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Solid-State Electronics 47 (2003) 691–694

SOLID-STATE ELECTRONICS

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Fabrication and electrical characteristics of polymer-based Schottky diode

Guirong Liang, Tianhong Cui *, Kody Varahramyan

Institute for Micromanufacturing, Louisiana Tech University, P.O. Box 10137, 911 Hergot Avenue, Ruston, LA 71272, USA

Received 17 June 2002; received in revised form 2 August 2002; accepted 8 August 2002

Abstract

Metal/polymer Schottky diodes have been fabricated using spin-coated poly(3,4-ethylenedioxythiophene) (PEDT) doped with poly(styrenesulfonate) (PSS) as the p-type semiconductor and aluminum as the metal. The current–voltage and capacitance–voltage characteristics have been studied at room temperature. The breakdown voltage and rectification ratio of the Al/PEDT Schottky diode are about 5.5 V and 1.3×10^4, respectively. A modified Norde function combined with conventional forward *I–V* method was used to extract the parameters including barrier height, rectification ratio, ideality factor, as well as the series resistance. This new method allows extraction of device characteristics from measured *I–V* curve that deviates from ideal *I–V* curve caused by series resistance.

Keywords: Polymer Schottky diode; Spin-coating; PEDT/PSS; *I–V* characteristics; Norde function

1. Introduction

Recently, there has been great interest in polymer microelectronic devices due to very promising applications such as organic light emitting diodes [1,2], photovoltaic cells, and field-effect transistors [3,4]. Because the electrical characteristics of the junction determine the device performance, the study of the Schottky contact characteristics is vital for the polymer-based devices.

Since 1990, some attempts to fabricate metal/polymer Schottky diodes and interpret their electrical characteristics have been made [5–7]. However, the fabrication methods described in previous papers appear complicated and the electrical characteristics of metal/polymer Schottky diodes need to be improved. The *I–V* curves deviated from ideality cannot be fit by the exponential equation. In this paper, we use the simple spin-coating technique to fabricate the polymer-based Schottky diode and present a new method to extract the correct electrical characteristics in which the effects of the series resistance and the ideality factor have been taken into account. The method is based on the modified Norde function method combined with the conventional forward *I–V* method.

2. Experimental

When metals having a lower work function than that of the semiconductor contact with the semiconductive polymer, a Schottky barrier may be formed at the interface. The energy diagram of the metal/polymer contact at zero bias is shown in Fig. 1. At the interface, we can find the energy level alignment and the band bending as shown in Fig. 1. To fabricate the polymer Schottky diode, heavily doped silicon wafer was used as an electrode (resistivity of about 0.01 $\Omega \cdot$cm). Poly(3,4-ethylenedioxythiophene) (PEDT)/poly(styrenesulfonate) (PSS) (Baytron P), functioning as the semiconductive layer, was then deposited on the silicon substrate by spin-coating with a thickness of 1 μm. Upon finishing

* Corresponding author. Tel.: +1-318-257-5122; fax: +1-318-257-5104.

E-mail address: tcui@coes.latech.edu (T. Cui).

PII: S0038-1101(02)00324-6

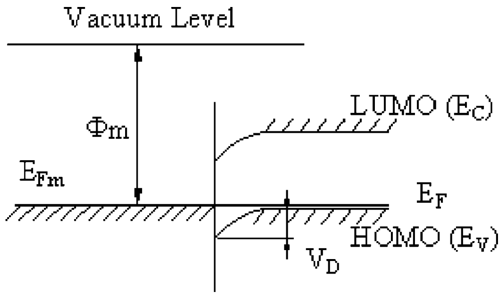

Fig. 1. Schematic energy diagram of metal/polymer structure at zero bias.

the spin-coating, the PEDT/PSS film was cured for 5 min at 120 °C and then slowly cooled down to room temperature in order to minimize the thermal stress. The resistivity of these PEDT/PSS films, as measured by Keithley 236 instrument using two parallel electrodes, was found to be 1.26 $\Omega \cdot$ cm. Then a 150 nm thick Al film was thermally evaporated on the PEDT/PSS film in vacuum. At last, the polymer Schottky diodes were formed by the reactive ion etching (RIE) technology with Al as the mask that can avoid the chemical attack from the solution. The electrical characteristics of the polymer Schottky diode were measured point-by-point with 1-min intervals to approach a steady-state condition with Keithley measurement system.

