A COMPARISON OF BASIC ELECTRICAL PARAMETERS OF THE Al/SiO_2/p-Si (MIS) STRUCTURE OBTAINED BY THERMIONIC EMISSION (TE), AND CHEUNG FUNCTIONS

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In the present paper electrical characteristics of Al/SiO_2/p-Si MIS structure was measured in the range of voltage ±4V. Silicon layer SiO_2 on the semiconductor wafer was obtained by thermal oxidation of Si. The Al/SiO_2/p-Si (MIS) structures were constructed on p-type (boron-doped) single-crystal silicon wafers with a (100) surface orientation. The a thickness of wafer is 350 μm, a diameter of 2 inches, and a resistivity of 1 Ω.cm. The thickness of SiO_2 layer in the MIS structure is 60 nm. On the basis of measured characteristics have been obtained basic parameters of structure such as potential barrier heigt (ϕ_{B0}), ideality –factor (n) and series-resistance (R_s). For the calculating of parameters have been used two methods - thermionic-emission (TE) theory and Cheung's functions. The results obtained by both methods were compared. The identified differences are due to the presence of inhomogeneities at the interface and in the volume.

Keywords: Schottky diode; Thermionic emission; Cheung's functions; Surface state density, Metal- insulator- semiconductors (MIS); SiO_2
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INTRODUCTION

The functioning of most modern electronic devices relies on a metal-semiconductor contact structure featuring a Schottky barrier (SB).Schottky diodes operate quickly because they eliminate diffuse and recombination processes that require additional time and the injection of minority charge carriers [1-3]. More than 99% of all semiconductor devices are made using silicon (Si). Silicon is widespread in nature and its processing technology has been well studied.

A silicon dioxide layer is easily created in silicon by conventional thermal oxidation. The thickness of this dielectric is usually 0.3-1.5 microns. But this layer is enough to protect silicon from the diffusion of impurities and provide better dielectric protection. In this regard, the growth of the oxide layer on the semiconductor is a more important step in the production process of MIS or MOS devices [2-4]. The generalized model of the contact structure takes into account the presence of a dielectric gap. It should be noted that the presence of a dielectric gap in the metal-oxide-semiconductor contact structure affects the distribution, concentration and activation of surface states, as well as the charge transfer mechanism [1-12]. The most common MOS (metal oxide semiconductor) structures on silicon with a layer of SiO_2, which is obtained by thermal oxidation of Si. Thermal silicon oxide SiO_2 is a key dielectric in silicon devices. As it is known from the scientific literature, to create a perfect interface, a layer of SiO_2 with a thickness ≈ 5 A is grown on silicon, and then a layer of high-k dielectric with a thickness of ≈ 50 A is deposited [4,12].

The electronic structure of SiO_2 has been intensively studied experimentally and theoretically for many years [13–15]. Despite this, some features of the electronic structure of SiO_2 have remained unclear over the past 50 years. In connection with the use of SiO_2 and contact structures with a dielectric gap in microelectronics, the study of MOS structures with a thin layer of Silicon Oxide is of practical interest.

In order to study the influence of surface states on the characteristics of the contact structure, the characteristics of MIS structures with various interfacial layers, such as SiO_2, SnO_2, Al_2O_3, ZrO_2, HfO_2 and organic layers, were investigated and analyzed [16-19].

In recent years, many studies have been carried out on the main parameters characterizing the processes at the interface between Si and thermally grown SiO_2. [12,20-22]. However, the mechanisms of current flow, key parameters of these structures, and their dependence on factors such as oxide layer thickness, the selection of contacting metal and semiconductor, as well as the impact of the manufacturing process, have yet to be thoroughly clarified. As is known from scientific literature the insulator thickness in these studies was in the range of 40–60 Å, 50–826 Å. In the presented article, the thickness of SiO_2 in the MIS structure is 60 nm. It is known that the dependence of the characteristics of a contact structure on frequency is determined by various processes: the inertia of the passage of charge carriers through the space charge region of the semiconductor (1E-11 sec ÷1E-13 sec), recharging of surface electronic states (1E-6 sec) and inertia associated with circuit reasons (1E-8 sec) [1-3].In this regard, preference was given to the study of electrical parameters of Al/SiO_2/p-Si from measurements of the static current-voltage characteristic. Thus, the purpose of the presented article is to study the main parameters of the Al/SiO_2/p-Si MIS structure (thickness of the dielectric gap of thermal SiO_2 is 60nm) using current-voltage characteristics measured at T=300K.

