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Electrical Interface Structure of Schottky Junctions by π-conjugated Polymer/III-nitride Hetero Structure

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1. Introduction

Developing high efficiency solar cells is becoming critical and global demand for establishing the zero-CO_2-emission, renewable, as well as enduring energy resource. Recently, tandem (multi-junction) thin-film solar cells, which enable utilizing whole solar spectrum by the structure consisting of various active semiconducting layers with different optical band gap, are more increasingly studied due to the potential capability of outstanding high efficiency. III-nitride, the direct transition wide gap semiconductor, is one of the most promising materials for the top part (top cell), which absorbs short wavelengths light, in the multi-junction solar cell.

The most significant issue on developing the top cell has been associated with the absence of a proper ultra-violet (UV) transparent conductive material, which covers the wide gap semiconductor layer to work for carrier collection. So far, a metal semi-transparent thin-film, such as Au/Ni bilayer, has been used as the carrier collection layer; however, the reflection and absorption of incident light by the metal layer become crucial disadvantage on improving the solar cell performance.

We have focused on π-conjugated polymers for the UV transparent conductive material of the multi-junction solar cell. Polyaniline and poly (3,4-ethylendioxythiophene):poly (styrenesulfonate) (PEDOT:PSS) are the typical π-conjugated hole conducting polymers, having high conductivity up to ~500 S·cm, high transparency (~90%) for short wavelength light and high workfunction (5.0-5.3 eV) comparable to that of Au and Ni. Recently, it was reported that PEDOT:PSS coated on ZnO exhibited excellent Schottky contact characteristics and photovoltaic action [1]. We found that a Schottky junction fabricated by the PEDOT:PSS and n-GaN showed Schottly contact characteristics and 0.55 V of the photovoltage [2].

In this study, we investigate the electrical properties of the Schottky junctions consisting of π-conjugated polymer and III-nitrides, and discuss the electrical interface structure.

2. Experiment

A Si-doped GaN epitaxial thin-film (Si doping concentration: 6.3×10^{17} cm^{-3}) grown on c-sapphire were utilized as the substrate. Polyaniline (PANI) or PEDOT:PSS were coated on the substrate using spin coat. The coated polymer solution was solidified by baking in the air. Subsequently, the polymer film was patterned to isolate cells with the size of several millimeters square. Sample A had a PANI film with 170 nm-thick by 7.1 mm^2 of the area size. Sample B had a PEDOT:PSS film with 420 nm-thick by 2.9 mm^2 of the area size. Ohmic contacts were formed on the GaN surface by soldering indium. The Schottky contact properties were investigated using current-voltage (*I-V*) measurement under dark condition. Capacitance-frequency (*C-f*) measurements were performed to investigate the frequency response and the properties of the depletion region.

3. Results and Discussion

Figure 1 shows *I-V* characteristics of the samples A and B (the inset depicts linear plot of the same data). It is notable that the leakage current is lower than 1×10^{-7} A/cm^2 at -3 V of the reverse bias; this leakage current value is 1~2 of magnitude lower than typical ones observed in conventional metal/n-GaN Schottky junctions. The low leakage current under reverse bias application is ascribable to the absence of the Fermi-level-pinning, which tends to be induced by the temperature effect in the case of metal deposition [3]. The diode ideal factor, n, and the Schottky barrier height (SBH), ϕ_B, were derived from the *I-V* characteristics at forward bias region by fitting theoretical line based on the equation of the thermionic theory:

$$J = A^* T^2 \exp\left(-\frac{\phi_B}{kT}\right) \cdot \left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \qquad (1)$$

where A^* represents the effective Richardson constant, which is defined as $A^* \equiv 4\pi m_e^* k^2 / h^3$ (26.4 $A \cdot cm^{-2} \cdot K^{-2}$ for GaN), T is the absolute temperature, k is the Boltzmann's constant, V is the applied bias, m^* is the effective electron mass (0.2 m_e for GaN), and h is the Planck's constant. The n were 1.84 and 1.33, and ϕ_B (SBH) were 0.89 eV and 1.25 eV for the samples A and B, respectively. The SBH values are comparable or even higher than typical ones by metal/n-GaN Schottky junctions [3].

