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On the Frequency *C-V* and *G-V* Characteristics of Au/Poly (3-Substituted thiophene) (P3DMTFT)/*n*-GaAs Schottky Barrier Diodes

A.F. Özdemir[a,*], D.E. Akcan[a], H.E. Lapa[a], and A.G. Yavuz[b] S.Duman[c]

[a]Department of Physics, Süleyman Demirel University, Isparta, Turkey

[b]Department of Chemistry, Süleyman Demirel University, Isparta, Turkey

[c]Department of Physics, Atatürk Üniversity, Erzurum, Turkey

The frequency-dependent electrical characteristics of Au/Poly (3-Substituted thiophene) (P3DMTFT)/ n-GaAs Schottky barrier diodes have been investigated by using capacitance-voltage (C-V) and conductance-voltage (G/ω-V) measurements at room temperature. Negative capacitance behavior has been observed in the C-V characteristic for each frequency. The magnitude of absolute value of C was found to increase with decreasing frequency in the forward bias region. The value of G/ω increases with decreasing frequency in the positive region. This can be attributed to the increase in the polarization at low frequencies and to the fact that more carriers are introduced into the structures. Negative capacitance phenomenon can be explained by the loss of interface charges from the occupied states below the Fermi level, caused by impact ionization process. According to obtained result, the values of C and G/ω are strong functions of frequency and applied bias voltage, particularly in the accumulation an inversion region. Doping concentration (N_{d}), diffusion potential (V_{d}), Fermi energy level (E_f), and barrier height ($\Phi_{\mathrm{b}}(C\text{-}V)$) values have been calculated from reverse bias C^{-2}-V plots for 3 MHz. Finally, the obtained value of R_{s} in the accumulation region increases with decreasing frequency.

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1. Introduction

Metal-insulator-semiconductor (MIS) structures are the most useful devices in the study of semiconductor interfaces. The electronic parameters of MIS contacts depend on the properties of insulator layer, the interface properties between metal and semiconductor, series resistance and inhomogeneities of Schottky barrier heights [1–4]. Particularly, gallium-arsenide-based structures have been used as the basic component for high speed electronic, optoelectronic, and lasers because of their technical importance [5–7].

Ideally the C-V and G/ω-V characteristics of Schottky barrier diodes (SBDs) are frequency independent, particularly at high frequency, and show an increase with the increasing forward bias voltage [8–14]. Deviations from this case can be seen at low and moderate frequencies, in depletion and accumulation regions, due to the contribution of carriers at interface states, interfacial insulator layer and R_{s} of device. It is known that the existence of an insulator layer, native or deposited at metal-semiconductor (MS) interface, changes the C-V and G/ω characteristics of the diode. Negative capacitance (NC) and anomalous peak have been observed in the forward bias C-V characteristics of MS or MIS SBDs [10–18]. The NC has been attributed to the interface states, the contact injection and minority carrier injection effects and the anomalous peak can occur due to interface states (N_{ss}) and R_{s} [19, 20]. The NC effect reported in the literature has been referred to as "anomalous" or "abnormal" [12]. NC measured experimentally has sometimes been attributed to instrumental problems, such as parasitic inductance or poor measurement experiment calibration [12, 15]. On the other hand, the inductive effect at a low frequency and capacitance arise from the high-level injection of minority carriers into the bulk semiconductor during the current transport only at forward bias voltage [6, 9]. In addition, there are many studies on NC effect at high frequency [16]. Contact structures can also be affected by the small-signal characteristics and thus give rise to NC in the forward bias C-V and G/ω characteristics [9, 21]. When the forward bias voltage reaches maximum value, the effect of the recombination exceeds that of diffusion and then the contact capacitance decreases rapidly and becomes negative [9, 14, 18].

