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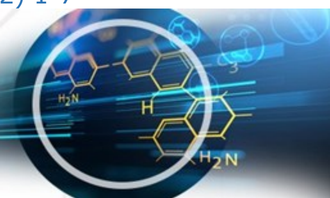

Frequency effect on capacitance and conductance characteristics of Au/HfO_2/p-Si Schottky diode prepared by RF sputtering method

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HfO_2 thin film was deposited on p type Si substrate by radio frequency sputtering method for the fabrication of Au/HfO_2/p-Si Schottky diode. The capacitance (*C*) and conductance (*G*) properties of the Au/HfO_2/p-Si diode were examined at various frequencies and voltages. The properties of the diode were investigated within the voltage range of (-3V) - (+3V) and frequency range of 1 kHz - 1 MHz. The characteristics of *C* and *G* against voltage of the diode were determined to be strongly dependent on bias frequency and voltage. The capacitance decreases significantly with increasing of the frequency, showing the existence of steady interface state density. The series resistance (R_s) and interfacial state density (N_{ss}) distributions of the produced diode were tried to be clarified. The frequency dependency of the R_s and N_{ss} were found using conductance and Hill–Coleman's technique and it has been determined that the R_s and N_{ss} decreases with increasing frequency from 997 Ω and 7.89 x10^{11} eV^{-1} cm^{-2} for 1 kHz to 144 Ω and 2.49 x 10^{11} eV^{-1} cm^{-2} for 1 MHz. The results of the study showed that the Au/HfO_2/p-Si structure fabricated by RF sputtering method can be used as a Schottky diode in electronic applications in a wide frequency range.

Keywords: *HfO_2, RF sputtering, Schottky diode, series resistance, interface state density*

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1. Introduction

Metal-oxide-semiconductor (MOS) type device attract a lot of attention due to their potential applications in high-performance power device such as telecommunication equipments and modern computers [1, 2]. In order to increase the performance of MOS structures, it is necessary to reduce the SiO_2 layer thickness on the silicon, but in this case, the direct tunneling current (leakage current) increases [3]. To eliminate this negativity, metal oxides with high dielectric constant such as HfO_2, ZrO_2, and TiO_2 are used [3, 4]. HfO_2 is a good material for reducing leakage current because it has a great dielectric constant of 25 and a big band gap of 5.68 eV and has good thermodynamic stability [5, 6].

The performance of MOS type Schottky diodes depends on oxide interface, series resistance, the interface states distribution, and formation of an oxide layer. In recent years, the fabrication of metal oxide layers with various techniques has gained significance for MOS Schottky diodes. HfO_2 thin films are prepared by different chemical and physical methods such as spray deposition [7], sputtering [8, 9], atomic layer deposition [10, 11], and spin deposition [12]. Some researchers have studied the electrical properties of HfO_2/GaAs or HfO_2/Si MOS type Schottky diodes [1, 10, 13-17]. Er et.al. have prepared Al/HfO_2/p-Si MOS type Schottky diodes by using the atomic layer deposition (ALD) method. They showed that the effect of temperature, frequency, and voltage on the dielectric properties of Al/HfO_2/p-Si diodes through conductance-voltage-frequency (*G-V-f*) and capacitance–voltage–frequency (*C*–

V–f) measurements [10]. Yildiz et al. have prepared Al/Ti/HfO_2/n-GaAs/In MOS type Schotky diodes and reported the electrical properties of the device produced were investigated by the *G-V-f* and *C-V-f* measurements in the temperature vary from 60 to 320 K [17].

The first aim of this study is to create MOS type Schottky diode by rf magnetron sputtering method and the second aim is to report the frequency dependent capacitance and conductivity properties of HFO_2 thin film deposited on p-Si. For this purpose, capacitance-voltage and conductance-voltage measurements were taken between 50 kHz and 1 MHz. The interface state density and series resistance behavior of the produced diode are revealed.

