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Effect of annealing on the electronic parameters of Au/poly(ethylmethacrylate)/n-InP Schottky diode with organic interlayer

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ABSTRACT

A thin poly(ethylmethacrylate) (PEMA) layer is deposited on n-InP as an interlayer for electronic modification of Au/n-InP Schottky structure. The electrical properties of Au/PEMA/n-InP Schottky diode have been investigated by current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) measurements at different annealing temperatures. Experimental results show that Au/PEMA/n-InP structure exhibit a good rectifying behavior. An effective barrier height as high as 0.83 eV (*I*–*V*) and 1.09 eV (*C*–*V*) is achieved for the Au/PEMA/n-InP Schottky structure after annealing at 150 °C compared to the as-deposited and annealed at 100 and 200 °C. Modified Norde's functions and Cheung method are also employed to calculate the barrier height, series resistance and ideality factors. Results show that the barrier height increases upon annealing at 150 °C and then slightly decreases after annealing at 200 °C. The PEMA layer increases the effective barrier height of the structure as this layer creates a physical barrier between the Au metal and the n-InP. Terman's method is used to determine the interface state density and it is found to be 5.141 × 10^{12} and 4.660 × 10^{12} cm^{-2} eV^{-1} for the as-deposited and 200 °C annealed Au/PEMA/n-InP Schottky diodes. Finally, it is observed that the Schottky diode parameters change with increasing annealing temperature.

1. Introduction

In recent years, there has been great interest in the fabrication and characterization of Schottky diodes organic light emitting diodes, organic field effect transistors (OFET), photo-voltaic cells, organic solar cells, organic field effect transistor, switching and memory systems, thermistors, negative–resistance devices using organic semiconductors and their derivatives, due to their stability and barrier height enhancement properties [1–6]. Indium phosphide (InP) is one of the most important semiconductors being considered for the above device applications. But, it has a major disadvantage of low Schottky harrier height (SBH) (0.40–0.45 eV) that makes it difficult to fabricate field-effect transistors (FET) directly on InP due to the serious leakage current problem through the gate electrode [7]. Attempts have been dedicated to fabricate InP Schottky junction with a high barrier height [8]. Different methods can be used to enhance the effective barrier height of the InP based Schottky diodes such as insertion of interlayer between metal and semiconductor [9–11] and de-pinning the Fermi level and by using a high work function metal [12]. Assuming that the surface Fermi level pinning is used by high surface state density, passivation technology is needed to reduce the surface states of InP. Organic interfacial layers can be sensitive probe useful in establishing process for minimizing interface states, surface impair dislocations and contaminations that may ultimately increase the quality of devices fabricated using the semiconductor [13–18]. Although, the performance of organic devices is quite well understood in many aspects, there are properties which are still subject of research worldwide.

Recently, electronic devices are moving to the ultimate scale of molecular entities, as demonstrated by the growing interest in understanding transport through organic molecules bridging two metal contacts [19,20] and metal/organic material/semiconductor structure [16,21–23]. Many researchers have explored various polymers as the interfacial layers at metal–semiconductor junction [16,21–29]. For example, Gullu [24] investigated the electrical properties of Al/DNA/n-InP Schottky diode with different thickness of the DNA interlayer at room temperature, reported that DNA increased the effective barrier height as high as 0.87 eV by influencing the space charge region of n-InP device. Soylu et al. [25] investigated the annealing effects on Au/Pyronine-B/moderately doped n-InP Schottky diode by current–voltage (*I*–*V*) and capacitance–voltage

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(C–V) measurements at room temperature. They reported that the barrier height increased as annealing temperature increased up to 100 °C and then decreased after annealing at 200 °C. Farag et al. [26] studied the rectification and barrier height inhomogeneity in Al/Rhodamine-B based Schottky diode, and reported that the diode parameters extracted from the I–V and C–V characteristics were strongly influenced by the effect of temperature. Gullu et al. [27] studied the electrical properties of Au/Rhodamine-101/n-InP Schottky diode, reported that the potential barrier was obtained as 0.88 eV by I–V method, which was attributed to the effect of formation of interfacial organic thin layer between Au and n-InP. Aydin et al. [28] investigated the electrical properties of Al/PEDOT:PSS/p-InP by I–V and C–V methods. They reported that the increase in barrier height and ideality factor can be attributed to PEDOT:PSS film formed at Al/p-InP interface. Recently, Reddy et al. [29] fabricated Au/polyvinyl alcohol (PVA)/n-InP Schottky diode and studied its electrical properties by I–V and C–V techniques as a function of annealing temperature. They found that the interfacial layer of PVA increases the barrier height of the conventional Au/n-InP Schottky diode.

The main aim of this work is to fabricate Au/poly(ethylmethacrylate)/n-InP Schottky structure using a thin poly(ethylmethacrylate) (PEMA) interlayer for the modification of conventional metal/n-InP Schottky diode. PEMA is methacrylic ester polymer. PEMA has excellent chemical resistance, high surface resistance and offers high optical transparency [30]. Especially, PEMA as a polymer waveguide and as optical and/or electronic components has become important. The molecular structure of the PEMA is given in Fig. 1(a). In this study, PEMA has been chosen to modify the barrier height of conventional metal/n-InP Schottky structure. The electrical properties of Au/PEMA/n-InP Schottky diode have been investigated at different annealing temperatures by using current–voltage (I–V) and capacitance–voltage (C–V) measurements in the dark. The ideality factor, barrier height and series resistance of Au/PEMA/n-InP Schottky barrier diode were cross-checked by employing various techniques such as forward I–V, C–V, Cheung, and Norde methods for their consistency and validity mainly based on the thermionic emission (TE) model.

