Frequency and gate voltage effects on the dielectric properties and electrical conductivity of Al/SiO₂/p-Si metal-insulator-semiconductor Schottky diodes

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The dielectric properties and electrical conductivity of Al/SiO₂/p-Si (MIS) Schottky diodes (SDs) in the frequency range of 10 kHz to 10 MHz and the gate voltage range of -2 to 6 V have been investigated in detail using experimental C - V and G/w - V measurements. Experimental results indicated that the voltage dependence of the real part of the dielectric constant (ϵ') and loss tangent ($\tan \delta$) characteristics have a peak at each frequency. The values of ϵ' increase with decreasing frequency and tend to be frequency independent in the negative voltage region. However, the values of the dielectric loss (ϵ'') increase with decreasing frequency at each voltage. In contrast, ϵ' and ϵ'' are almost found to decrease, and the ac electrical conductivity (σ_{ac}) and the real part of the electric modulus (M') increase, with increasing frequency. In addition, the imaginary part of the electric modulus (M'') showed a peak that shifts to a higher frequency with increasing applied voltage. It can be concluded that interfacial polarization can more easily occur at low frequencies, and consequently the majority of interface states at the Si-SiO₂ interface contribute to the deviation of the dielectric properties of Al/SiO₂/p-Si (MIS) SDs. © 2011 American Institute of Physics. [doi:10.1063/1.3602090]

I. INTRODUCTION

Silicon (Si), which is mostly used in semiconductor technology, is a source amply found in nature, and one of the important characteristics of Si is that it allows the formation of an insulator layer (SiO₂) on the crystal surface. The preparation of clean Si surfaces and the growth of the insulator or oxide on this surface in device fabrication influences the stability and reliability of metal-insulator-semiconductor (MIS) Schottky diodes (SDs).¹ These devices have been gaining importance due to a wide variety of opto-electronic and high-frequency applications.^{2,3} The MIS diodes have a thin insulator layer ($\delta < 100$ Å) at the metal-semiconductor interface; this insulator layer can prevent inter-diffusion between the metal and the semiconductor substrate, and also it can alleviate the electric field reduction issue in MIS SDs.¹ Therefore, an insulator layer in the MIS diode gives the properties of a capacitor to these devices, which store the electric charges by virtue of the dielectric property of the oxide layers. The formation of an insulator layer on Si via traditional means of oxidation or deposition cannot completely passivate the active dangling bonds at the semiconductor surface.² The oxygen ions give rise to space charge effects, especially at low frequency regions. Thus, it is important to study the dielectric properties and ac conductivity over a wide range of frequencies via the impedance spectroscopy method (C - V) and G/w - V . The performance and reliability of these devices is especially dependent on the formation of the interfacial insulator layer and the density distribution of the interface states at the Si-SiO₂ interface. In recent years, due to the technical importance of MIS diodes, there have

been a lot of studies in the literature,^{3–16} but the voltage and frequency dependent dielectric characteristics of these devices are still not clarified. The frequency dependences of ϵ' , ϵ'' , and $\tan \delta$ are dominated especially at low frequencies, the physical origin of which has long been in question. Particularly at high angular frequencies ($\omega = 2\pi f$), because the carrier lifetime (τ) is much larger than $1/\omega$, the charges at the interface states cannot follow an ac signal.^{10–21}

In our previous work,²² we reported experimental results related to the I- V characteristics of Al/SiO₂/p-Si SDs as a function of temperature. However, the dielectric properties of these SDs have not been investigated in detail yet. Therefore, we aimed to investigate the effect of the frequency and gate bias on the dielectric properties of this device by using forward and reverse bias admittance measurements over the frequency range of 10 kHz–10 MHz. The variation of ϵ' , ϵ'' , $\tan \delta$, σ_{ac} , M' , and M'' has been investigated depending on previously determined frequency and applied voltage ranges.