A series of articles [5–7] have studied the electrical properties of Au/n-GaAs junction, covered with various organic semiconductor materials. Relationships between the properties of organic layer and the values of fundamental electronic parameters of Au/n-GaAs contact have been reported. In this study, the forward and reverse bias C-V and G/ω-V characteristics of Au/Poly (3-Substituted thiophene) (P3DMTFT)/ n-GaAs SBDs have been investigated in the frequency range of 10 kHz–3 MHz, under applied bias voltage of −3 V to +3 V, at room temperature. The measured C of Au/Poly (3-Substituted thiophene) (P3DMTFT)/ n-GaAs SBDs increases with increasing applied voltage,

*corresponding author; e-mail: farukozdemir@sdu.edu.tr

then it decreases, particularly at forward bias, and finally takes negative values for all frequencies.

2. Experimental procedure

In this study, to fabricate Schottky diode with polymer interface, n-type GaAs wafer with (1 0 0) orientation and carrier concentration of $2-5\times10^{17}$ cm^{-3} was used. The wafer was dipped into $5H_2SO_4+H_2O_2+H_2O$ solution for 1.0 min and then into H_2O+HCl solution, to remove surface damaged layer and the undesirable impurities and then rinsed in de-ionized water of 18 MΩ. Immediately after the etching process, after removing water using high purity nitrogen, wafer was inserted into the deposition chamber. Au-Ge (88% and 12%) was evaporated on the back of the wafer in a vacuum-coating unit of 10^{-5} Torr. Then low resistance ohmic contact was formed by thermal annealing at 450 °C for 3 min in flowing N_2 in a quartz-tube furnace. Poly (3-Substituted thiophene) (P3DMTFT) conductive polymer solution was dropped by a pipette on the front face of the n-GaAs wafer. Finally, in order to realize Schottky contact, Au was evaporated on the polymer layer, deposited on the front face of the n-GaAs wafer. The surface area of Schottky contact formed in Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs structure was 1.8×10^{-2} cm^2. C-V and G/ω-V measurements were performed using a HP4192A LF Impedance analyzer at room temperature in the dark.

3. Results and discussion

Frequency-dependent C-V and G/ω-V characterization of Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs SBDs has been carried out in the frequency range from 100 kHz to 3 MHz at room temperature. C-V characteristics of Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs SBDs are given in Fig. 1. G/ω-V characteristics for the same frequency range are shown in Fig. 2. As shown in Fig. 1a and Fig. 2a, both C-V and G/ω-V characteristics exhibit accumulation, depletion and inversion regions. It is clear from these figures that both C and G/ω characteristics increase with increasing frequency in the inversion region.

As can be seen from Fig. 1b, the values of C increase with decreasing frequency in the forward bias region. The NC values can be observed with the increase of the applied voltage for all frequencies. In this case, NC behavior is important because it implies that the increment of bias voltage produces a decrease in the charge on the electrodes [14]. According to Wu, et al. [13] the concept of NC can be explained by considering the loss of interface charge at occupied states below Fermi level due to impact ionization. The physical mechanism of the NC in different devices is different and can be attributed to the contact injection, interface states or minority-carrier injection [9, 12, 13]. The effects of NC can be seen by external inductors or parasitic resistances in series, forming

