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Equivalent Circuit of Al/SiO$_2$/*n*-Si Structures Irradiated by Helium Ions with Energy 5 MeV at Fluence 10^{12} cm^{-2}

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Abstract

Recently, metal-oxide-semiconductor structures using silicon dioxide is the most common microelectronic structures. Silicon dioxide (SiO_2) is used to isolate pole gate dielectric, and it is also the main material used to make stable, high-performance devices of integrated circuits. Electrical parameters at the Si-SiO_2 interface created by gamma irradiation depends on the type and penetration of the implanted ions. The paper provides a method of determining the equivalent circuit of a metal-oxide-semiconductor structure to determine its electrical parameters. The structure Al/SiO_2/n-Si irradiated by helium ions with energy 5 MeV at fluence 10^{12} cm^{-2} are studied to find its equivalent circuit. Result, the structure's equivalent circuit composing of a resistor and parallel RC circuit in series does not describe the frequency dependence of the electric loss in an alternating current at the frequency range 20 – $3{\cdot}10^6$ Hz. In the inversion region with voltage U = -40 V, equivalent circuits are developed and implemented in a wide frequency range. These circuits allow us to easily calculate electrical parameters through the frequency dependence of impedance characteristics.

Keywords: equivalent circuit, Al/SiO_2/n-Si structures, fluence.

1. Introduction

Silicon dioxide (SiO_2) is used to isolate pole gate dielectric (Hsu et al., 2016), and it is also the main material used to make stable, high-performance devices of integrated circuits (Mogeb et al., 1986). At present, the models of defects responsible for localization of electrons and holes in SiO_2 still continue to be discussed (Skuja, 1998; Pacchioni, Ierano, 1998; Gritsenko et al., 1998). Electron levels at the Si-SiO_2 interface created by gamma irradiation depends on the type and penetration of the implanted ions (Kaschieva et al., 2003; Kaschievaa, Todorovab, 2004). The main reason for changing the parameters of such materials under the impact of irradiation is related to the charge accumulation in the gate dielectric, as well as the increase in the density of surface states at the interfaces of the silicon layer with dielectric (Ogorodnikov et al., 2019).

The electrical parameters of the structure when exposed to ionizing radiation are the charge buildup in the dielectric and the increase in the density of surface states at the interface of the insulator/semiconductor (Ogorodnikov et al., 2019; Sze, 2008; Bentarzi, 2011). Therefore, we need the equivalent circuit that replaces the irradiated structure measured at inversion region (with voltage U = -40V) to calculate its electrical parameters.

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The purpose of this paper is to study the frequency dependence of the electric loss and then propose the equivalent circuits in inversion region of $Al/SiO_2/n$-Si structures, such the metal-oxide-semiconductor structures using silicon dioxide, irradiated by helium ions with energy 5 MeV at fluence 10^{12} cm^{-2} which are provided by OAO "INTEGRAL" of Ruhr University (Bochum, Germany).

2. Experiment

$Al/SiO_2/n$-Si structures are manufactured at OAO "INTEGRAL" under the cooperation agreement with BSU. These structures are then irradiated with the helium ions at fluence 10^{12}, which are produced by the accelerator of Ruhr University (Bochum, Germany). All the irradiations are performed at room temperature. $Al/SiO_2/n$-Si structures are fabricated on single-crystal n-type silicon sheets developed by Czochralski method (Shimura, 2012; Shimura, 2007). The resistivity of silicon is 4.5 Ohm.cm. A 420-nm thick layer of silicon dioxide (SiO_2) is formed by thermal oxidation at 950 °C for 225 minutes. Aluminum is deposited in the plane on SiO_2 layer by thermal spraying. The area of aluminum needle having a thickness of 0.7 µm is 1.85 × 1.85 mm². Bridges to the uneven side are also formed by A_l sputtering. The plates are divided into chips with area of 2.5 × 2.5 mm².

