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THE ELECTRICAL IMPEDANCE OF A METAL-SILICON STRUCTURE WITH A THIN SiO_2 LAYER

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ABSTRACT

Background. Silicon-based Metal-Oxide-Semiconductor (MOS) structures with an SiO_2 dielectric layer are widely used in various modern electronic devices. Therefore, investigating the electrical properties of such structures remains a relevant task. Impedance spectroscopy is particularly valuable for studying these properties, as it enables the examination of charge transport mechanisms, interfacial properties, and the determination of parameters for equivalent electrical circuits.

Materials and Methods. Samples of n-type monocrystalline silicon were investigated, featuring the following characteristics: doping impurity – arsenic, resistivity – ρ = 0.003 Ohm·cm, thickness – 0.5 mm, area – 30 mm^2. A metal-semiconductor-metal type structure (Ag-SiO_2-Si-SiO_2-Ag) was formed on the surface of such a sample.

To study the frequency dependencies of the impedance of the formed structure, a setup based on the HIOKI IM3536 RLC meter was used.

Results and Discussion. The frequency dependencies of the real and imaginary components of the impedance of the Ag-SiO_2-Si-SiO_2-Ag structure were investigated in the frequency range from 4 Hz to 8 MHz at different excitation electric field amplitudes. It was established that for all values of the excitation signal amplitude, the real component of the impedance, *Re(Z)*, decreases as the frequency and AC excitation amplitude increase. The frequency dependencies of the imaginary component of the impedance, *Im(Z)*, demonstrate the presence of relaxation maxima. With an increase in the excitation signal amplitude, the amplitude of these maxima decreases significantly. The observed changes in the impedance of such a structure can be explained based on its multilayer nature and the properties of highly-doped silicon and the thin layers of native silicon oxide.

Conclusion. The impedance spectroscopy study of Ag-SiO_2-Si-SiO_2-Ag structures with native oxide layers revealed a strong non-linear dependence of electrical properties on the AC signal amplitude. The results demonstrate that in MOS structures with ultra-thin oxides, the “insulating” layer acts as a field-dependent tunneling resistor. Impedance spectroscopy proves to be an effective method for distinguishing between capacitive accumulation and tunneling leakage regimes in such highly doped semiconductor systems.

Keywords: silicon, impedance spectroscopy, MOS structure, Nyquist plot.

INTRODUCTION

Investigating the electrical properties of Metal-Oxide-Semiconductor (MOS) structures is a highly relevant task in modern electronics. Such structures form the basis for a wide range of devices, including memory elements, sensors, photovoltaic converters, and other

components of integrated circuits [1-3]. Systems containing thin dielectric layers, such as native silicon oxide, and highly-doped semiconductor substrates are of particular interest. The properties of such structures are largely determined by the characteristics of the dielectric layers and the dielectric-semiconductor and metal-dielectric interfaces, which necessitate the use of comprehensive methodologies for their study.

Impedance spectroscopy is particularly valuable for studying these properties [4-6]. This technique allows for the investigation of charge transport mechanisms, polarization phenomena, interfacial properties, and the determination of parameters for equivalent electrical circuits. In the case of structures with ultra-thin dielectric layers (on the order of several nanometers) and highly doped semiconductors, such as n^+-Si, quantum-mechanical effects, particularly the tunneling of charge carriers through the dielectric barrier, may play a significant role [7, 8]. Understanding and controlling these processes are critically important for the further development and miniaturization of electronic devices.

MATERIALS AND METHODS

In this work, a sample of monocrystalline silicon doped with an arsenic donor impurity was used. The resistivity of the working surface with a (111) crystallographic orientation was ρ = 0.003 Ohm·cm. The surface area of the experimental sample was 30 mm^2, and the thickness was 0.5 mm. The surface treatment was carried out using isopropyl alcohol to remove physisorbed molecules. However, a native oxide (SiO_2) remained on the silicon surface, the thickness of which, according to experimental studies, can be several nanometers [9].

The next stage involved forming the metal contact by applying a conductive paste containing silver particles to both planes, followed by curing in air at room temperature. Simultaneously, silver wires were attached to the film at the moment of application to serve as lead contacts. Silver is often used in integrated electronics for the fabrication of silicon structures and metallization in general, as it is resistant to oxidation and corrosion and is a less expensive raw material compared to other noble metals [10].