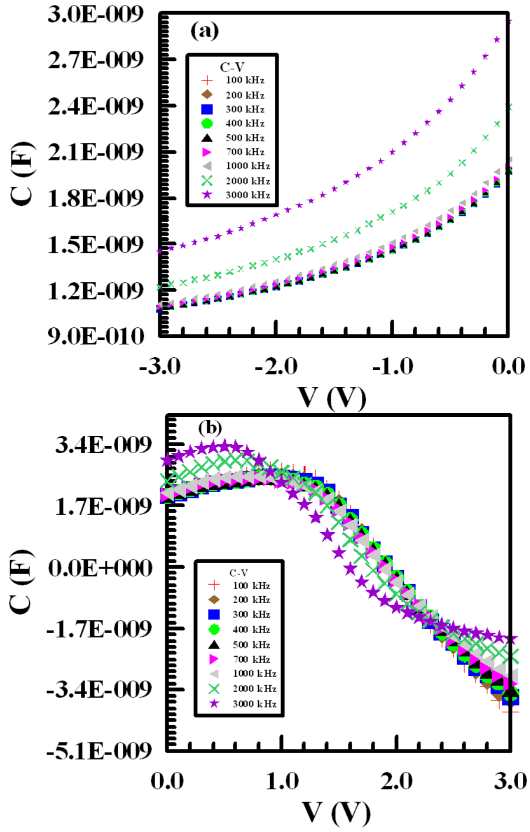

Fig. 1. Capacitance-voltage (C-V) characteristics of Au/Poly (3-Substituted thiophene) (P3DMTFT)/ n-GaAs SBDs for different frequencies, at room temperature.

part of the structure [15]. Many electronics phenomena occur due to conducting interface of ohmic and rectifying contacts with an interfacial layer or interface states, the bulk traps, where charges can be stored and released when the appropriate bias and ac voltages are applied. A large effect may be produced since the interfacial layer (native or deposited) is thin [9, 22].

Figure 2b shows that values of G/ω decrease with the increasing frequency in the depletion and accumulation regions. The high value of conductance in the forward bias region at low frequency can be ascribed to the low value of R_s at high frequencies. In addition, the low value of R_s at high frequencies occurs because of an inductive contribution to the impedance, that is composed of high-level injection of minority carriers into the bulk semiconductor [9, 17]. Moreover, the values of C and G/ω are remarkable at low frequencies. The values of C of Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs SBDs increase to a maximum value with the increase of the applied bias voltage and then decreases and finally become negative for all frequencies. Similar results of the NC behavior have been reported for GaAs based SBDs [6, 9, 14, 18]. This behavior of C-V-f and G/ω-V-f can be explained by an inductive behavior [9, 14]. Some studies have shown that the observed inductive effect at

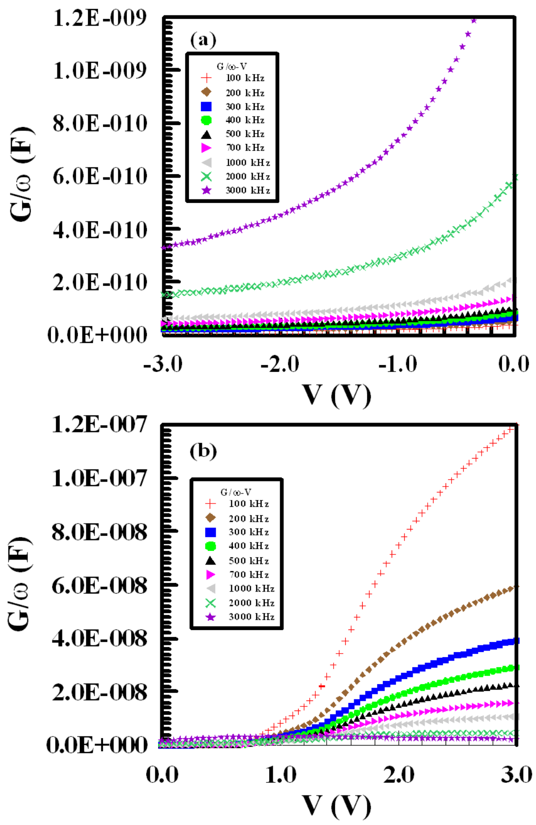

Fig. 2. Conductance-voltage (G/ω-V) characteristics of Au/Poly (3-Substituted thiophene) (P3DMTFT)/ n-GaAs SBDs for different frequencies at room temperature.