2. Experimental

The properties of p-Si wafer we used in this work are in the form of a (100) orientation, 300 µm thickness, 10 Ω-cm resistivity and grown by CZ method with B-doped. According to the cleaning procedure, RCA techniques were used to remove the oxide on silicon surface [18, 19]. Aluminum (Al) metal was used to form the contact and 200 nm Al was deposited on p type Si by thermal evaporation technique at $5x10^{-6}$ torr pressure. The sample was heated at 500 ºC for 3 minutes in a nitrogen gas environment to create ohmic contact. The Hafnium oxide (HfO_2) film was deposited on the other part of the p-Si wafer by RF magnetron sputtering technique. The deposition conditions are given in Table 1. The HfO_2 film fabricated on p-Si was annealed to form HfO_2 in the oven at 400 ºC for 10 minutes. After HfO_2/p-Si/Al contact, Schottky rectifier contact with gold (Au) metal was made on HfO_2/n-Si structure. Gold thickness and vacuum pressure are 200 nm and $6x10^{-5}$ torr, respectively. Ultimately, Au/HfO_2/p-Si/Al Schottky barrier diode was prepared. Figure 1 displays the 3D presentation of Au/HfO_2/p-Si/Al diode. In order to analysis the interface state density and series resistance characteristics of the diode produced, conductance-voltage (*G-V*) and capacitance-voltage (C-*V*) measurements were taken in the vary from 50 kHz to 1 MHz at room temperature. The measurements of Au/HfO_2/p-Si/Al Schottky diode was realized by means of a Keysight E4990A Impedance Analyzer.

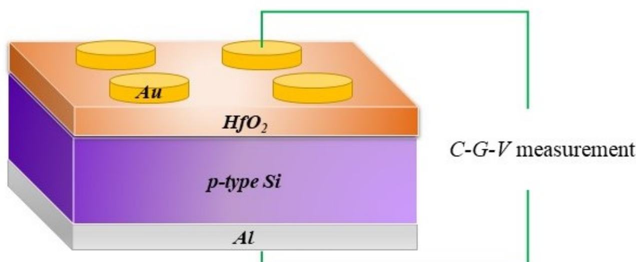


Figure 1: 3D view of Au/HfO_2/p-Si/Al Schottky diode structure

Table 1. RF magnetron sputtering deposition conditions of HfO_2 film

Parameter	Conditions
RF power	150 W
Working pressure	6 x 10^{-1} Pa
Base pressure	$1x10^{-6}$ Pa
Target to substrate distance	25 mm
Substrate temperature	450 ºC
Operation time	20 minutes in argon gas atmosphere
Film thickness	50 nm

3. Results

Capacitance-voltage (*C-V*) and conductance-voltage (*G-V*) measurements were taken to reveal the frequency-dependent series resistance and interfacial state density distributions of the produced device. These measurements were made in a broad measuring range of -3V- +3V and 50 kHz-1 MHz. The measured capacitance (C_m) of the diode is plotted in Figure 2 with varying voltage in the various frequencies (50 kHz – 1 MHz). Figure 2 depicts that the capacitance values are nearly independent of especially low frequency at inversion region. As we increase the frequency applied to the sample, the total capacitance of the diode is significantly affected by the bulk resistance and the capacitance of the depletion layer. The result is a capacitance dispersion associated with electron and hole flow from slow-response deep level impurity levels. Figure 2 clearly show that there are three regions of accumulation, depletion, and reversal, confirming typical metal oxide-semiconductor (MOS) behavior for each A.C. frequency. The measured conductance (G_m) of the diode is plotted in Figure 3 with varying voltage in the various frequencies (50 kHz – 1 MHz). The observed behavior in G_m-*V* plots at lower frequencies (f <100 kHz) can be refered by the interface traps and reordering of traps under an external electric field. Conductance values don't almost vary with increasing frequency in the negative voltage part. The movement of conductance with increasing frequency is due to the presence of surface state at the between HfO_2 and p-Si interface [20-22].

