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On the anomalous peak at low and moderate frequency *C-V* curves of Al/SiO_2/p-Si structure at the forward bias region

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The low and moderate frequency capacitance-voltage (*C-V*) and conductance-voltage (G/ω-V) characteristics of the Al/SiO_2/p-Si (MIS) structures were investigated by considering the effect of interface states (N_{ss}) and series resistance (R_s). Experimental results show that in the existence of R_s, the forward bias *C-V* curves exhibit a peak at efficiently high bias region, and this peak positions shift toward lower bias voltage with decreasing frequency. In addition, the values of *C* and G/ω of these structures increase with decreasing frequency. The doping densities of acceptor atoms (N_A) and barrier height (Φ_B) obtained from the slope of the C^{-2} vs. *V* plot in the inversion region at each frequency. The values of N_A give a minimum at 0.7 kHz while the values of Φ_B increase with increasing frequency. In addition, the values of R_s and N_{ss} calculated using Nicollian and Goetzberger and Hill-Coleman methods, respectively. It has been seen that the values of R_s and N_{ss} decrease with increasing frequency.

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1. Introduction

Using a thin insulator layer such as SiO_2, SnO_2 and Si_3N_4 at the metal/semiconductor interface, MS structure can be converted to MIS structure. The existence of such an insulator layer will prevent the interface diffusion and reaction between the metal and semiconductor. The electrical characteristics of these devices are dependent especially on the formation of insulator layer at M/S interface and series resistance of the device and particular distribution of interface states at semiconductor/insulator interface [1-3]. In addition, the change in frequency has important effects on the determination of the main device parameters such as doping concentration (N_A), Barrier height (Φ_B), and series resistance (R_s) of device [1-4]. Therefore, when a voltage is applied across the MIS, the combination of insulator layer, depletion layer, and series resistance of the device will share applied bias voltage.

In the idealized case, the capacitance (*C*) and conductance (G/ω) of MIS structures are usually frequency independent. However, the situation is different especially at low and intermediate frequencies since surface states can easily follow the ac signal, especially at low frequencies. Also both an excess capacitance and conductance which depends on the time constant (τ) of the interface states (N_{ss}) and frequency of the applied ac signal yield. There may be a capacitance due to the interface states in excess to depletion layer capacitance. Since this excess capacitance depends strongly on the frequency, the magnitude of capacitance peak and its position in the *C–V* plot are affected [3-9].

In recent years, some investigations [5,10-12] have been reported regarding the anomalous peak observed in the forward bias *C–V* characteristics. The origin of this anomalous peak is attributed to the interface states by Ho et al. [13] who compared the *C–V* plot for as-deposited and annealed silicide-Si interface. Besides, Chattopadhyay and Raychaudhuri [5], Werner et al.[11] and Bati et al. [14] showed that the observed peak in the forward bias *C–V* characteristics is due mainly to the series resistance. On the other hand, Chattopadhyay et al. [15] showed theoretically that the peak value of the capacitance varies with series resistance and interface state density in the forward bias *C–V* plots of MIS Schottky barrier diodes. The peak value of the *C* and its position depend on various parameters such as N_{ss}, doping concentration, R_s of device, and the thickness of the interfacial insulator layer [5]. In order to achieve a better understanding of the effects of different charge interface states and series resistance on the metal-insulator-semiconductor (Al/SiO_2/p-Si) structures we have obtained the forward and reverse bias *C–V* and G/ω–V measurements especially at low and intermediate frequencies of these structures by the use of a computerized HP 4192A LF impedance analyzer (5 Hz–13 MHz) at room temperature. It is contrary to high frequencies, the N_{ss} can easily follow the ac signal, at low and intermediate frequencies and the excess capacitance yields [1,2,4].

In this work, it is investigated experimentally the frequency dependence of the *C-V* and G/ω–V characteristics of MIS structure by considering the N_{ss} and R_s effects. Therefore, to achieve a better understanding the effects of N_{ss} and R_s on the *C–V* and G/ω–V

characteristics, it has been obtained that the forward and reverse bias *C–V* and *G/ω–V* measurements of these structures in the low and intermediate frequency in the range of 0.2 kHz-50 kHz and at room temperature. However, at high frequencies ($f \geq 50$ kHz), the capability follow of surface states of ac signal is remarkably reduced. In addition, the frequency dependence of interface states density was obtained from the *C–V* and *G/ω–V* measurements using the Hill-Coleman method [16].