The simplest experimental devices for measuring conductivity in alternating current (AC) are usually based on Wheatstone bridge circuit (Grafov, Ukshe, 1973; Poklonski, Gorbachuk, 2005). In order to calculate the frequency dependence of the electrical loss, the frequency dependence of the actual impedance and the virtual impedance are measured with the Agilent 4285A precision LCR meter in the frequency range from 20 Hz to 30 MHz. The sinusoidal voltage amplitude does not exceed 40 mV. At the same time as the measurement of alternating current, we add the direct current U from -40 V (the inverse voltage U_r) to 0.2 V (the positive voltage U_f) on two poles of the $Al/SiO_2/n$-Si structure. The measurements are made at room temperature.

3. Results and discussion

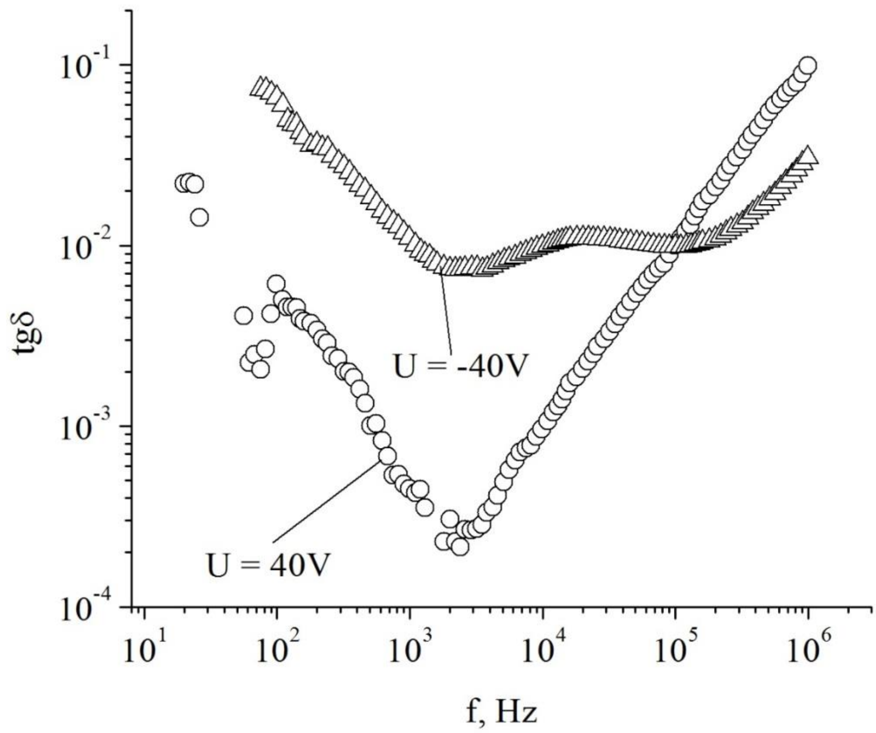

Fig. 1. The frequency dependence of the electrical loss on the structures irradiated by helium ions with fluence F = 10^{12} cm^{-2}

Figure 1 shows the frequency dependence of the electrical loss at the different voltage values U = -40 V (corresponding to inversion region) and U = 40 V (corresponding to accumulation region).

In the inversion region (U = -40 V), at 10-30 kHz, there is the presence of the maximum tgδ. However, the maximum position does depend on the polarity voltage. The higher the voltage is, the higher the transmission loss is, but the maximum is actually different among three regions. For p^+-n diodes, which are irradiated by electrons (Poklonski et al., 2010), the presence of the maximum loss at frequencies in the order of tens of kHz is determined by the charging loss of the radiation defect in the space charge region. With an decrease in the bias voltage, the tgδ increases, thereby leading the presence of the maximum. This maximum is associated with the reloading of radiation defects, and its position depends on the polarization voltage.

The position of the minimum depends on the U voltage. As the voltage decreases, the minimum moves to a higher frequency. The increase in tgδ under irradiation levels of 10^{12} cm^{-2} is also contributed by the recombination process which generated in the space charge region. The accumulation of radiation defects actually not only leads to the offset of impurities, but also increases the speed of generation of charged particles, which contributes to the increase of the current.