The Al/SiO_2/p-Si (MIS) structures were constructed on p-type (boron-doped) single-crystal silicon wafers with a (100) surface orientation. These wafers had a thickness of 350 μm, a diameter of 2

inches, and a resistivity of 1 Ω.cm. Initially, the wafers were degreased using organic solvents and then rinsed in de-ionized water with a resistivity of 18 MΩ.cm for 10 minutes. Oxide layers, 60 nm thick, were grown at 750°C for 1.5 hours and 900°C for 4 hours, respectively. After the oxidation step, circular aluminum dots with a purity of 99.999%, a diameter of 1.2 mm, and a thickness of about 2000 Å were deposited as rectifying contacts on the oxidized surface, using a Si shadow mask in a vacuum system with a liquid nitrogen trap, maintaining a pressure of ~1E-7 Torr. Following this, aluminum with a thickness of ~2000 Å was thermally evaporated onto the entire back side of the wafer, after the oxide layer (SiO_2) had been etched away using HF, to create ohmic/back contacts. The thickness of the metal layers and their deposition rates were measured using a quartz crystal thickness monitor. Finally, I–V measurements were carried out at room temperature using a Keithley 2400 I–V source meter.

RESULTS AND DISCUSSIONS

Figure 1 presents the typical forward and reverse-bias semilogarithmic I–V characteristics of the Al/SiO_2/p-Si MIS structure measured at room temperature. As depicted in the figure, the semilogarithmic I–V plot demonstrates clear rectifying behavior, with an exponential increase in forward current (IF) and a weak voltage dependence in the reverse current (IR). The rectification ratio (RR) for this structure is calculated as RR = I_f/I_r = 3.88. It is noticeable that the reverse current gradually increases with applied reverse bias, without showing any signs of saturation. This slight non-saturation or ‘soft’ behavior observed in the reverse-bias region of the experimental I–V plot may be attributed to spatial inhomogeneity within the contact structure [12, 23, 24]. In the case of inhomogeneous Schottky barrier (SB) contacts, the reverse current is likely dominated by current flowing through regions with lower Schottky barrier height (SBH).

For forward bias conditions (V ≥ 3kT/q), the current through the SB can be described by the thermionic emission (TE) theory,is given by

$$I = I_0 exp\left(\frac{q(V-IR_s)}{nkT}\right)\left[1-exp\left(-\frac{q(V-IR_s)}{kT}\right)\right] \quad (1)$$

where I_0 is the reverse saturation current, where q is the electronic charge, $A*$ is the effective Richardson constant and is equal to 120A $cm^{-2}K^2$ for p-type Si, A is the effective diode area, k is the Boltzmann constant, T is the absolute temperature in K, ϕ_{B0} is the zero-bias barrier height and n is the ideality factor .

The reverse saturation current can be described as

$$I_0 = AA^*T^2\exp\left(-\frac{q\phi_{B0}}{kT}\right) \quad (2)$$

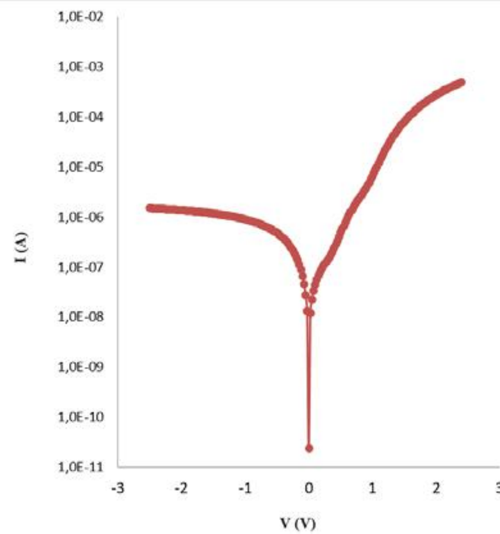

Fig.1. Semilogarithmic I–V plots for Al/SiO_2/p-Si MIS structure.