2. Experimental procedure

The Al/SiO_2/p-Si structures used in this study were fabricated using p-type Si wafer with <100> surface orientation, having thickness of 280 µm, 2" diameter and 8 Ω-cm resistivity. For the fabrication process, the Si wafer was degreased for 5 min. in boiling trichloroethylene, acetone, and ethanol consecutively and then etched in a sequence of H_2SO_4 an H_2O_2, 20% HF, a solution of $6HNO_3$: 1HF: $35H_2O$, 20% HF. Preceding each cleaning step, the wafer was rinsed thoroughly in de-ionized water of resistivity of 18 MΩ-cm. The details of fabrication procedures are given in the previous study [6]. Small sinusoidal signal of 40 mV peak to peak from the external pulse generator is applied to the sample in order to meet the requirement [1,2]. All measurements were carried out with the help of a microcomputer through an IEEE-488 AC/DC converter card.

3. Results and discussion

There are several methods to estimate the R_s of MIS structures [3], and among them the most important one is the conductance method [3]. The frequency dependent *C–V* and *G/ω–V* characteristics of sample are given in Fig. 1(a) and (b), respectively, in the frequency range of 0.2 kHz- 50 kHz and at room temperature. The regions of accumulation, depletion, and inversion are clearly seen, verifying a typical MIS behavior. According to conductance method, the real R_s of the MIS structure can be extracted from the behavior of the values of C_m and G_m/ω. Comparing the real and imaginary parts of the admittance, R_s can be obtained as [3];

$$R_s = \frac{G_m}{G_m^2 + (\omega C_m)^2} \tag{1}$$

where C_m and G_m represent the measured C_m and G_m. Also, the insulator layer capacitance C_{ox} is obtained at high frequency as

$$C_{ox} = C_m\left[1 + \left(\frac{G_m}{\omega C_m}\right)^2\right] = \frac{\varepsilon_i \varepsilon_0 A}{d_{ox}} \tag{2}$$

where $\varepsilon_i = 3.8\varepsilon_o$ [2,3] and ε_o (=8.85×10^{-14} F/cm) are the permittivity of the SiO_2 and free space, respectively. The SiO_2 thickness d_{ox} which was obtained from high frequency ($f \geq 1$ MHz) *C-V* curve using the Eq. (2) was found to be 32 Å in the strong accumulation region [6].

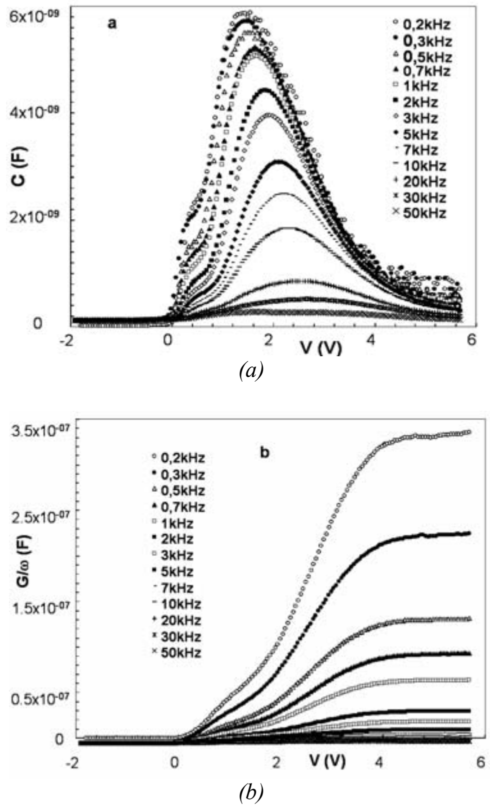

Fig. 1. The C-V-f and G/ω-V-f characteristics of MIS structure, respectively, at room temperature.

As it can be seen from Fig. 1(a), the C_m and G_m increase with decreasing frequency. The values of *C* shifting to inversion region with decreasing frequency show a strong peak especially at low frequencies. The higher values of *C* and *G/ω* at low frequencies are resulting from the N_{ss} in equilibrium with *Si* material together with τ [1,2,4]. When the thickness of insulator layer is lower than 30Å, N_{ss} is in equilibrium with metal [1,2]. These behaviors show that the carriers have enough energy to escape from the traps located at Si/SiO_2 interface in the Si band gap. The values of *G/ω* as a function of voltage at different frequencies [Fig.1 (b)] increase with decreasing frequency at forward bias voltages, but increase with increasing bias voltage especially at depletion region and become almost constant at strong accumulation region.

When the applied voltage is sufficiently large, a frequency dependence of the *C–V* curves deviated from in the ideal case due to interfacial insulator layer and R_s. The C^{-2}–*V* plots obtained in the frequency range (0.2 kHz-50 kHz) are presented in Fig. 2. As shown in Fig. 2, the C^{-2} – *V* plots were found to be linear in wide range of applied voltage region (such that carrier life time (τ) is closer or becomes larger than $1/2\pi f$) [3], but low frequencies C^{-2}–V plots deviated from the linear behavior. Such behavior of non-linearity of C^{-2} versus V plots at low frequencies can be entirely explained on the basis of the assumption that a lot of the interface states can easily follow the applied ac signal [3-7].