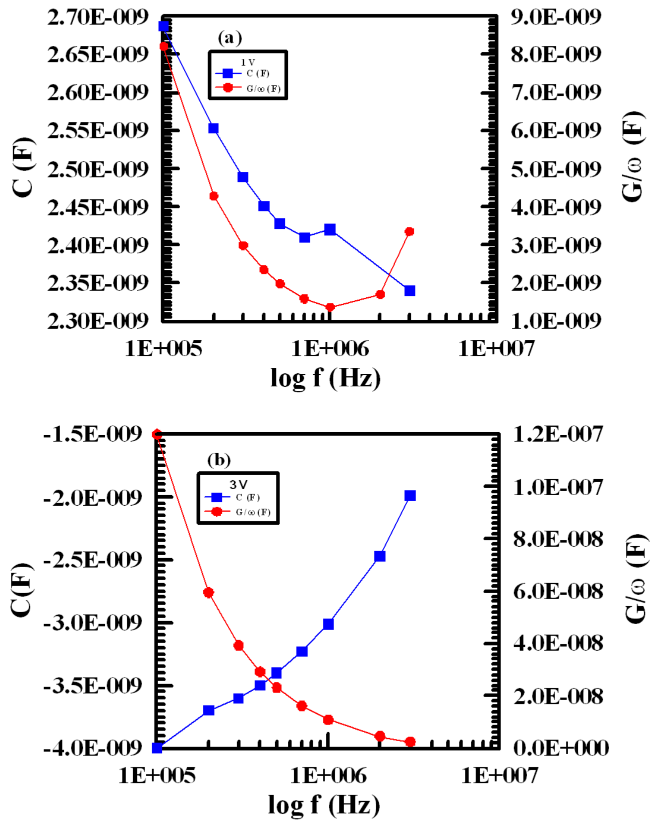

Fig. 3. Variation of C and G/ω characteristics with applied voltage in frequency range of 100 kHz–3 MHz.

low frequencies arises from the high-level injection of minor carriers into the bulk semiconductor in the Si based SBD [23].

The C and G/ω values as functions of frequency for two applied bias voltages of 1 V and 3 V are shown in Fig. 3 to explain the effect of the applied bias voltage in the depletion region. As can be seen, the decrease in the C corresponds to an increase in the G/ω and the minimum value of the C coincides with the maximum value of G/ω, especially at 3 V. The increase in G/ω at low frequency can be explained by the increase in the number of charge carrier available for a given relaxation time of the interface states [9]. It is clear form Fig. 3, that the changes in the C and G/ω become important particularly at low frequencies for high applied bias voltage in the accumulation region. The C-V and G/ω-V characteristics are given in order to see the dispersion profiles in the C and G/ω for 100 kHz, 700 kHz, 3 MHz, respectively (Fig. 4a–4c). This behavior of the C-V and G/ω-V characteristics is similar to that of Fig. 3. Finally it can be said that such behavior of C and G/ω with the applied bias voltage and frequency is a result of influence of the interface states, the R_s of the device, injection of minority carriers and surface polarization [16, 18, 23].

It is clear from Fig. 4, that the discrepancy between C-V and G/ω-V characteristics decreases with the increasing frequency. It is known that the existence of localized interface states at M/S interface results in a formation of charge dipole at the interface. Under forward bias, most of the applied bias voltage across the diode is shared by the semiconductor, series resistance of device and the interfacial dipole [9, 17, 18, 23]. Hence, it is thought that the capacitance values decrease with the increasing polarization and more carriers are introduced into the structure [9].

Both C and G/ω measurements can be affected by the R_s of diode, especially at high frequencies in the accumulation region. According to the Nicollian and Brews [8], the value of R_s can be obtained from the measured capacitance and conductance in the strong accumulation region at high frequencies ($f \geq 1$ MHz). The voltage-dependent value of R_s can be determined from the measured C and G values for any given bias voltage.

$$R_s = \frac{G}{G^2 + \omega^2 C^2}. \qquad (1)$$

The R_s values of Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs SBDs, calculated according to Eq. (1) are given Fig. 5 for various frequencies, for the forward bias region.