In the accumulation region (Sze, 2008), the equivalent circuit of the irradiated structure consists of a insulator capacitor (C_o) in series with a circuit whose a capacitor is connected in parallel with a resistor in series with the series resistance (R_s). In this parallel circuit, the capacitance of the capacitor corresponds to the C_d capacitance of the space charge, and the resistance of the resistor corresponds to its R_d resistance. However, in the case when $\omega = 2\pi f \gg 1/R_dC_d$, it is necessary to take into account the series resistance R_s (Figure 2, № 1).

The simplest equivalent circuit (Figure 2, № 1) does not allow us to explain experimental frequency dependencies of tgδ. This can be proved by analyzing the dependence of electric loss on frequency. The electric loss is determined for circuit № 1 by the formula (Poklonski, Gorbachuk, 2005; Barsoukov, Macdonald, 2005; Berman, Lebedev, 1981):

$$Z = R_s + \frac{R_d}{1+i\omega C_d R_d} + \frac{1}{i\omega C_0} = R_s + \frac{R_d}{1+\omega^2 C_d^2 R_d^2} - i\left(\frac{\omega R_d^2 C_d}{1+\omega^2 C_d^2 R_d^2} + \omega C_0\right) = Z' - iZ'' \quad (1)$$

Here, $\omega = 2\pi f$ – corner frequency, Z' and Z'' – real impedance and virtual impedance:

$$Z' = R_s + \frac{R_d}{1+\omega^2 C_d^2 R_d^2} = R_s + \frac{R_d}{1+(\omega\tau)^2} \quad (2)$$

$$Z'' = \frac{\omega R_d^2 C_d}{1+\omega^2 C_d^2 R_d^2} + \omega C_0 = \frac{\omega\tau R_d}{1+(\omega\tau)^2} + \omega C_0 \quad (3)$$

$\tau = R_dC_d$ – time constant

So from formula (2) và (3) we have:

$$\mathrm{tg}\delta = \frac{Z'}{Z''} = \frac{R_s + \frac{R_d}{1+(\omega\tau)^2}}{\frac{\omega\tau R_d}{1+(\omega\tau)^2} + \omega C_0} = \frac{R_s\left(1+(\omega\tau)^2\right)+R_d}{\omega\tau R_d + (1+(\omega\tau)^2)\omega C_0} \quad (4)$$

Therefore, the minimum of the derivative $tg\delta$ in ω (corner frequency) is inconsistent in Figure 1 for the experimental data of the irradiated structure. In order to describe electrical loss depending on the frequency of the irradiated structure, the study should use more complex equivalent circuits, such № 2 and № 3 alternative equivalent circuits shown in figure 2 (Poklonski, Gorbachuk, 2005; Barsoukov, Macdonald, 2005). Equivalent circuit № 2 takes into account the capacitance C_{SC} and circuit № 3 contain a constant phase element (CPE). These two circuits correspond to the three-layer model: the first layer is the space charge layer, the second layer is the quasi-continuous radiation-disturbed layer and the third layer is the base layer.

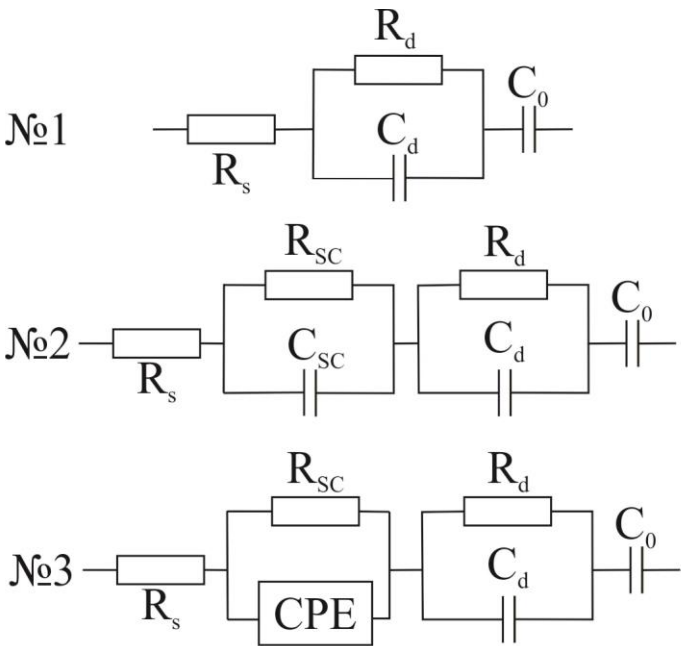

Fig. 2. The equivalent circuit replaces the structure Al/SiO_2/*n*-Si
№1 – structure in the accumulation region; №2 and №3 – structure in the inversion region