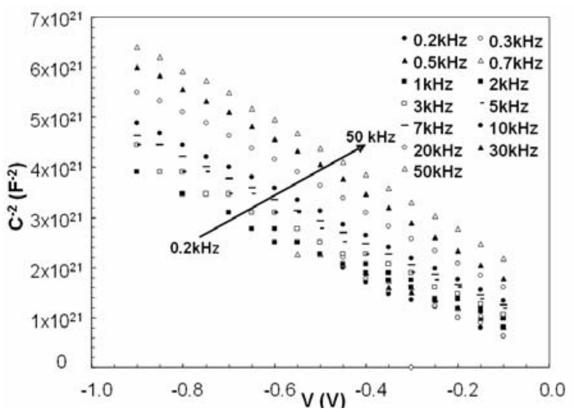

Fig. 2. The forward-bias C^{-2}-V characteristics of $Al/SiO_2/p$-Si structure at room temperature.

The depletion layer capacitance of MS or MIS structures can be expressed as [1,2] ;

$$\frac{1}{C_m^2} = \frac{2(V_R + V_o)}{q\varepsilon_s\varepsilon_o N_A A^2} \tag{3}$$

The values of N_A were determined from the slope of the linear part plot of the C^{-2}–V characteristics (Fig. 2) for each frequency. The barrier height $\Phi_B(C\text{–}V)$ was calculated using the value of voltage intercept V_o of the C^{-2}–V plot at each frequency, at same figure in the relation is given by

$$\Phi_B(C-V) = (V_o + kT/q) + E_F = V_D + E_F \tag{4}$$

where V_D and E_F are the diffusion potential and Fermi energy, respectively. E_F is given by [1,2];

$$E_F = (kT/q)\,ln\,(N_V / N_A) \tag{5}$$

The values of $\Phi_B(C\text{–}V)$, N_A, V_D, and E_F were obtained from the C^{-2}–V plots for each frequency and are given in Table 1. As it can be seen in Table 1, the value of Φ_B at 50 kHz is 0.754 eV which is about twice the value of 0.374 eV at 200 Hz. The value of N_A at 50 kHz is 8.74×10^{13} cm^{-3} which are lower than $3.23\text{x}10^{14}$cm^{-3} at 200 Hz. Such behavior can be entirely explained on the basis of the assumption that not all the interface states would follow the applied ac signal at low frequencies. Similar results have been reported in the literature [9,10].

Table 1. The values of various parameters for $Al/SiO_2/p$-Si structure obtained from C^{-2}–V data at room temperature.

f (kHz)	N_A (cm^{-3})	V_D (eV)	E_F (eV)	Φ_B (C–V) (eV)
0.2	3.23×10^{14}	0.117	0.264	0.374
0.3	3.01×10^{14}	0.129	0.261	0.383
0.5	1.72×10^{14}	0.131	0.280	0.406
0.7	1.33×10^{14}	0.139	0.287	0.420
1	1.40×10^{14}	0.157	0.285	0.437
2	1.34×10^{14}	0.200	0.286	0.480
3	1.44×10^{14}	0.240	0.285	0.519
5	1.49×10^{14}	0.288	0.284	0.565
7	1.55×10^{14}	0.320	0.283	0.595
10	1.62×10^{14}	0.363	0.282	0.638
20	1.73×10^{14}	0.459	0.280	0.731
30	9.51×10^{13}	0.460	0.295	0.748
50	8.74×10^{13}	0.463	0.297	0.754

The values of N_{ss} can be obtained using the following relation [16];

$$N_{ss} = \frac{2}{qA}\frac{(G_m/\omega)_{max}}{\left[((G_m/\omega)_{max}C_{ox})^2 + (1 - C_m/C_{ox})^2\right]} \tag{6}$$

where ω is the angular frequency. $(G_m/\omega)_{max}$ is the measured maximum G/ω–V with its corresponding measured C_m. The values of N_{ss} and R_s obtained from C–V and G/ω–V data at room temperature are given in Table 2.