Once the applied voltage exceeds 3kT/q, the primary electrical properties of these Schottky diodes (SDs) can be extracted from the linear region using thermionic emission (TE) theory, as depicted in Figure 2 [1, 3, 11, 13]. The forward-bias ln(I)−V plots for the fabricated Al/SiO_2/p-Si MIS structure, shown in Figure 2, exhibit strong rectifying behavior, where the current rises almost exponentially with increasing voltage at moderate voltage levels. The ideality factor, which provides insight into the diode's performance, is calculated from the slope of the linear region in the forward-bias ln(I)−V plot. According to equation (1), it can be expressed as follows:

$$n = \frac{q}{kT}\left(\frac{d(V-IR_s)}{d(\ln I)}\right) \quad (3)$$

The zero-bias barrier height ϕ_{B0} determined from the extrapolated I_0 and is given by

$$\phi_{B0} = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_s}\right) \quad (4)$$

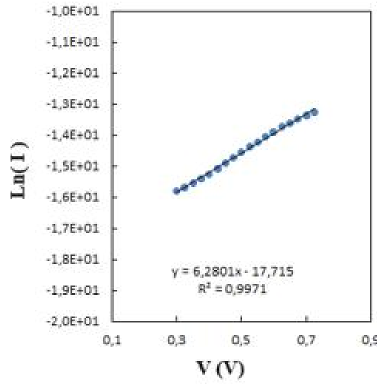

Fig. 2 Semilogarithmic ln (I)–V plots of Al/SiO_2/p-Si MIS structure.

The values of the ideality factor (n) and saturation current (I_S) for the Al/SiO_2/p-Si MIS structure were determined from the slope and intercept of the ln(I) vs. V graph (Fig. 2b). Using the calculated Is and the diode area (A), the barrier height (Φ_{B0}) was then computed according to Eq. 4. The potential barrier height (Φ_{B0}) and ideality factor (n) for the Al/SiO_2/p-Si MIS structure were found to be 0.75 eV and 5.24, respectively, while the saturation current (Io) was calculated as 2.025E-8 A. The electrical characteristics of the structure are influenced by both the series resistance (Rs) and shunt resistance (R_{sh}). These values were calculated based on the basic application of Ohm's law (R_i = dV/dI) at both reverse and forward biases, as illustrated in Figure 3. The extracted values for Rsh and Rs were 2.15 MΩ and 5.13 kΩ, respectively.

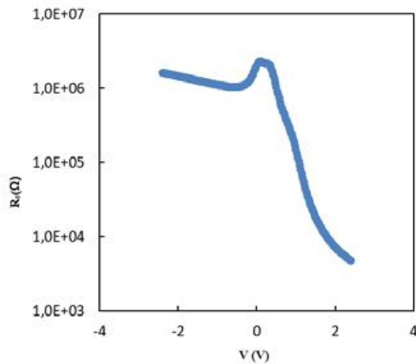

Fig 3. The voltage dependent profile of resistance (R_i) plot for Al/SiO_2/p-Si contact structure.

To investigate more clear electrical properties, electrical parameters (n, I_0 , Φ_B) were extracted from following Cheung's methods Eq. 2(a-b) [25]:

$$\frac{dV}{d(\ln I)} = IR_s + \frac{nkT}{q} \quad (2a)$$

$$H(I) = V - \frac{nkT}{q} ln\left(\frac{I}{AA^*T^2}\right) = IR_s + n\phi_B \quad (2b)$$