II. EXPERIMENTAL PROCEDURE

Al/SiO₂/p-Si (MIS) SDs were fabricated on float zone $\langle 100 \rangle$ p-type (boron-doped) single crystal silicon wafers having a diameter of 2 in., a thickness of 280 μ m, and a resistivity of 8 Ω cm. For the fabrication process, the Si wafer was degreased in an organic solvent of CHCl₃, CH₃COCH₃, and CH₃OH; etched in a sequence of H₂SO₄ and H₂O₂, 20% HF, and a solution of 6HNO₃:1HF:35 H₂O, 20% HF; and finally quenched in de-ionized water with a resistivity of 18 M Ω cm for a prolonged time. High purity (99.999%) aluminum (Al) with a thickness of ~ 2000 Å was thermally evaporated from the tungsten filament onto the whole backside of half of a wafer at a pressure of $\sim 2 \times 10^{-6}$ Torr. The Ohmic

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contacts were prepared by sintering the evaporated Al back contact at about 500 °C for 75 min under dry nitrogen flow at a rate of 2 l/min. This process served to sinter the Al on the upper surface of the Si wafer. After the deposition of the Ohmic contact, the front surface of the Si wafer was exposed to air in a sterile glass box for a prolonged time at room temperature. The front rectifier contacts were produced via the evaporation of 2500 Å thick Al dots of ~1 mm in diameter onto the Si wafer. The interfacial layer thickness was estimated to be about 55 Å from the oxide capacitance measurement in the strong accumulation region at high frequency (1 MHz). The C-V and G/w-V measurements were carried out with the use of an HP4192 A LF impedance analyzer. All measurements were carried out with the help of a microcomputer through an IEEE-488 ac/dc converter card.

III. RESULTS AND DISCUSSION

The frequency dependence of ϵ' , ϵ'' , $\tan \delta$, σ_{ac} , M' , and M'' were evaluated based on the knowledge of capacitance and conductance measurements for Al/SiO₂/p-Si MIS SDs in the frequency range of 10 kHz-10 MHz at room temperature. The complex permittivity can be written²³ as

$$\epsilon^* = \epsilon' - i\epsilon'', \quad (1)$$

where ϵ' and ϵ'' are the real and the imaginary parts of the complex permittivity, and i is the imaginary root of -1 . The complex permittivity formalism has been employed to describe the electrical and dielectric properties. In the ϵ^* formalism, in the case of admittance Y^* measurements, the following relation holds:

$$\epsilon^* = \frac{Y^*}{j\omega C_o} = \frac{C}{C_o} - i \frac{G}{\omega C_{oi}}, \quad (2)$$

where C and G are the measured capacitance and conductance of the dielectric material at the M-S interface and ω is the angular frequency ($\omega = 2\pi f$) of the applied electric field.²⁴ At the various frequencies, the real part of the complex permittivity, the dielectric constant (ϵ'), is calculated using the measured capacitance values at the strong accumulation region from the relation^{17,25}

$$\epsilon' = \frac{C}{C_o} = \frac{C d_i}{\epsilon_o A}, \quad (3)$$

where C_o is the capacitance of an empty capacitor, A is the rectifier contact area of the structure in cm⁻², d_i is the interfacial insulator layer thickness, and ϵ_o is the permittivity of the free space charge ($\epsilon_o = 8.85 \times 10^{-14}$ F/cm). In the strong accumulation region, the maximal capacitance of the structure corresponds to the insulator capacitance ($C_{ac} = C_i = \epsilon' \epsilon_o A / d_i$). At the various frequencies, the imaginary part of the complex permittivity, the dielectric loss (ϵ''), is calculated using the measured conductance values from the relation

$$\epsilon'' = \frac{G}{\omega C_i} = \frac{G d_i}{\epsilon_o \omega A}. \quad (4)$$