Table 2. The values parameters of MIS determined from C-V and G/ω-V characteristics at room temperature.

f (kHz)	V_m (V)	C_m (F)	$(G/\omega)_{max}$ (F)	N_{ss} (eV^{-1}cm^{-2})	R_s (kΩ)
0.2	1.55	5.60×10^{-9}	6.00×10^{-8}	9.25×10^{14}	13.16
0.3	1.65	5.50×10^{-9}	5.40×10^{-8}	6.72×10^{14}	9.74
0.5	1.70	5.40×10^{-9}	3.43×10^{-8}	4.57×10^{14}	9.06
0.7	1.75	5.13×10^{-9}	2.61×10^{-8}	2.90×10^{14}	8.39
1	1.85	4.95×10^{-9}	1.98×10^{-8}	1.97×10^{14}	7.57
2	1.95	4.32×10^{-9}	1.20×10^{-8}	8.41×10^{13}	5.87
3	2.10	3.84×10^{-9}	9.83×10^{-9}	5.47×10^{13}	4.68
5	2.25	2.98×10^{-9}	7.53×10^{-9}	2.93×10^{13}	3.66
7	2.40	2.80×10^{-9}	6.44×10^{-9}	2.35×10^{13}	2.97
10	2.40	2.74×10^{-9}	5.07×10^{-9}	1.81×10^{13}	2.43
20	2.65	7.52×10^{-10}	3.25×10^{-9}	6.26×10^{12}	2.33
30	2.80	4.08×10^{-10}	2.38×10^{-9}	4.19×10^{12}	2.17
50	1.90	1.68×10^{-10}	1.66×10^{-9}	2.75×10^{12}	1.90

It is clear that while the frequency increases, the peak value of the C and R_s are found to decrease. These results are found to be in good agreement with the literature [16]. As a result, it can be concluded that in the low frequencies, the N_{ss} can easily follow the ac signal and the excess C and G/ω yield. However, the N_{ss} cannot follow ac signal at highly moderate frequency range [1-3].

4. Conclusions

In order to make a satisfying understanding of the N_{ss} and R_s on the MIS structures, the $C–V$ and $G/\omega–V$ characteristics of structures were investigated in the frequency range of 0.2 kHz-50 kHz. The experimental data show that both the $C–V$ and $G/\omega–V$ characteristics are strongly dependent on frequency and exhibit anomalous peaks at forward bias due to the N_{ss} and R_s. This behavior of $C–V$ and $G/\omega–V$ characteristics can be explained by the fact that the N_{ss} can follow the ac signal and the excess C and G/ω yield. The magnitude of this anomalous peak is attributed to the amount of interface states and series resistance. The $C^{-2}–V$ plots give a straight line in a wide-bias region. The values of $\Phi_B(C–V)$, N_A, V_D and E_F were obtained from these C^{-2}–V plots for each frequency. While the value of $\Phi_B(C–V)$ increases with increasing frequency, the value of N_A decreases. The value of N_A at 50 kHz is 8.74×10^{13} cm^{-3} which is lower than 3.23×10^{14}cm^{-3} at 0.2 kHz. Such behavior can be entirely explained on the basis of the assumption that the majority of interface states can be follow the applied ac signal at very low frequencies. It can be concluded that the characteristics of MIS structures at low and moderate frequencies are controlled by the interfacial insulator layer and N_{ss}.

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References

[1] S. M. Sze, Physics of Semiconductor Devices, 2nd Ed. John Wiley & Sons, New York, 1981.
[2] E. H. Rhoderick, R. H. Williams, Metal Semiconductor Contacts, Clarendon, Oxford, 1988.
[3] E. H. Nicollian, J. R. Brews, John Wiley & Sons. New York, 1982.
[4] H. C. Card, E. H. Rhoderick, J. Phys. D **4**, 1589 (1971).
[5] P. Chattopadhyay, B. Raychaudhuri, Solid-State Electron. **35**, 875 (1992).
[6] İ. Yücedağ, Ş. Altındal, A. Tataroğlu, Microelectron. Eng. **84**, 180 (2007).
[7] A. Singh, Solid-State Electron. **28**(3), 223 (1985).
[8] N. Konofaos, I. P. McClean, C. B. Thomas, Phys. Stat. Sol. (a) **161**, 111 (1997).
[9] Z. Ouennoughi, Phys. Stat. sol. (a) **160**, 127 (1967).
[10] F. Parlaktürk, Ş. Altındal, A. Tataroğlu, M. Parlak, A. Agasiev, Microelectron. Eng. **85**, 81 (2008).
[11] J. Werner, A. F. J. Levi, R. T. Tung, M. Anzlowar, M. Pinto, Phys. Rev. Lett. **60**, 53 (1988).
[12] R. T. Tung, Matter. Sci. Eng. R. **35**, 1 (2001).
[13] P. S. Ho, E. S. Yang, H. L. Evans, X. Wu, Phys. Rev. Lett. **56**, 177 (1986).
[14] B. Bati, Ç. Nuhoglu, M. Sağlam, E. Ayyildiz, A. Türüt, Physica Scripta **61**, 209 (2000).
[15] P. Chattopadhyay, B. Raychaudhuri, Solid-State Electron. **35**, 1023 (1992).
[16] W. A. Hill, C. C. Coleman, Solid State Electronics **23**, 987 (1980).

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