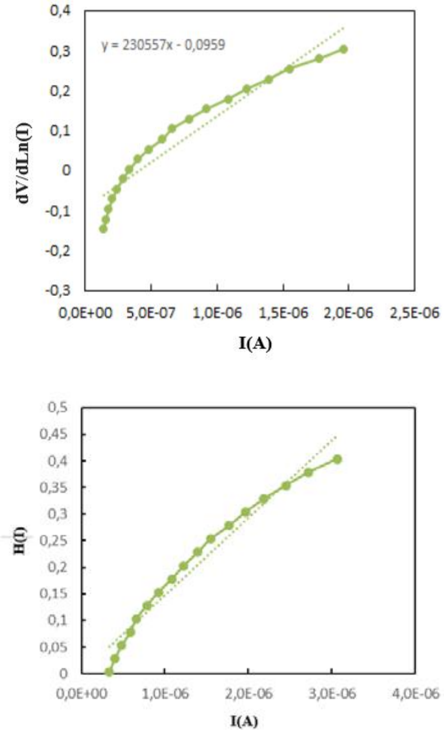

Fig 4. a) dV/dln(I) – I and b) H(I)-I plots for

From these functions, the series resistance (R_s) and ideality factor (n) can be derived from the slope and intercept of the dV/dln(I) vs. I plot. Similarly, Rs and the barrier height (Φ_{B0}) can be obtained from the slope and intercept of the H(I) vs. I plot. Figure 4a and 4b illustrate both the dV/dln(I) vs. I and H(I) vs. I graph, respectively, providing a visual representation of these relationships. Barrier height, ideality factor and series resistance shown in Table1.

Table 1.

Basic electrical parameters of Al/SiO_2/p-Si MIS structure

parameters	*From Thermionic Emission (TE) Theory*	*Cheung's functions (dV/d(lnI)–I)*	*Cheung's functions (H(I)- I)*
ϕ_{B0}(eV)	0.75	0.672	0.697
n	5.24	6.43	7.43
R_s(kΩ)	5.13	7.21	7.84

As observed from the results, discrepancies exist in the parameter values calculated using different methods. These differences can be attributed to factors such as the presence of surface states, local inhomogeneities both in the bulk and on the contact surface, and the mismatch of crystal lattice parameters

between contacting materials. These factors introduce some distortion in the accurate determination of the main parameters. Consequently, the values obtained for the primary parameters of the $Al/SiO_2/p$-Si MIS structure should be considered effective values rather than exact ones.

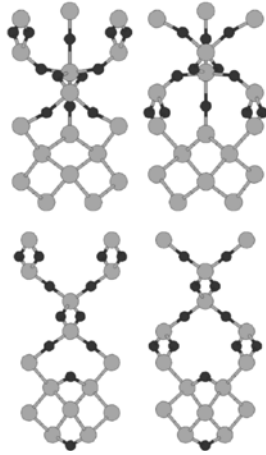

Fig. 5. xz - (a, c) and yz -projections of the relaxed structure of the Si/SiO_2 superlattice for various models.

It is widely understood that the main characteristics of the electronic structure are primarily governed by the types of atoms involved in forming chemical bonds [26,27]. Studies on the equilibrium structure of Si/SiO_2 superlattices reveal that structural optimization leads to significant atomic rearrangement from the original lattice models due to atom redistribution near the interfaces. Figure.5 illustrates two initial model structures that, after relaxation, produce distinct interface structures, which are likely to result in variations in their physical properties. Furthermore, research indicates that the thickness of both Si and SiO_2 layers can impact not only the vibrational properties of the superlattices but also the atomic structure at the interfaces.

CONCLUSION

The parameters of the $Al/SiO_2/p$-Si MIS structure were analyzed based on I-V measurements. The key parameters were calculated using two different methods: thermionic emission (TE) theory and the Cheng method. Upon analyzing and comparing the values of parameters such as the barrier height (ΦB), ideality factor (n) and the series resistance (R_s) obtained through these methods, only minor differences were observed. These deviations from ideal values are primarily due to the presence of inhomogeneities at the interface between the contacting materials. Both calculation methods are limited in their ability to accurately account for lattice mismatches, surface and bulk inhomogeneities, and the imperfections that can arise spontaneously during the fabrication process. As a result, these methods cannot fully capture the complexities of the material structure, leading to slight discrepancies in the calculated parameter values.

[1] *S.M. Sze.* Physics of Semiconductor Devices, second ed., Willey, New York, 1981.Roder.

[2] *V.I. Strikha.* Theoretical bases of metal–semiconductor contact's work. Kiev: Naukova Dumka; 1974 [in Russian].