The calculation of parameters of equivalent circuits is made for frequencies in the range from 20 Hz to 30 MHz using the complex non-linear least squares (CNLS) method (Kaschievaa, Todorovab, 2004; Barsoukov, Macdonald, 2005):

$$\Omega = \sum_i \left\{ \frac{\left[C_m^*(\omega_i) - C_m(\omega_i)\right]^2}{C_m^{*2}(\omega_i)} + \frac{\left[G_m^*(\omega_i)/\omega_i - G_m(\omega_i)/\omega_i\right]^2}{G_m^{*2}(\omega_i)/\omega_i^2} \right\} \tag{3.1}$$

where $C_m^*(\omega_i), G_m^*(\omega_i)$ – experimental value of capacitance and admittance; $C_m(\omega_i)$, $G_m(\omega_i)$ – the values are calculated for equivalent circuits.

Therefore, to describe the frequency dependence of the impedance of the Al/SiO_2/*n*-Si structure in the accumulation region, we use the equivalent circuit shown in figure 2 (circuit №1). According to the approximate results, the values of Al/SiO_2/*n*-Si structure irradiated with fluence 10^{12} cm^{-2} are obtained for the elements of equivalent circuit № 1: R_d = (1.3±0.196)·10^6 Ω; C_d = (7.05±0.497) ×10^{-9} F; R_s = (29.15±0.24) Ω; C_0 = (2.82 ±0.008)x10^{-10} F. Same to the equivalent circuits № 2 and № 3, the results are obtained in the Table 1.

