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Frequency dependent capacitance and conductance properties of Schottky diode based on rubrene organic semiconductor

Behzad Barış *

Department of Physics, Faculty of Arts and Sciences, Giresun University, Gazipaşa Campus, Giresun 28100 Turkey

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ABSTRACT

Al/rubrene/p-Si Schottky diode has been fabricated by forming a rubrene layer on p type Si by using the spin coating method. The frequency dependent capacitance–voltage (C–V–f) and conductance–voltage (G–V–f) characteristics of Al/rubrene/p-Si Schottky diyotes has been investigated in the frequency range of 5 kHz–500 kHz at room temperature. The C–V plots show a peak for each frequency. The capacitance of the device decreased with increasing frequency. The decrease in capacitance results from the presence of interface states. The plots of series resistance–voltage (R_s–V) gave a peak in the depletion region at all frequencies. The density of interface states (N_{ss}) and relaxation time (τ) distribution profiles as a function of applied voltage bias have been determined from the C–V and G–V measurements. The values of the N_{ss} and τ have been calculated in the ranges of 8.37×10^{11}–4.85×10^{11} eV^{-1} cm^{-2} and 5.17×10^{-6}–1.02×10^{-5} s, respectively.

1. Introduction

Since rubrene ($C_{42}H_{28}$, 5,6,11,12 tetraphenylnaphthacene) is one of the most promising organic materials, considerable research efforts have been devoted to the investigation of organic semiconductor devices based on rubrene because of their low-cost manufacturing, easy processing, and promising for many electronic and optoelectronic applications, such as organic photovoltaic (OPV) devices [1], organic light emitting diodes (OLEDs) [2,3], and organic field effect transistors (OFETs) [4,5]. Organic materials such as rubrene semiconducting, in order to be used in many applications, must be integrated into device structures in which they are interfaced with inorganic materials, often metals. Therefore, processes occurring at such interfaces and their influence on the device performance are of great interest.

The performance and reliability of organic based Schottky barrier diodes especially depends on the formation of interfacial layer at metal-semiconductor (MS) interface, the level of interface states (N_{ss}) at organic layer/Si interface, series resistance (R_s) of devices. Therefore, it is important to determine the interface properties of such a organic based Schottky diode [6–9]. To determine the density of interface states, the more common method, as developed by Nicollian and Goetzberger [10], is the conductance method. The C–f and G–f curves are usually frequency independent in the idealized case [10,15,20–22]. However, this idealized case is often disturbed due to the presence of the interface states at the interfacial layer and semiconductor interface [20–22]. Therefore, the frequency dependent reverse and forward bias C–V and G–V measurements in the wide range of frequency can give us important information about the energy distribution of the interface states and the relaxation time of these structures. The effects of interfacial layer and interface states on the capacitance–voltage (C–V) characteristic of MS [11–15], metal–insulator–semiconductor (MIS) [16–19] and organic/inorganic [6–9] contact have been reported by several authors. Tuğluoğlu et al. [15] investigated the electrical characterization of a In/p-Si Schottky diode using capacitance–frequency (C–f) and conductance–frequency (G–f) measurements to obtain valuable information about the interface states. Forrest and Schmidt reported the conductance and capacitance versus frequency characteristics of metal-semiconductor contacts with organic interfacial layer [13]. Çakar et al. [6] investigated the conductance– and capacitance–frequency characteristics of the rectifying junctions formed by sublimation of organic Pyronine-B on p-type silicon. Altındal et al. [7] syntheized a novel binuclear zinc(II) phthalocyanine of the clamshell type and fabricated a Au/Pc/p-Si Schottky barrier diode using this phthalocynanine compound. They determined the interface properties of the prepared structure from capacitance–voltage (C–V), conductance–voltage (G–V) in the frequency range between 20 and 2×10^6 Hz.

The aim of the present study is to investigate the frequency dependent electrical and interface state properties of Al/rubrene/p-Si Schottky diode using capacitance–voltage (C–V) and conductance–voltage (G–V) measurements at a wide frequency range from 5 kHz to

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* Corresponding author. Tel.: +90 4542141495.
E-mail address: behzadbaris@gmail.com

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1 MHz and also to characterize the density distribution and relaxation time of the interface states by capacitance–frequency (*C–f*) and conductance–frequency (*G–f*) characteristics.

2. Experimental procedure

The rubrene is known as 5,6,11,12-tetraphenylnaphthacene and its chemical structure is shown in Fig. 1(a). p-type B-doped Si crystalline wafer of 300 μm thick with (1 0 0) surface orientation and 20 Ω-cm resistivity was used. The Si wafer was chemically cleaned using ultrasonic agitation in $CHClCCl_2$, CH_3COCH_3, and CH_3OH for 5 min and then rinsed in de-ionized water of 18 M Ω and dried with high purity nitrogen gas. The Si wafer was cleaned using the RCA cleaning procedure (i.e., a 10 min boil in NH_3+H_2O_2+$6H_2O$ followed by a 10 min boil in HCl+H_2O_2+$6H_2O$). Ohmic contact is made by evaporation of 99.99% purity aluminum (Al) metal with thickness of 150 nm in a pressure of approximately 4×10^{-4} Pa on the non-polished side of the Si substrate and then by thermal annealing at 450 °C for 3 min in vacuum. The native oxide on the front surface of the Si substrate was removed in HF: H_2O (1:10) solution and the wafer was rinsed in de-ionized water of 18 M Ω for 60 s before forming the rubrene layer on the p-Si substrate. A rubrene organic film on the Si substrate was deposited by spin coating method with a MTI–VTC 100 Spin Coater. After then, Schottky contacts were fabricated on rubrene organic film with a diameter of 2 mm by a metal shadow mask by evaporating 99.99% purity aluminum (Al) metal with thickness of 150 nm in a pressure of approximately 4×10^{-4} Pa. The schematic diagram of the prepared device is shown in Fig. 1(b). The capacitance–voltage (*C–V*), conductance–voltage (*G–V*) characteristics were carried out with an HP 4192 A LF (5 Hz–13 MHz) Impedance Analyzer at the frequency range of 5 kHz–500 kHz and the capacitance–frequency (*C–f*), conductance–frequency (*G–f*) characteristics were carried out at the various biases (0.0–2.0 V with steps 0.2 V) at room temperature and in the dark.