The loss tangent ($\tan \delta$) can be expressed as follows:^{24,25}

$$\tan \delta = \frac{\epsilon''}{\epsilon'}. \quad (5)$$

The ac electrical conductivity (σ_{ac}) of the dielectric material can be given by the following equation^{24,25}:

$$\sigma_{ac} = \omega C \tan \delta (d/A) = \epsilon'' \omega \epsilon_o. \quad (6)$$

The complex impedance (Z^*) and complex electric modulus (M^*) formalisms have been discussed by various authors with regard to the analysis of dielectric materials.^{18,22} Analysis of the complex permittivity (ϵ^*) data within the Z^* formalism ($Z^* = 1/Y^* = 1/i\omega C_o \epsilon^*$) is commonly used to separate the bulk and the surface phenomena and to determine the bulk dc conductivity of the material.^{24,25} Many authors prefer to describe the dielectric properties of these devices by using the electric modulus formalism.^{26,27} The complex impedance or the complex permittivity ($\epsilon^* = 1/M^*$) data were transformed into the M^* formalism using the following relation:²⁸⁻³¹

$$M^* = i\omega C_o Z^* \quad (7)$$

or

$$M^* = \frac{1}{\epsilon^*} = M' + jM'' = \frac{\epsilon'}{\epsilon'^2 + \epsilon''^2} + j \frac{\epsilon''}{\epsilon'^2 + \epsilon''^2}. \quad (8)$$

The real component M' and the imaginary component M'' were calculated from ϵ' and ϵ'' .

Figure 1 shows the voltage dependence of the real part of the dielectric constant (ϵ') of the Al/SiO₂/p-Si MIS SDs at various frequencies. As can be seen from this figure, the voltage dependence of ϵ' has a peak, especially at low frequencies. It is noticed that the values of ϵ' increase with decreasing frequency and tend to be frequency independent in the negative voltage region. The reason for the decrease in ϵ' with increasing frequency might be that the polarization decreases with increasing frequency and then reaches a constant value due to the fact that beyond a certain frequency of external field, the electron hopping cannot follow the alternative field. The dispersion in ϵ' with frequency can

FIG. 1. The variations of the dielectric constant vs the applied voltage at various frequencies of Al/SiO₂/p-Si SD at room temperature.

FIG. 2. The variations of the dielectric loss vs the applied voltage at various frequencies of Al/SiO₂/p-Si SD at room temperature.

be attributed to the Maxwell-Wagner type interfacial polarization, i.e., the fact that inhomogeneities give rise to a frequency dependence of the conductivity because charge carriers accumulate at the boundaries of less conducting regions, thereby creating interfacial polarization.³² Figures 2 and 3 show the voltage dependence of ϵ'' and $\tan \delta$ of the Al/SiO₂/p-Si MIS SDs at various frequencies. As can be seen in Fig. 2, the values of ϵ'' increase with decreasing frequency, and Fig. 3 shows that the values of $\tan \delta$ characteristics have a peak at each frequency. The peak values of $\tan \delta$ - V have increased with increasing frequency in the range of 10 kHz to 200 kHz. In contrast, the peak values of $\tan \delta$ - V have decreased with increasing frequency in the range of 500 kHz to 10 MHz, and the peak positions strongly shift toward a negative bias region with increasing frequency. The peak behavior of ϵ' and $\tan \delta$ depends on a number of parameters, such as the doping concentration, the interface state density, the series resistance of the diode, and the thickness of the interfacial insulator layer.³¹ In the literature, it is stated^{10–21} that the capacitance and conductance

FIG. 3. The variations of the tangent loss vs the applied voltage at various frequencies of Al/SiO₂/p-Si SD at room temperature.

are extremely sensitive to the interface properties and series resistance. This can occur because of interface states that respond differently to low and high frequencies. Some authors attributed such a peak to only interface states in the literature.^{20,31–34}