Figure 2(a) describes capacitance-frequency (*C-f*) characteristics of the samples A and B. The *C-f* measurement was performed with zero-bias condition. The capacitance shows significant drop starting from 5 kHz (Sample A: PANI) and 10 Hz (Sample B: PEDOT:PSS) toward higher

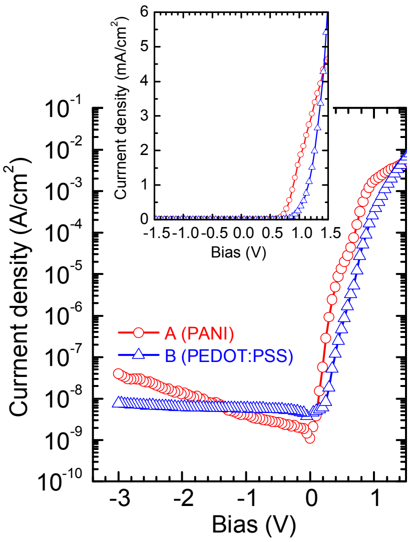

Fig. 1 *I-V* characteristics of the sample A (PANI) and sanple B (PEDOT:PSS)

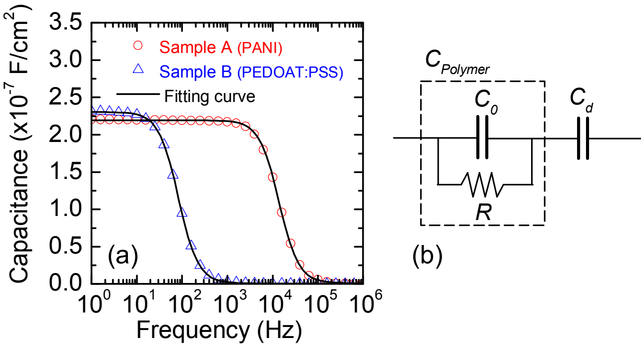

Fig. 2 (a): *C-f* characteristics of the sample A (PANI) and sample B (PEDOT:PSS), represented with open circle and open triangle, respectively. The solid line indicates fitting curves obtained by calculation of eqs. (2) and (3). (b): Assumed equivalent circuit of the π-conjugated polymer/III-nitride hetero structures. $C_{polymer}$ is the variable capacitance of polymer, consisting of specific capacitance C_0 and impedance R. C_d is the capacitance of depletion region.

frequency. Here we discuss the cause of the *C-f* characteristics by assuming an equivalent circuit model based on Debye's dielectric dispersion theory [4, 5]. Figure 2(b) illustrates the assumed equivalent circuit. C_0 and R represent the specific capacitive component and the impedance element in the π-conjugated polymer, respectively. C_d represents the capacitance of the depletion layer in n-GaN. It is assumed that the C_d is dependent only on the applied bias but independent on the modulation frequency. The effective capacitance contributed by π-conjugated polymer, $C_{polymer}$ can be expressed as following equation using the components described above:

$$C_{polymer} = C_0 + \frac{1}{4\pi^2 f^2 R^2 C_0}, \qquad (2)$$

where f is the modulating frequency. The total capacitance C_{total} is formed by the series connection of the two capacitances, $C_{polymer}$ and C_d:

$$C_{total} = C_d \cdot \left(1 + \frac{C_d}{C_{polymer}}\right)^{-1}. \qquad (3)$$

The theoretical *C-f* curves were fitted to the experimental *C-f* plot utilizing the equation (2) and (3) (solid lines in Fig 2 (a)). The values of C_0 and R, which are determined by the fitting, were 1.1 x 10^{-9} F/cm^2 and 753 Ω (Sample A: PANI), and 7.1 x 10^{-10} F/cm^2 and 150 kΩ (Sample B: PEDOT:PSS), respectively. From the discussion made above, we can deduce that the substantial cause of the drastic change of the interface capacitance of π-conjugated polymer/III-nitride hetero structures is attributed to the transition of electrical property of the π-conjugated polymer from capacitive to conductive. The depletion layer width of the samples A and B, which were estimated from the capacitance at the lower limit frequency, were 38 nm and 37 nm, respectively. The good agreement of the depletion widths between the two different samples (polymers) ensures the reliability of the capacitance measurements.

4. Conclusions

We developed the Schottky junctions consisting of π-conjugated polymer and III-nitrides. The Schottky junctions exhibited notable low leakage current at reverse bias application; this is probably due to the absence of the Fermi-level-pinning, which tends to be induced by the temperature effect in conventional metal Schottky contacts. The interface capacitance showed rapid decrease at high frequency range. This is ascribable to the transition of electrical property of the π-conjugated polymer from capacitive to conductive.

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