Figure 4 (a) and (b) display the measured capacitance–frequency (C_m− f) and conductance-frequency ($G_m - f$) plots of the Au/HfO_2/p-Si diode at a voltage range between -3V and 3V with steps of 0.5 V and in the 50 kHz–1000 kHz. We observed form Figure 4 (a) that the values of capacitance

have a top in the low-frequency part, reducing in the middle frequency part, and unchanging in the high- frequency part at voltages measured. The conductance behavior in Figure 4 (b) is the opposite of the capacitance behavior in Figure 4 (a). At low frequencies, the low conductance value increases towards high frequencies. Furthermore, Figure 4 (a) shows that the produced diode produces a high capacitance value at only low frequencies and has charge carriers that can follow the AC signal sent to the diode. The capacitance values of the prepared diode at 0V of the reduced from $2.58x10^{-10}$ F to $1.18x10^{-10}$ F as the value of frequency rised from 50 kHz to 1 MHz, respectively. The values of conductance of the prepared diode at 0V of the rised from $6.92x10^{-5}$S to $25.7x10^{-5}$ S as the value of frequency rised from 50 kHz to 1 MHz, respectively.

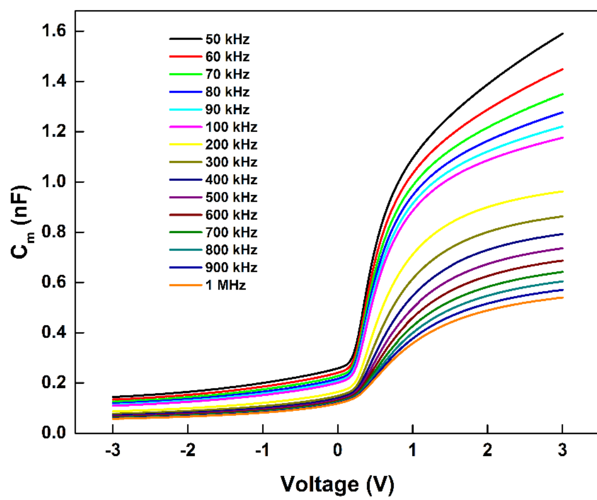


Figure 2: Plots of $C_m - V$ of the Au/HfO_2/p-Si diode in various frequencies 50 kHz-1 MHz.

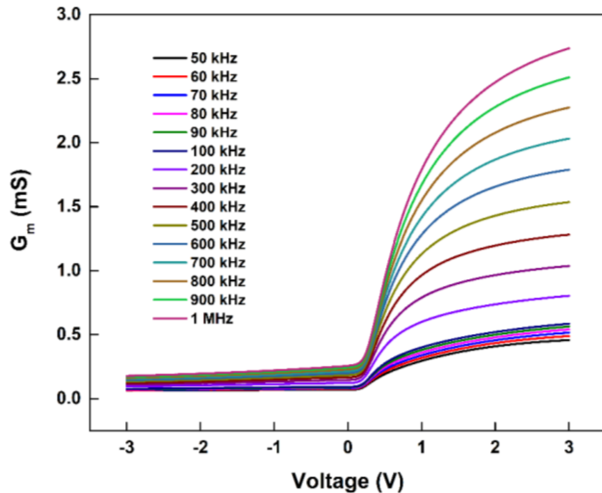
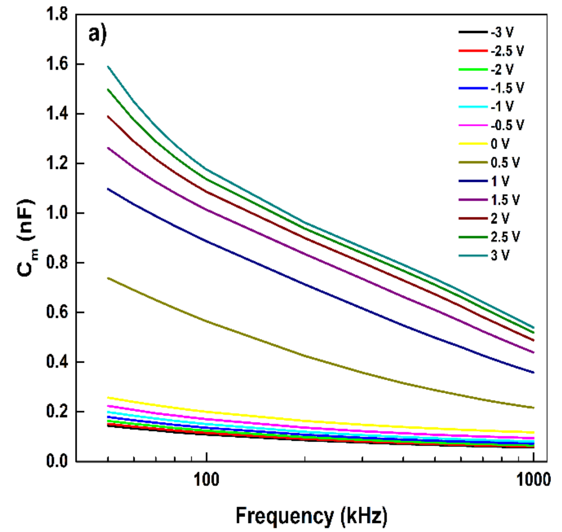


Figure 3: Plots of $G_m - V$ of the Au/HfO_2/p-Si diode in various frequencies 50 kHz-1 MHz.