The frequency dependences of the ϵ' , ϵ'' , and $\tan \delta$ of Al/SiO₂/p-Si SDs at different voltages are presented in Figs. 4(a), 4(b), and 4(c), respectively. The values of the ϵ' , ϵ'' , and $\tan \delta$ obtained from the measured capacitance and conductance were found to be strongly a function of the applied voltage in certain frequency regions. As can be seen from Figs. 4(a) and 4(b), ϵ' and ϵ'' show a gradual decrease with increasing frequency at each voltage. The values of ϵ' decrease with increasing bias voltage at any frequency lower than ≈ 200 kHz (Fig. 4(a)). However, the values of ϵ'' increase with increasing bias voltage at any frequency lower than ≈ 200 kHz (Fig. 4(b)). On the other hand, the values of $\tan \delta$ (Fig. 4(c)) show a peak at each voltage. Its intensity increases with decreasing voltage and shifts slightly toward the higher frequency side. In addition, it is clearly seen in Fig. 4 that the values of the ϵ' , ϵ'' , and $\tan \delta$ of Al/SiO₂/p-Si SDs are almost independent of voltage at high frequencies.

FIG. 4. The frequency dependence of (a) ϵ' , (b) ϵ'' , and (c) $\tan \delta$ at various applied voltages of Al/SiO₂/p-Si SD at room temperature.

FIG. 5. The frequency dependence of the ac electrical conductivity (σ_{ac}) at various applied voltages of Al/SiO₂/p-Si SD at room temperature.

In this respect, at low frequencies, all four types of polarization processes (i.e., the electronic, ionic, dipolar, and interfacial or surface polarization) contribute to the values of ϵ' and ϵ'' . Moreover, at high frequencies, the values of ϵ' become closer to the values of ϵ'' due to the fact that the interface states (N_{ss}) cannot follow the ac signal at high-enough frequencies ($f \geq 500$ kHz).^{16,26,27,35}

The behavior of the ac electrical conductivity (σ_{ac}) of the Al/SiO₂/p-Si SDs at different voltages is presented in Fig. 5. It is noticed that the dc conductivity generally

FIG. 6. (a) The real part M' and (b) the imaginary part M'' of the electric modulus M^* vs the frequency of Al/SiO₂/p-Si SD at room temperature.

increased with increasing frequency. This dc conductivity contributes only to the dielectric loss, which becomes infinite at zero frequency and which is important at high frequencies.^{34–36} The increase of the ac electrical conductivity is accompanied by an increase of the eddy current, which in turn increases the energy loss to $\tan \delta$. This behavior can be attributed to a gradual decrease in the series resistance with increasing frequency.³⁶

The variation of the real part of the electric modulus M' and the imaginary part M'' of Al/SiO₂/p-Si SDs as a function of frequency at various bias voltages is given in Figs. 6(a) and 6(b), respectively, at room temperature. As shown in Fig. 6(a), M' increases with increasing voltage between 10 kHz and ≈ 300 kHz and decreases with increasing voltage after ≈ 300 kHz. It is clearly seen in this figure that there is a symmetric change in $M'-f$ as a function of frequency and voltage due to the effect of the polarization. It can be seen in Fig. 6(b) that the M'' of the electric modulus M^* versus f has two peaks at high voltages, but it has only one peak at low voltages, and the values of the peaks increase with decreasing applied voltage at 1 MHz.

IV. CONCLUSION

The frequency dependence of the dielectric properties of Al/SiO₂/p-Si SDs has been studied in detail in the wide frequency range of 10 kHz–10 MHz at room temperature using the measured C-V and G/w-V characteristics. Experimental results show that the values of ϵ' and ϵ'' are almost found to decrease, whereas the ac electrical conductivity σ_{ac} and the real part of the electric modulus increase, with increasing frequency. It can be said that the dielectric parameters (ϵ' , ϵ'' , $\tan \delta$, M' , and M'') of the prepared sample in this study are strongly dependent on the frequency and the applied bias voltage. This behavior is attributed to the interface charges and polarization. These interface charges in interface states can easily follow the ac signal at low frequencies and yield an excess capacitance and conductance that depend on the relaxation time of the interface states and the frequency of the ac signal.

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