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Electrical properties of Au/polyvinylidene fluoride/n-InP Schottky diode with polymer interlayer

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ABSTRACT

The effect of polyvinylidene fluoride (PVDF) polymer interlayer on the rectifying junction parameters of Au/n-InP Schottky diode has been investigated using current–voltage (I–V) and capacitance–voltage (C–V) measurements at room temperature. The calculated barrier heights (BHs) are 0.57 eV (I–V), 0.72 eV (C–V) and 0.73 eV (I–V), 0.88 eV (C–V) for the Au/n-InP and Au/PVDF/n-InP Schottky diodes, respectively. Results showed that the BH of the Au/PVDF/n-InP Schottky diode is higher than that of the Au/n-InP Schottky diode, and that the PVDF film increases the effective BH by influencing the space charge region of the n-type InP. The values of the barrier height, ideality factors and series resistance estimated by I–V, Cheung's and Norde methods are compared. Experimental results showed that the interface state density of the Au/PVDF/n-InP Schottky diode is lower than that of the Au/n-InP Schottky diode. Further, the reverse leakage current conduction mechanism is investigated. Schottky emission mechanism is found to dominate the reverse leakage current in the Au/n-InP Schottky diode. However, for the Au/PVDF/n-InP Schottky diode, the Schottky conduction mechanism is found to be dominant in the higher bias region, whereas the Poole–Frenkel conduction is found to be dominant in the lower bias region. Apart from that, the discrepancy between BHs determined from I–V and C–V techniques is explained. Besides, the capacitance–frequency (C–f) and conductance–frequency (G–f) characteristics of the Au/PVDF/n-InP Schottky diode are discussed.

1. Introduction

Due to the direct band gap, high electron mobility, high saturation velocity and breakdown voltage, indium phosphide (InP) is a promising material for high-speed electrical and optoelectronic devices [1]. However, a barrier height greater than 0.5 eV is difficult to obtain on InP [2,3] due to the surface Fermi level pinning which arises from the presence of large surface states and other nonstoichiometric defects. Such a small barrier height causes a large reverse leakage current and hinders the fabrication of InP device applications. Several attempts have been made to realize a modification and continuous control of the barrier height by using an organic layer [4,5] at InP metal–semiconductor (MS) contacts. This layer converts a metal/semiconductor structure into a metal/organic layer/semiconductor device. Such organic layers have drawn significant attention because of their ease of device processing, low cost, suitability for large-area devices, and large range of applications in electronic and optoelectronic devices [6,7]. Most inorganic materials have higher electron mobility compared to organic materials and therefore there have been attempts to make high-performance electronic devices that have the advantage of both organic and inorganic semiconductors. Recently, several researchers focused on the enhancement of the barrier heights of MS structure by using an organic interfacial layer between the metal and semiconductor [8–17]. For example, Dokme et al. [11] prepared the Au/polyvinyl alcohol (Co, Zn-doped)/n-Si Schottky barrier diode (SBD) and reported that the interface states and series resistance have a significant effect on electrical characteristics of the SBD. Farag and Yahia [12] investigated the current–voltage (I–V) and capacitance–voltage (C–V) characteristics of Al/Rhodamine-B based Schottky diode and reported that the diode parameters extracted were strongly influenced by the effect of temperature. Aydin et al. [13] studied the electrical properties of Al/poly(3,4-ethylenedioxithiophene)/poly (styrenesulfonate) (PEDOT:PSS)/p-InP by I–V and C–V methods and reported that the increase in barrier height and ideality factor can be attributed to the PEDOT:PSS film formed at Al/p-InP interface. Gullu et al. [14] studied the electrical properties of Al/deoxyribonucleic acid (DNA)/n-InP Schottky diode and reported that DNA increases the effective barrier height as high as 0.87 eV by influencing the space charge region of the Al/n-InP diode. Reddy et al. [15] investigated the electrical properties of Au/polyvinyl alcohol (PVA)/n-InP Schottky diode as a function of annealing temperature and reported that the Schottky diode parameters changed with an increase in the annealing temperature. Also, they reported that the PVA interfacial layer increases the barrier height by influencing the space charge region of the Au/n-InP Schottky diode. Gullu et al. [16] investigated the electrical properties of Au/Rhodamine-101/n-InP Schottky diode and found the diffusion potential and the barrier height to be 0.78 V and 0.88 eV respectively using C–V measurement. Recently,