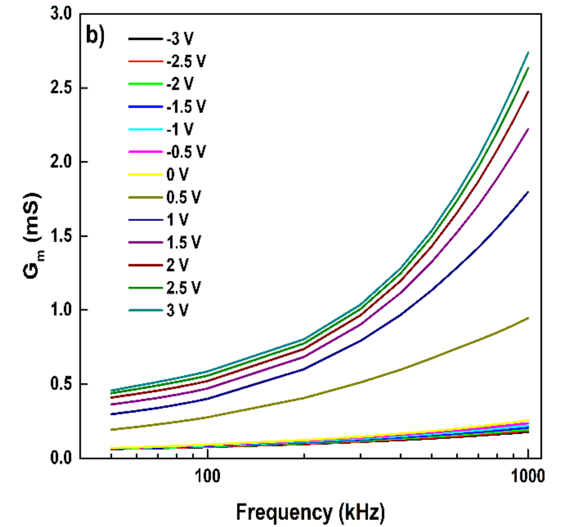


Figure 4: Plots of (a) $C_m - Logf$ and (b) $G_m - Logf$ of the Au/HfO_2/p-Si diode in various voltages.

The presence of series resistance (R_s) creates the non-ideal action of the electrical properties of the MOS diode. Its calculation and its effect must be subtracted from the measured capacitance and conductance values. Series resistance values can be calculated with the Niccolian and Goetzberger technique [21, 23]:

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

where C_m and G_m are the measured capacitance and conductance values at all frequency region, respectively.

The calculated series resistance (R_s) of the diode is plotted in Figure 5 as a function of voltage for different frequencies (50 kHz-1MHz). The series resistance values obtained at all frequencies decrease towards positive voltages with the highest value in negative voltages. However, the series resistance values decrease as the frequency increases. The series resistance values of the prepared diode at 1 MHz of

the reduced from 1102 Ω to 144 Ω as the voltage increased from -3V to 3V, respectively.

Figure 6 displays the series resistance–frequency ($R_s - f$) curves of the Au/HfO_2/p-Si MOS diode at a voltage range between -3V and 3V with 0.5V in the frequencies 50 kHz–1 MHz. As can be seen Figure 6, the series resistance values decrease as the frequency and voltage increase. The series resistance values of the prepared diode at 0V of the reduced from 6.09 kΩ to 415 Ω as the value of frequency rised from 50 kHz to 1 MHz, respectively.

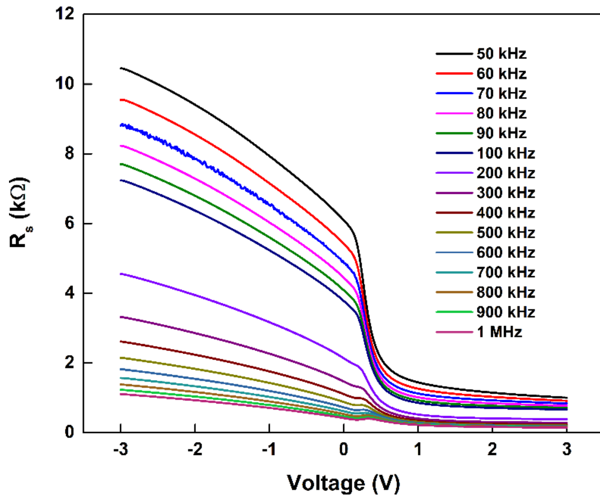


Figure 5: Plots of $R_s - V$ of the Au/HfO_2/p-Si MOS diode in various frequencies.