The value of R_s becomes important, hence special attention should be given to effects of R_s on the C-V and G/ω-V characteristics. As can be seen, the value of R_s is strongly dependent on frequency and the applied bias

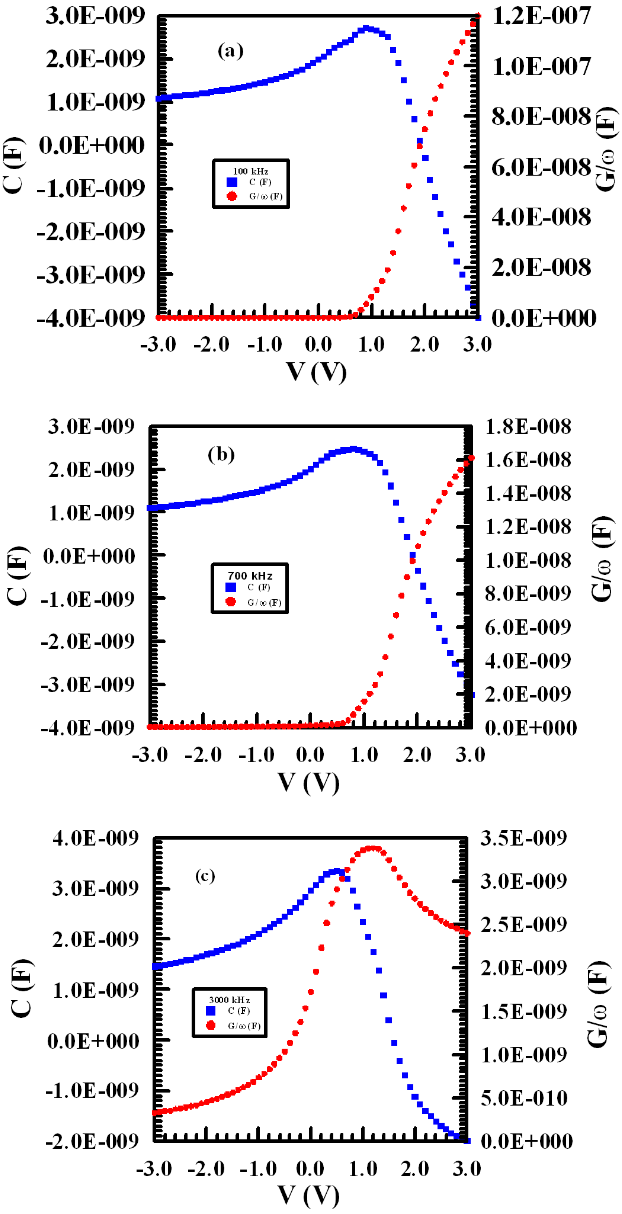

Fig. 4. C and G/ω characteristics of Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs SBDs as a function of bias voltage at different frequencies, at room temperature.

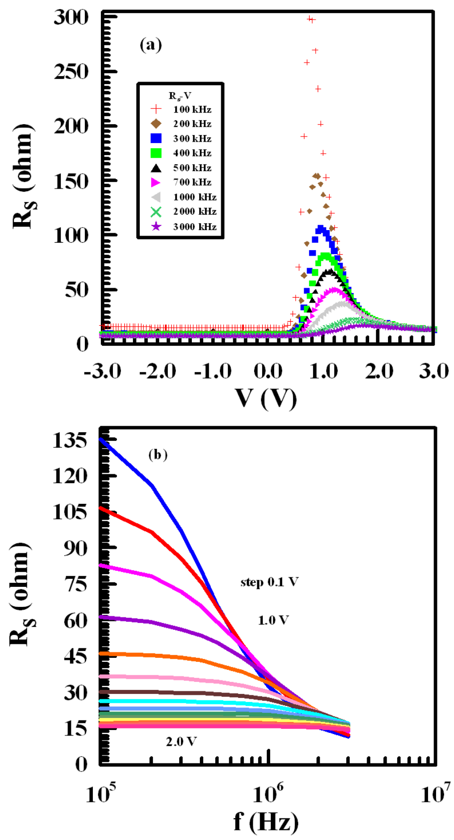

Fig. 5. R_s-V and R_s-log f characteristics of Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs SBDs at various frequencies.

voltage. There is a peak in the R_s-V characteristics, at about 1 V, which depends on frequency (Fig. 5a), due to a particular distribution of surface states. The magnitude of this peak decreases with the increasing frequency. As shown in Fig. 5b, value of R_s decreases with the increasing applied bias voltage for each frequency and as the frequency is increased further, the value of R_s remains almost constant, such that this value at strong accumulation region corresponds to the real value of R_s.