3. Results and discussion

The electrical characteristics of Al/(PEDT/PSS) junction have been analyzed by assuming the standard thermionic emission theory of the Schottky barrier model holds. In using this theory, it is usually assumed that the current is only controlled by the transport of carriers across the junction interface, and the drift and diffusion of carriers within the depletion region are unimportant. Then, the current as a function of applied bias V is given by Eq. (1) when the forward bias $V > 3kT/q$:

$$I = I_S \exp(qV/nkT) \tag{1}$$

where I_S, the saturation current that could be obtained from the extrapolation of the linear portion of $\ln I$–V plot, is given by

$$I_S = AA^*T^2 \exp(-q\phi_B/kT) \tag{2}$$

where A is the contact area, A^* is the effective Richardson constant (120 A/K^2 cm^2), k is the Boltzmann's constant, T is the absolute temperature, ϕ_B is the barrier height, and q is the elementary charge.

Fig. 2 shows the I–V characteristics of the Al/PEDT contact. The breakdown voltage of the diode is shown to be about 5.5 V, which is much lower than the silicon diode but almost 3 times higher than the breakdown voltage of the Al/PP (doped polypyrrole) Schottky diode [5]. Due to the low conductivity of the PEDT/PSS polymer, the measured I–V curve shows an excessive series resistance, and the conventional I–V extraction method for parameters like Schottky barrier height does not work well in this case. Here, we use the modified Norde function method to determine the Schottky barrier height while overcoming the series resistance problem.

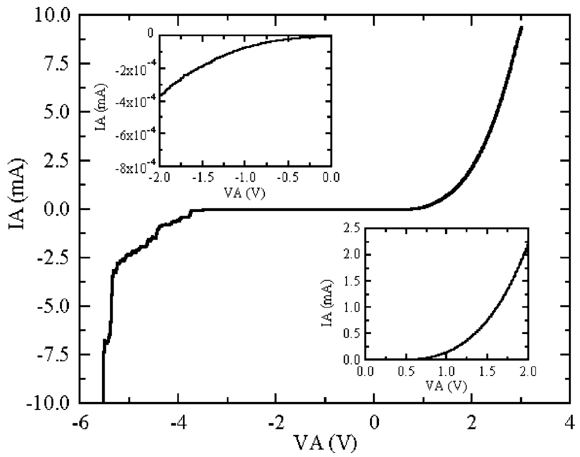

Fig. 2. The I–V characteristics of Al contact on PEDT/PSS deposited by spin-coating.

The modified Norde function [8] $F(V)$ is defined as

$$F(V) = \frac{V}{\alpha} - \frac{1}{\beta} \ln\left[\frac{I(V)}{AA^*T^2}\right] \tag{3}$$

where $I(V)$ is from the measured I–V curve, α is an integer greater than 1, and β is a temperature-dependent value calculated with Eq. (6). For a series resistance of value α, we can obtain a series of corresponding minimum values for $F(V)$ from

$$V_A = V - IR_S \tag{4}$$

$$I = I_S \exp\left(\frac{V_A\beta}{n}\right) \tag{5}$$

$$\beta = q/kT \tag{6}$$

where V_A is the voltage applied on the barrier region. We can then derive the equation

$$I_\alpha = \frac{1}{R_S\beta}\alpha - \frac{n}{R_S\beta} \tag{7}$$

Once we know the minimum values of $F(V)$, we can plot the corresponding I_α–(α/β) curve as shown in Fig. 3. From the slope, we can calculate the value of series