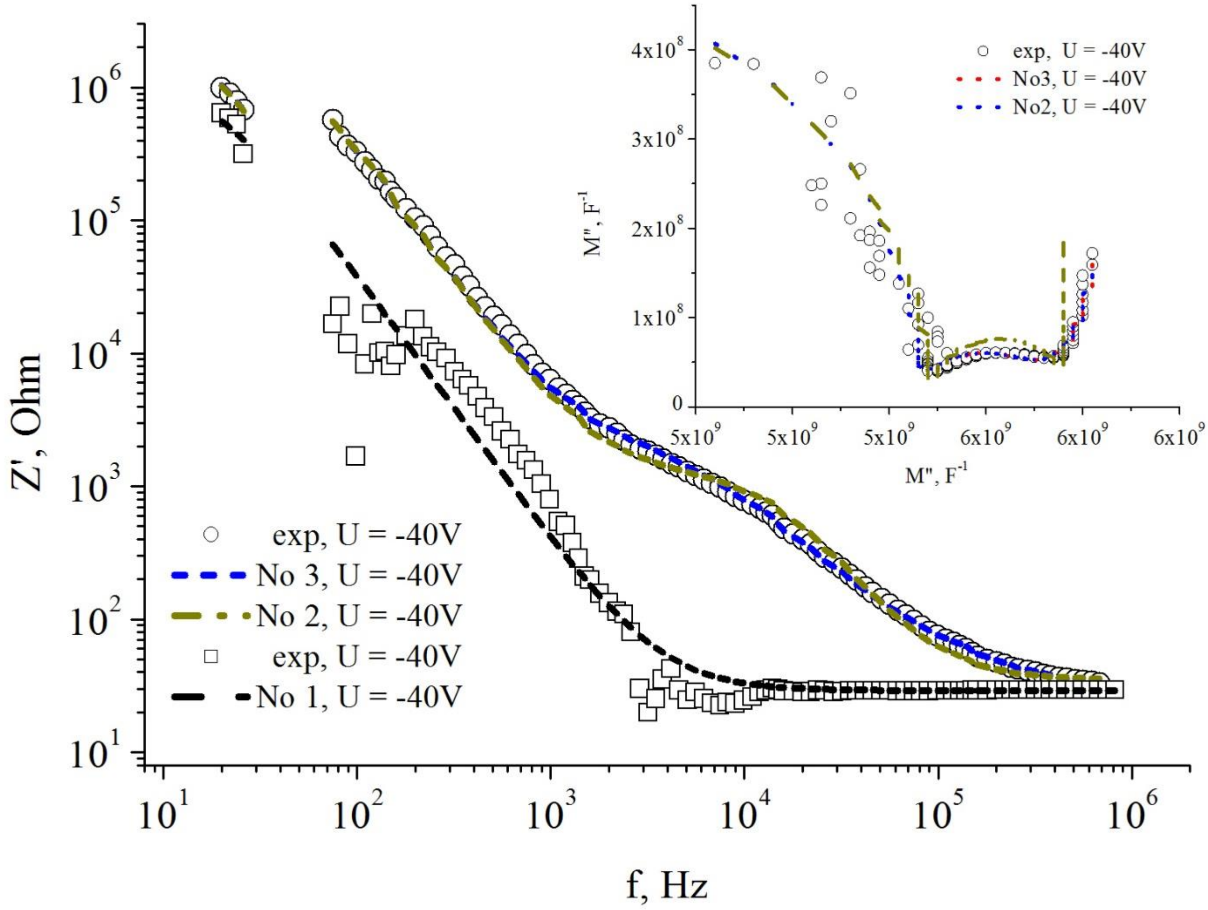

Fig. 3. Dependence of the real impedance Z' on the frequency f.
Right corner is the hodograph of the complex electrical module

Figure 3 shows the measurements at voltage U = -40 V (corresponding to the № 2 and № 3 equivalent circuits), U = 40 V (corresponding to the № 1 equivalent circuit), the real impedance Z' depending on the frequency of the structure irradiated with fluence 10^{12} cm^{-2} is calculated in most frequency bands.

Table 1. The values of equivalent circuits are obtained by approximating the real impedance depending on the frequency of the structure irradiated with fluence 10^{12} cm^{-2}.

Element	Equivalent circuit (fig. 2)		
	№ 1	№ 2	№ 3
R_d, MΩ	1.3 ± 0.19	4.29 ± 0.31	4.86 ± 0.31
R_{sc}, kΩ	-	1.242 ± 0.69	2.18 ± 0.18
R_s, Ω	29.15 ± 0.24	35.11 ± 1.21	25.5 ± 1.45
C_d, nF	7.05 ± 0.49	7.13 ± 0.15	1.01 ± 0.03
C_{sc}, nF	-	1.06±0.036	-
C_o, nF	0.28±0.0008	0.22±0.001	0.22±0.001
CPE – A_o, $10^{-8}\,\Omega^{-1}.s^{\alpha}$	-	-	3.46 ± 0.508
CPE - α	-	-	0.88 ± 0.010

The constant phase elemant (CPE) has an admittance Y:

$$Y_{CPE} = A_0(i\omega)^{\alpha} = A_0\omega^{\alpha}[\cos(0.5\pi\alpha) + i\sin(0.5\pi\alpha)], \quad (1.10)$$

where A_0 – coefficient depends on value α. If $\alpha = 1$, the CPE element is the capacitor and A_0 has a capacitive size, if $\alpha = 0$, the CPE is the load and A_0 has a resistor size. In the intermediate case we can consider that the size of A_0 is $\Omega^{-1}.s^{\alpha}$.

The CPE element introduced in the equivalent circuit №3 takes into account the additional frequency dispersion, which may be due to the recharge of depth centers in the space charge region (Sze, 2008; Barsoukov, Macdonald, 2005; Poklonski et al., 2010).

Therefore, it can be argued that the equivalent circuit of the Al/SiO_2/n-Si structure must take into account the n-Si resistance in the accumulative region and the space charge region resistance R_{sc} in the inversion region.

4. Conclusion

Experimental results show that equivalent circuit composed of a resistor (series resistance) and a parallel RC circuit in series does not allow us to describe the dependence of the electric loss on the frequency of the alternating current. In the accumulation region, it is advisable to take into account the resistance of a substrate. And in the inversion region, the additional frequency dispersion of the impedance in the space charge region should be taken into account.

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