The C^{-2}-V characteristic of Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs SBDs at 3 Mhz is shown in Fig. 6. When a polymer layer is inserted between metal and semiconductor, the capacitance for the MIS device is expressed by following relation:

$$C^{-2} = \frac{2\,(V_d + V)}{q\varepsilon_s\varepsilon_0 A^2 N_d}, \tag{2}$$

where A is the area of diode, N_d is the doping concentration, V_d is the diffusion potential at zero bias [24]. The depletion layer width can be expressed as $W_d = [2\varepsilon_s\varepsilon_0 V_d/qN_d]^{1/2}$. Here ε_s and ε_0 are the relative permittivity of the semiconductor ($\varepsilon_s = 13.1$) and permittivity of the free space, respectively. The values of V_d and N_d can be calculated from the intercept and slope of C^{-2} vs. V plot by Eq. (2), respectively.

The calculated values of N_d and V_d are 2.7×10^{17} cm^{-3} and 0.90 eV, respectively. The barrier height for MIS diode can be obtained using the following relation [25]:

$$\Phi_b = V_d + E_F, \tag{3}$$

where E_F is the potential of the Fermi level, given by

$$E_F = \frac{kT}{q}\ln\left(\frac{N_c}{N_d}\right). \tag{4}$$

Here N_c is the effective density of states. The value of Φ_b has been calculated as 0.91 eV using Eq. (3) and Eq. (4). As can be seen in Fig. 6, C^{-2}-V plots give a straight line in a wide range of applied bias voltages. The value of intercept voltage (V_0) was calculated as 0.87 eV from the slope of the linear part of $1/C^2$ versus V plots. The value of W_d was calculated as 6.94×10^{-6} cm.

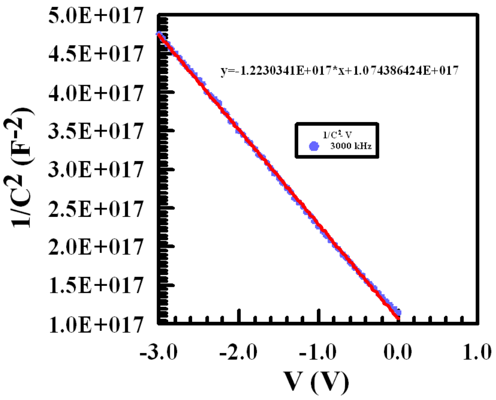

Fig. 6. The $1/C^2$-V plot of Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs SBDs for 3 MHz at room temperature.

4. Conclusion

The negative capacitance in Au/Poly (3-Substituted thiophene) (P3DMTFT)/n-GaAs SBDs was investigated using the capacitance-voltage-frequency (C-V-f) and conductance-voltage-frequency (G/ω-V-f) measurements in the frequency range of 100 kHz–3 MHz at room temperature. According to experimental results both C and G/ω are quite sensitive to the frequency and applied bias voltage. The NC is more remarkable at low frequencies and the magnitude of absolute value of C increases with the decreasing frequency in the forward bias region. On the other hand, contrary to C, the values of G/ω increase with the decreasing frequency in same region. This behavior of NC can be ascribed to the loss of interface charges of the occupied states below Fermi level due to impact ionization processes. Also, it can be attributed to an increase in the polarization, particularly at low frequencies, and to introduction of more carriers into the structure. The value of R_s is an important parameter because of its influence over the C and G/ω values, particularly at high frequencies.

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