[3] *E.H. Rhoderich.* Metal–semiconductor contacts. Moscow: Radio I svyaz; 1982 [in Russian]. R. Castagne, A. Vapaille, Surface Science 28(1), 157 (1971).

[4] *J.M. Poate, K.N. Tu, J.W. Mayer.* Thin films – interdiffusion and reactions. Moskow: Mir; 1982 [in Russian].

[5] *E.V. Buzanyova.* Microstructures of integrated electronics. Moscow, Radio i Svyaz, 1990.

[6] *U. Kelberlau, R. Kassing.* Solid-State Electron. 24, 321 (1981).

[7] *N. Konofaos, E.K., Evangelou, Zhongchun Wang, V. Kugler, U. Helmersson.* Journal of Non Crystalline Solids. 303, 185 (2002).

[8] *E.J. Miller, X.Z. Dang, H.H. Wieder, P.M. Asbeck, E.T. Yu, G.J. Sullivan, J.M. Redwing.* J. Appl. Phys., 87(11), 8070 (2000).

[9] *Ş. Altındal, H. Kanbur, İ.Yücedağ, A. Tataroğlu.* Microelect. Eng. 85, 1495 (2008).

[10] *A. Tataroğlu, Ş Altındal.* Microelect. Eng.85, 2256 (2008).

[11] *M. Kuhn.* Solid State Electron. 13(6), 873 (1970).

[12] *Ş. Altindal, Y. Şafak Asar, A. Kaya, Z. Sönmez.* Investigation of interface states in $Al/SiO_2/p$-Si (MIS) structures with 50 and 826 Å SiO_2 interfacial layer using admittance spectroscopy method/Journ. of optoelectronics and advanced materials, vol. 14, № 11- 12, 2012, p. 998 – 1004.

[13] *E.H. Nicollian, J.R. Brews.* MOS (metal/oxide/semiconductor) Physics and Technology, John Wiley & Sons, New York (1982).

[14] *A. Tataroğlu, Ş Altındal.* Microelect. Eng. 85, 2256 (2008).

[15] *W. Mönch.* Semiconductor Surfaces and Interfaces, third ed. Springer Verlag Pres, 2001.

[16] *M. Çakar, A. Türüt.* Synthetic Metals, 13, 549 (2003).

[17] *Y. Çağlar, M. Çağlar, S. Ilican, F. Yakuphanoğlu.* Microelect. Eng., 86, 2072 (2009).

[18] *L. Truong, Y. G. Fedorenko, V.V. Afanasev, A. Stesmans.* Microelectronics Reliability, 45, 823 (2005).

[19] *A. Tataroğlu.* J. Optoelectron. Adv. Mater.13(8), 940 (2011).

[20] *E.H. Nicollian, A. Goetzberger.* Bell Syst.Tech. J. 46, 1055 (1967).

[21] *K.K. Hung, Y.C. Cheng.* Appl. Surf. Sci., 30, 114 (1987).

[22] *E.H. Nicollian, A. Goetzberger, A.D. Lopez.* Solid-State Electron. 12, 937 (1969).

[23] *C.N. Berglund.* IEEE Trans. Nucl. Sci. ED-13(10), 701 (1966).

[24] *A. Tataroğlu, Ş. Altındal, M.M. Bülbül.* Microelect. Eng. 81, 140 (2005).
[25] *S.K. Cheung, N.W. Cheung*. 1998. Extraction of Schottky diode parameters from forward current-voltage characteristics. Applied Physics Letters, 49, 85.
[26] *Р.М.Х. Исхакзай*, *В.Н. Кручинин*, *В.Ш. Алиев*, *В.А. Гриценко*, *Е.В. Дементьева* , *М.В. Заморянская*. Ранспорт заряда в нестехиометрическом SiO$_x$, полученном обработкой термического SiO$_2$ в водородной плазме электронно-циклотронного резонанса. Микроэлектроника, 2022, Т. 51, № 1, стр. 28.
[27] *С.С. Некрашевич, В.А. Гриценко*. Электронная структура оксида кремния (Обзор) Физика твердого тела, 2014, том 56, вып. 2, с.209-223.