2. Experimental details

In this work, the n-type InP wafers were used with a carrier concentration of 4.5×10^{15} cm^{-3} (as received from the manufacturer). The wafer was sequentially cleaned with warn organic solvents like tricholoroethylene, acetone and methanol by means of ultrasonic agitation for the duration of 5 min each to remove contaminates and then rinsed in deionized (DI) water. Then, the wafer was etched with HF:H_2O (1:10) solution for 30 s to remove the native oxide from the substrate, followed by rinsing in DI water and dried in N_2 flow. First, low resistance ohmic contact on the rough side of the n-InP was made by thermal evaporation of indium (In), followed by annealing 350 °C for 2 min in N_2 atmosphere. After the above procedure, the poly(-ethylmethacrylate) (PEMA) 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. It was evaporated by itself for drying of the solvent in nitrogen atmosphere for 1 h. The thickness of the organic film on the semiconductor was measured to be about 20 nm by profilometer. The thickness so obtained across the full substrate surface was uniform. In order to make Schottky barriers, finally, metal dots with a diameter of 0.7 mm were formed by evaporation of gold (Au) with a thickness of 50 nm through stainless steel mask by e-beam evaporation system at a pressure of 5×10^{-6} mbar. Thus, the Au/PEMA/n-InP Schottky diodes were obtained and diodes were sequentially annealed at 100 °C, 150 °C, and 200 °C for duration of 1 min in N_2 atmosphere in rapid thermal annealing (RTA) system. The current–voltage (I–V) and capacitance–voltage (C–V) measurements of the Au/PEMA/n-InP Schottky structure (see Fig. 1(b)) were made using a computer controlled Keithley 2400 voltage source and automated deep level transient spectrometer (DLS-83D) at room temperature and in the dark, respectively. Atomic force microscopy (model no: MOD-1M plus, make: nano Focus, operating mode: non-contact, tip size < 100 nm) was employed to characterize the surface morphology of the Au/PEMA/n-InP Schottky diode as a function of annealing temperature.

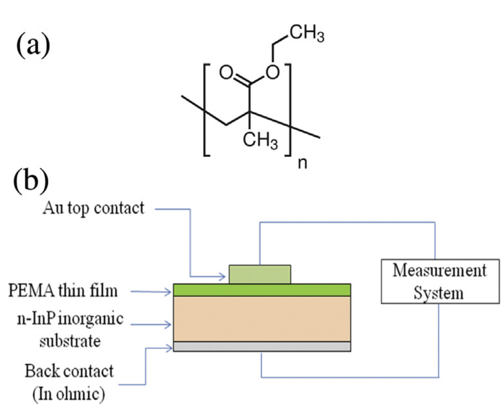

Fig. 1. (a) Chemical structure of poly (ethylmethacrylate) (PEMA), and (b) experimental setup diagram for Au/PEMA/n-InP Schottky diode.

3. Results and discussion

The interfacial roughness of the polymer film plays significant role in determining the properties of any organic device, as the metal/inorganic semiconductor interface strongly affects transport across a junction. The AFM images obtained from the PEMA/n-InP Schottky structure before and after annealing temperature at 200 °C are shown in Fig. 2. As can be seen from Fig. 2(a), the surface morphology of the as-deposited contact is reasonably smooth with a root-mean-square (RMS) roughness of 1.269 nm. However, for the contacts annealed at 100 °C and 150 °C, Fig. 2(b) and (c), the surface morphology of the PEMA/n-InP Schottky contacts are slightly degrade with an RMS roughness of 2.317 nm and 5.128 nm as compared with that of the as-deposited one. When the contact is annealed at 200 °C, Fig. 2(d), the surface morphology is further degraded with an RMS roughness of 11.269 nm. This may be due to the formation of surface defects such as pinholes.

Fig. 3 shows the experimental semi-logarithmic I–V characteristics of Au/PEMA/n-InP Schottky structure for different annealing temperatures measured at room temperature. As can be seen from Fig. 3, the Au/PEMA/n-InP Schottky structure shows a good rectification behavior. The measured reverse leakage current is 1.563×10^{-7} A at -1 V for the as-deposited contact. When the contacts are annealed at 100 °C and 150 °C, the reverse leakage current is decreases to 1.923×10^{-8} A and 5.966×10^{-9} A at -1 V, respectively. However, the reverse leakage current increases to 4.599×10^{-8} A after annealing at 200 °C. When a Schottky diode with series resistance and an interfacial layer is considered with respect to the forward bias voltages $V > 3kT/q$, according to the thermionic emission (TE) theory, can be described as [31]

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

where $V_d = (V - IR_s)$ is the diode voltage. I_o is the saturation current derived from the straight line intercept of ln (I) at zero-bias and is given by