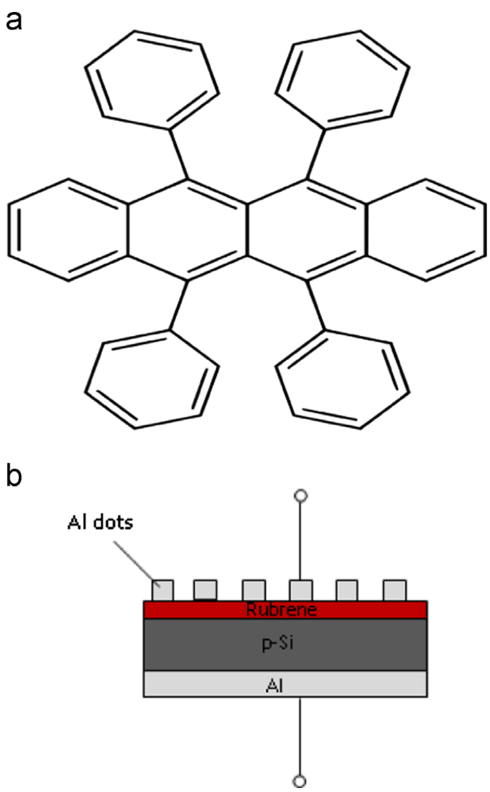

Fig. 1. (a) Molecular structure of a rubrene organic compound and (b) Cross-sectional view of Al/rubrene/p-Si Schottky diode for electrical characterization.

3. Results and discussion

3.1. Capacitance–voltage and conductance–voltage characteristics

Fig. 2(a) and (b) depict the measured capacitance–voltage (C_m–V) and measurements under forward and reverse-bias voltages in the frequency range of 5 kHz–500 kHz at room temperature for Al/rubrene/p-Si Schottky diode. As shown in Fig. 2 (a) and (b), the values of C_m are dependent on both frequency and bias voltage. The capacitance of the device within the range of the about −0.7 and 2 V has displayed a increasing trend with decreasing frequency due to the existence of N_{ss}, $R_s$and interfacial rubrene layer. A dispersion is observed in accumulation and this behavior is fairly common for measurement on MOS structures [19–21]. Fig. 3 (a) and (b) depict the measured conductance–voltage (G_m–V) measurements under forward and reverse-bias voltages in

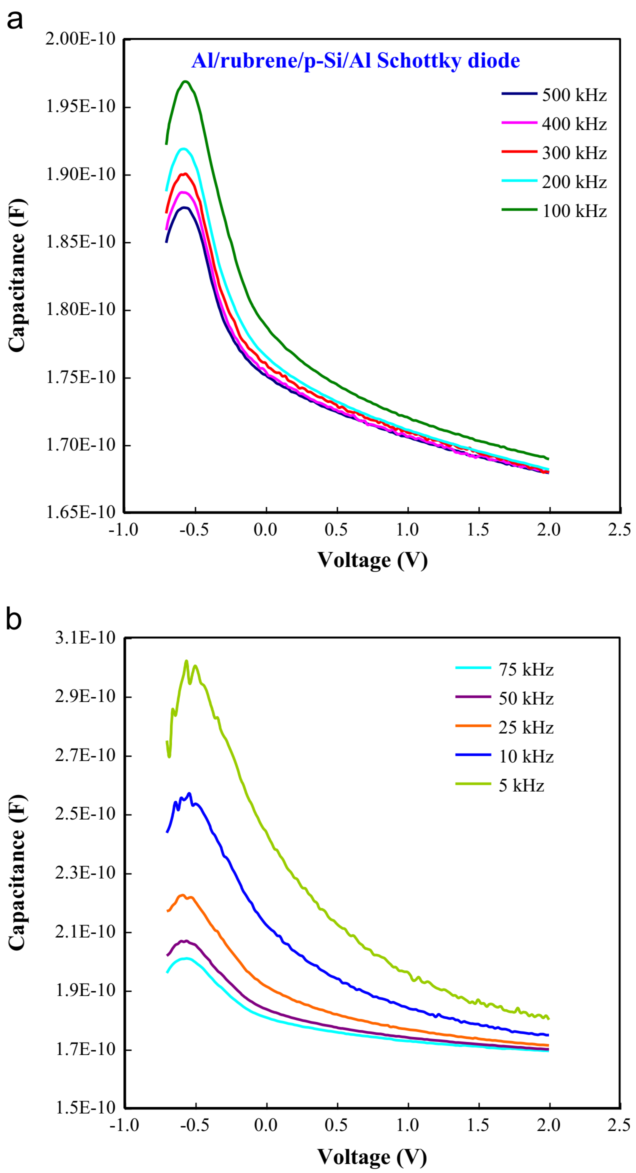

Fig. 2. Frequency dependence of the measured capacitance–voltage (*C–V*) characteristics of Al/rubrene/p-Si Schottky diode (a) from 500 kHz to 100 kHz and (b) from 75 kHz to 5 kHz at room temperature.