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Reddy et al. [17] investigated the electrical properties of Au/polymethyl methacrylate (PMMA)/n-InP Schottky diode at different annealing temperatures using I–V and C–V techniques and reported that the interface state density and series resistance have a significant effect on the electrical characteristics of the Au/PMMA/n-InP Schottky diode.

In recent years, organic compounds have attracted significant interest for their applications in molecular electronic and optoelectronic devices such as organic light emitting diodes, field effect transistors, photovoltaic, solar cells and gas sensors [10]. Polyvinylidene fluoride (PVDF) is a kind of piezoelectric polymer, and it is considered to have a stronger piezoelectric response compared with other polymers. The molecular formula of PVDF is – CH2 – CF2 –. It has a highly polar arrangement of the hydrogen and fluorine atoms. PVDF chain has a coupling of positive and negative charges referred to as a dipole. The negatively charged fluorine atoms are coupled with the positively charged hydrogen atoms. The dipoles are rigidly attached to the carbon backbone. Other than its piezoelectric properties, PVDF is a useful polymer due to its chemical stability, resistance to organic solvents, and high elastic modulus compared with other polymers. In addition, the PVDF has many important properties such as high rigidity, resists deformation, good resistance to wear, high temperature, corrosion, and weather as well as good electric insulation. It is also anti-ultraviolet ray, anti-radiation and easily machined. With low processing temperature and good melting flow, it could be processed easily to make pipe, plate, rod, film and fiber. Furthermore, it has good chemical resistance, so that it is widely used as insulation material in electronic/electric industries, computer industry, and air/space industry to make cable sheathing, coating layer, and condenser films [18–21]. In this study, the PVDF is considered to be a good candidate for barrier height modification of the Au/n-InP Schottky diode. PVDF is used as an interfacial layer because of its ease of processing, minimizing interface states, surface damages and dislocations which may ultimately increase the device quality fabricated using the semiconductor. In view of these foremost features of PVDF, the aim of the present work is to fabricate and characterize the Au/polyvinylidene fluoride (PVDF)/n-InP Schottky diode formed by insertion of a PVDF interlayer between n-InP semiconductor and Au metal. The electrical characteristics of the Au/PVDF/n-InP Schottky diode have been investigated using current–voltage (I–V) and capacitance–voltage (C–V) measurements at room temperature. Further, the capacitance–frequency (C–f), conductance–frequency (G–f) and series resistance–frequency (R_s–f) characteristics of the Au/PVDF/n-InP Schottky diode have been measured at room temperature, and at various biases in dark. Besides, the possible reverse current conduction mechanism of the Au/PVDF/n-InP Schottky diode is described and discussed.

