width in a Schottky contact between aluminum and rr-P3HT. The depletion width is calculated from the drain current in the transistor when a small  $V_{DS}$  (-0.3V) is applied. The result indicates an exponential dependence between the depletion width and the voltage across the junction.

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Figure 1. The structure of a Metal-Semiconductor Field Effect Transistor (MESFET).

Figure 2. The source-drain I-V curve of a 200 nm thick rr-P3HT film.

Figure 3. The I-V curve (inset: semi-log I-V curve) of the Schottky diode between the drain/source and the gate electrodes in the organic MESFET.

Figure 4. The drain current versus the gate voltage in the organic MESFET at VDS=-0.3V.

Figure 5. The depletion width versus the voltage. ( $\blacktriangle$ ) calculated W from the drain current ( $\bullet$ ) fit curve calculated from equation 4, ( $\blacksquare$ ) W<sup>2</sup> versus the voltage.



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