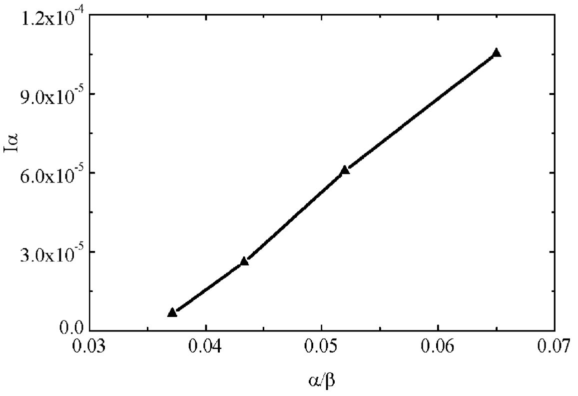

Fig. 3. I_α–(α/β) curve.

resistance, $R_S = 7.34\ \Omega$. By extrapolating the I_α–(α/β) curve, we also can calculate the value of the ideality factor of the polymer-based Schottky diode, $n = 1.42$. Based on the calculated R_S and n values, we can plot an I–VA curve and obtain the Schottky barrier height by using the traditional I–V method. Using this method, the Schottky barrier height is determined to be 0.97 eV. The rectification ratio is determined to be 1.3×10^4 at 1.5 V, which is attributed to the Al/PEDT interface.

To further study of the junction properties, the bias-dependent capacitance was investigated at a fixed frequency of 100 kHz. Fig. 4 shows the capacitance–voltage characteristics of the Al/PEDT Schottky diode under small reverse bias. According to Schottky theory, the depletion layer capacitance is given by

$$C^{-2} = 2[V_D + V_R - (kT/q)]/q\varepsilon_0\varepsilon N A^2 \quad (8)$$

where C is the capacitance, V_R is the applied reverse bias, q is the electronic charge, A is the device area, N is the hole-carrier concentration, and $\varepsilon_0\varepsilon$ is the dielectric con-

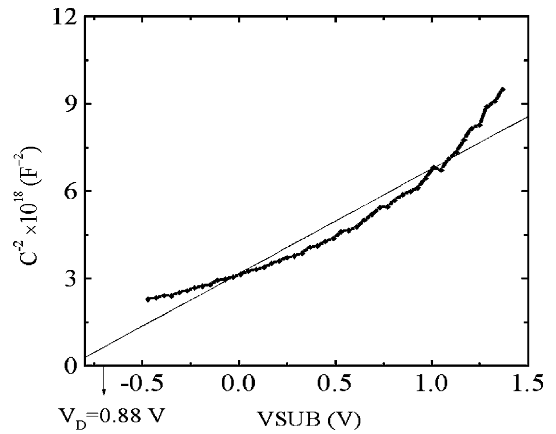

Fig. 4. The reverse bias C^{-2}–V plot of Al/PEDT/PSS Schottky diode.

stant of a semiconductor. We can find the carrier concentration from the slope of linear part in Fig. 4:

$$N = (2/q\varepsilon_o\varepsilon A^2)\frac{dV}{d\left(\frac{1}{C^2}\right)} \quad (9)$$

Assuming $\varepsilon = 3$ [9], the approximate carrier concentration is about $2.09 \times 10^{18}\ \text{cm}^{-3}$. The non-linearity shown in Fig. 4 that indicates a non-uniform dopant density profile is attributed to the interface states introduced by the interfacial layer and the surface irregularities that cause the variation of the effective area. The voltage axis intercept of the C^{-2}–V plot gives a value of about 0.88 V for diffusion voltage, V_D. The work function of Al is 4.28 eV. From the equation $\phi_S - \phi_m = V_D$, the work function of PEDT/PSS is found to be 5.16 eV. And we know the bandgap of PEDT/PSS is 1.6 eV [10], thus from the barrier height and V_D, the Fermi level E_F is obtained to be 0.09 eV above valence band or the highest occupied molecular orbital.

4. Conclusion

In summary, we have fabricated a new polymer-based Schottky diode with a semiconductive polymer PEDT as the semiconductor using simple spin-coating and RIE technologies, and have studied the I–V characteristics and the bias-dependent capacitance of the diodes. The electrical parameters are extracted by a new technique combining the modified Norde function method with the standard forward I–V method. We have shown Al/PEDT diode has a relatively high breakdown voltage of about 5.5 V and a large rectification ratio of about 1.3×10^4. In addition, the Fermi level and the carrier concentration of the PEDT/PSS have been determined.

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