2. Experimental procedure

In the present work, the samples used were one side polished n-type InP wafer with a carrier concentration of 4.9–5.0 × 10^{15} cm^{-3} (as received from the manufacturer). The n-InP surfaces were prepared by degreasing wafer in warm organic solvents like trichloroethylene, acetone and methanol for 5 min each, followed by rinsing in deionized (DI) water. Then, the wafer was etched with HF (49%) and H_2O (1:10) for 30 s to remove the native oxides from the substrate and the wafer was rinsed in DI water followed by drying in N_2 flow. After the above procedures, the ohmic contact was made by evaporating indium (In) on the rough side of the n-InP, followed by a rapid thermal treatment at 350 °C for 1 min in N_2 ambient. The commercial polyvinylidene fluoride (PVDF) pellets were dissolved in dimethylformamide (DMF) at 60 °C on a hot plate for 24 h. Then, the PVDF solution was directly formed on the polished side of the n-InP wafer by using spin coating (Spin coater, Model No. WS-650Mz-23NPP, 60 s at 2000 rpm) method and evaporated by itself for drying of the solvent in nitrogen atmosphere for 1 h. The thickness of the PVDF film on the semiconductor was measured to be about 30 nm by profilometer. The thickness so obtained across the full substrate surface was uniform. The contacting top metal dots with diameter of 0.7 mm were formed by evaporation of gold (Au) metal with a thickness of 50 nm through a stainless steel mask. Also, the Au/n-InP reference Schottky diode was fabricated without the organic layer to compare with the electrical parameters of the Au/PVDF/n-InP Schottky diode. Au evaporation processes were carried out in a vacuum coating unit at a pressure of about 5 × 10^{-4} Pa. The current–voltage (I–V), capacitance–voltage (C–V) and capacitance–frequency (C–f) characteristics of Au/n-InP and Au/PVDF/n-InP Schottky diodes were measured using a Keithley source measuring unit (2400) and LCR meter (model PSM 1700) at room temperature and in the dark, respectively.

3. Results and discussion

3.1. Current–voltage (I–V) characteristics of Au/n-InP and Au/PVDF/n-InP Schottky diodes

Fig. 1 shows the semilogarithmic forward and reverse current–voltage (I–V) characteristics of the Au/n-InP and Au/PVDF/n-InP Schottky diodes measured at room temperature. The measured reverse leakage current of the Au/PVDF/n-InP Schottky diode (2.387 × 10^{-7} A at −1 V) is lower than that of the Au/n-InP Schottky diode (6.809 × 10^{-5} A at −1 V). This indicates that the electrical characteristics improved after the insertion of PVDF as an organic interlayer between the Au and n-InP. The diode parameters are determined from the forward bias I–V characteristics, which are usually described with the thermionic emission (TE) theory and are given by [22]

$$I = I_o\left(\frac{qV_d}{nkT}\right)\left[\exp\left(\frac{qV_d}{kT}\right)-1\right] \tag{1}$$

where I: measured current, V_d: = (V − IR_s) diode voltage, q: electronic charge, k: Boltzmann constant and T: absolute temperature. I_o is the reverse saturation current derived from the straight-line intercept of ln (I) at zero bias and is given by

$$I_o = AA^*T^2\exp\left(\frac{-q\phi_b}{kT}\right) \tag{2}$$

where A: diode area, A^*: Richardson constant (equal to 9.4 A cm^{-2} K^{-2} for n-InP [23]), ϕ_b: barrier height at zero bias and is given by

$$\phi_b = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_o}\right). \tag{3}$$

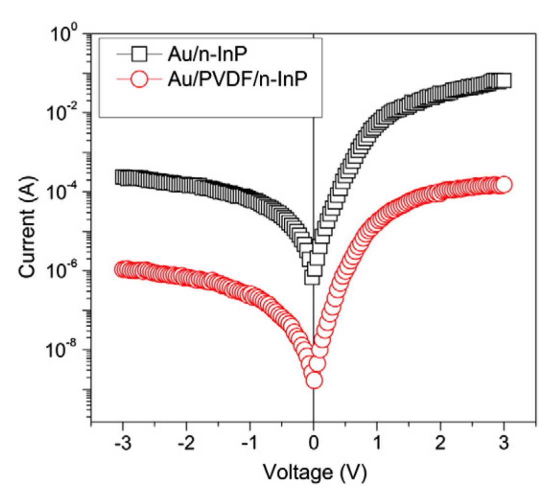

Fig. 1. The forward and reverse bias current–voltage (I–V) characteristics of the Au/n-InP and Au/PVDF/n-InP Schottky diodes at room temperature.