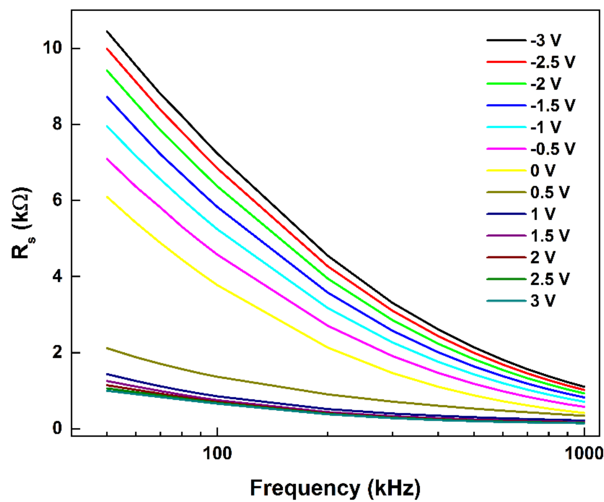


Figure 6: Plots of $R_s - Logf$ of the Au/HfO_2/p-Si MOS diode in various voltages.

The measured C and G characteristics can be corrected to remove the effect of Rs in the inversion, depletion and accumulation regions using the following equations [20, 24-26]:

$$G_c = \frac{(G_m^2+\omega^2 C_m^2)a}{a^2+\omega^2 C_m^2} \tag{2}$$

$$C_c = \frac{(G_m^2+\omega^2 C_m^2)C_m}{a^2+\omega^2 C_m^2} \tag{3}$$

$$a = G_m - (G_m^2 + \omega^2 C_m^2)R_s \tag{4}$$

where C_c and G_c are the corrected capacitance and conductance values at all frequency region, respectively.
The corrected capacitance (C_c) of the diode is plotted in Figure 7 as a function of voltage for different frequencies (50 kHz-1 MHz). After eliminating the series resistance effect, the corrected capacitance values were obtained larger than the measured capacitance values. For example, at 1 MHz measurements, it increased from 5.0×10^{-10} F to 7.6×10^{-10} F at 3V for C_m and C_c, respectively. As seen in Figure 8, the $G_c - V$ characteristics at all frequencies have a peak in the depletion region and the corrected G_c values increase as the frequency increases. These peaks shift towards higher voltages, especially at high frequencies. The presence of a peak at each frequency corresponds to the presence of interfacial states [20, 24-26].

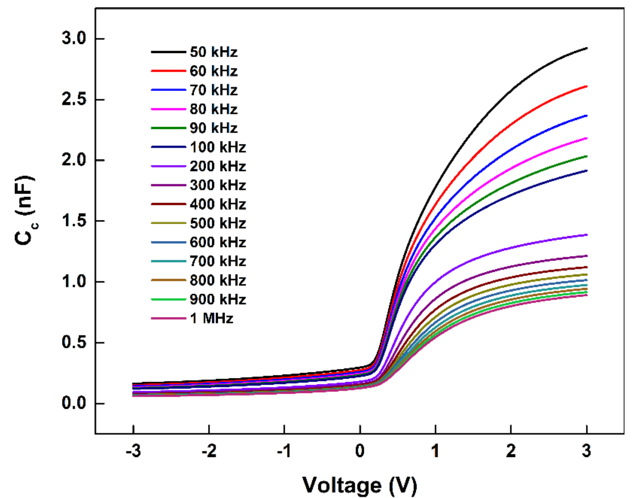


Figure 7: Plots of $C_c - V$ of the Au/HfO_2/p-Si diode in various frequencies 50 kHz-1 MHz.

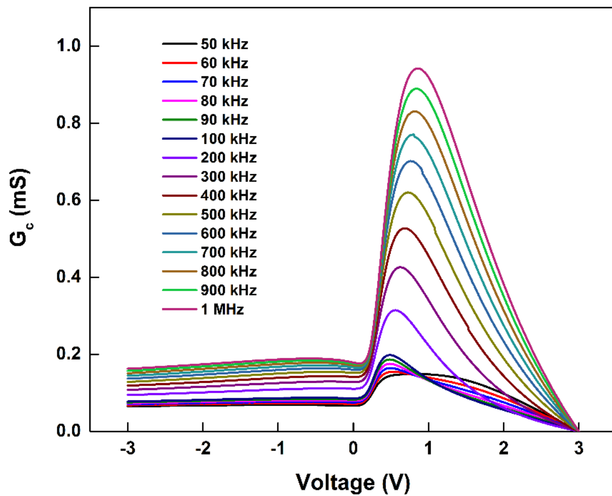


Figure 8: Plots of $G_c - V$ of the Au/HfO_2/p-Si diode in various frequencies 50 kHz-1 MHz.

One of the most techniques for calculation the interface state density (N_{ss}) value is Hill-Coleman technique [27]. According to Hill-Coleman technique, the N_{ss} values of the diode as a function of frequency can be calculated using the peak values of conductance-voltage curves by using equation below [27, 28]:

$$N_{ss} = \frac{2(G_{c,max}/\omega)}{qA}\left[(1\, C_c/C_i)^2\left(G_{c,max}/\omega C_i\right)^2\right]^{-1} \quad (5)$$

N_{ss} values were calculated according to equation 5 using the corrected conductance peaks and were plotted in Figure 9. As can be seen in Figure 9, N_{ss} values decrease as the frequency increases. The reason for this decrease is that the charge carriers cannot contribute to the capacity at high frequencies. N_{ss} values were found to be 7.89x10^{11} eV^{-1} cm^{-2} and 2.49x10^{11} eV^{-1} cm^{-2} for 50 kHz and 1 MHz, respectively.

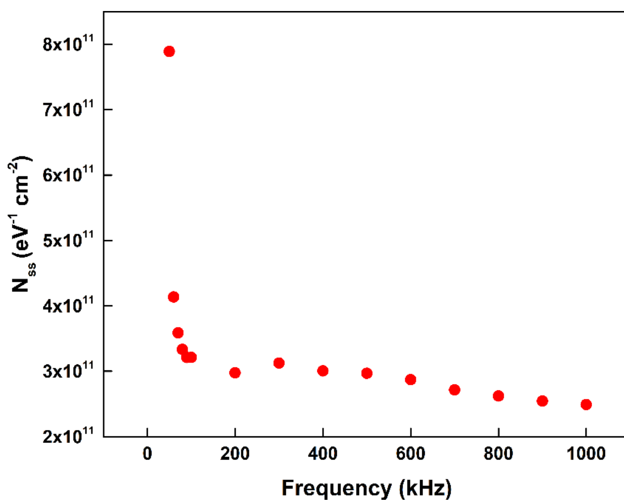


Figure 9: Characteristics of the Au/HfO_2/p-Si Schottky diode based on a Hill-Coleman conduction methods

4. Conclusion

In this work, it was aimed to improve the performance of the diode by depositing the HfO_2 interfacial layer between p-Si and Au by RF magnetic sputtering method since it has a high dielectric constant. The reverse and forward bias *C-V* and *G-V* characteristics of Au/HfO_2/p-Si Schottky diode were taken in the frequency vary from 50 kHz to 1 MHz. With frequency from 50 kHz to 1 MHz, the corrected capacitance values decreased while the conductivity values increased. The distribution profiles of series resistance and interface state density have been found from *G-V* and *C-V* measurements versus frequency for the Au/HfO_2/p-Si Schottky diode structure. The series resistance (R_s) of the structure produced yields a peak in the voltage vary from 0.13 to 0.33 V in the depletion region while frequency decreased. Furthermore, at all frequency values the series resistance appears small increase in the inversion and to be constant in the accumulation part. The values of R_s for 3V decrease with increasing frequency and values varied from 997 Ω at 50 kHz to 144 Ω at 1 MHz. The big quantity of interface states observed in low-frequency (50 kHz) capacitance-voltage measurements was effectively decreased by capacitance-voltage measurements up to 1 MHz. We have determined that the N_{ss} values decrease as frequency increased and values varied from 7.89x10^{11} eV^{-1} cm^{-2} at 50 kHz to 2.49x10^{11} eV^{-1} cm^{-2} at 1 MHz due to the charge carriers cannot contribute to the capacity as the frequency increases. The all results offer us that the fabricated Au/HfO2/p-Si Schottky diode may be a potential device for electronic applications.

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