The study of the frequency dependencies of the impedance of the formed structure was performed on an experimental setup using the HIOKI IM3536 RLC meter. During the experiment, the real *Re*(*Z*) and imaginary *Im(Z)* components of the impedance were measured in the frequency range from 4 Hz to 8 MHz. The amplitude of the alternating electrical signal was 0.1 V, 0.5 V, and 1.0 V. All measurements were carried out at room temperature.

RESULTS AND DISCUSSION

Fig. 1 presents the frequency dependencies of the Real (a) and Imaginary (b) components of the impedance for the Ag-SiO_2-Si-SiO_2-Ag structure at different excitation electric field amplitudes: U = 0.1 V, 0.5 V, and 1.0 V.

It is seen from **Fig. 1a** that for all values of the excitation signal amplitude, the Real component of the impedance, *Re(Z)*, decreases with increasing frequency. A significant decrease in *Re(Z)* is also observed with an increase in the magnitude of the applied voltage over the entire investigated frequency range. At low frequencies (around 10 Hz), *Re(Z)* decreases by a factor of 13 (from approximately 2600 Ohm at U = 0.1 V to approximately 200 Ohm at U = 1.0 V. The frequency dependencies of the Imaginary component of impedance (*Im(Z)*), shown in **Fig. 1b**, demonstrate the presence of relaxation maxima. With an increase in the applied voltage, the amplitude of these maxima decreases by more than 11 times (from ~ 1100 Ohm at U = 0.1 V to ~ 95 Ohm at U = 1.0 V), and their position shifts toward the higher frequency region (from ~ 10 kHz at U = 0.1 V to ~ 50-70 kHz at U = 1.0 V).

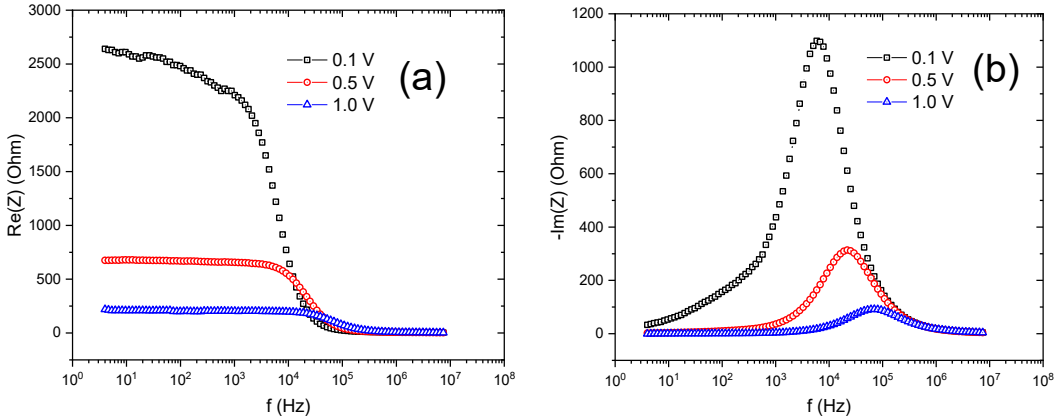

Fig. 1. Frequency dependencies of the Real (*Re(Z)*) (a) and Imaginary (*Im(Z)*) (b) components of the impedance of the Ag-SiO_2-Si-SiO_2-Ag structure at different excitation electric field amplitudes.

For an analysis of the impedance characteristics, impedance hodographs (Nyquist plots) – the dependencies of *Im(Z)* on *Re(Z)* – were plotted. These diagrams are presented in **Fig. 2**. A dominant, somewhat distorted semicircle is observed on all Nyquist plots. The high-frequency intercept of the plot with the *Re(Z)* axis is close to zero for all voltages. The most noticeable feature is the significant decrease in the diameter of this semicircle with an increase in the amplitude of the electric field. At U = 0.1 V, the diameter of the semicircle is approximately 2600 Ohm. When the voltage is increased to U = 0.5 V, the diameter decreases to approximately 650-700 Ohm, and at U = 1.0 V, to approximately 200 Ohm.

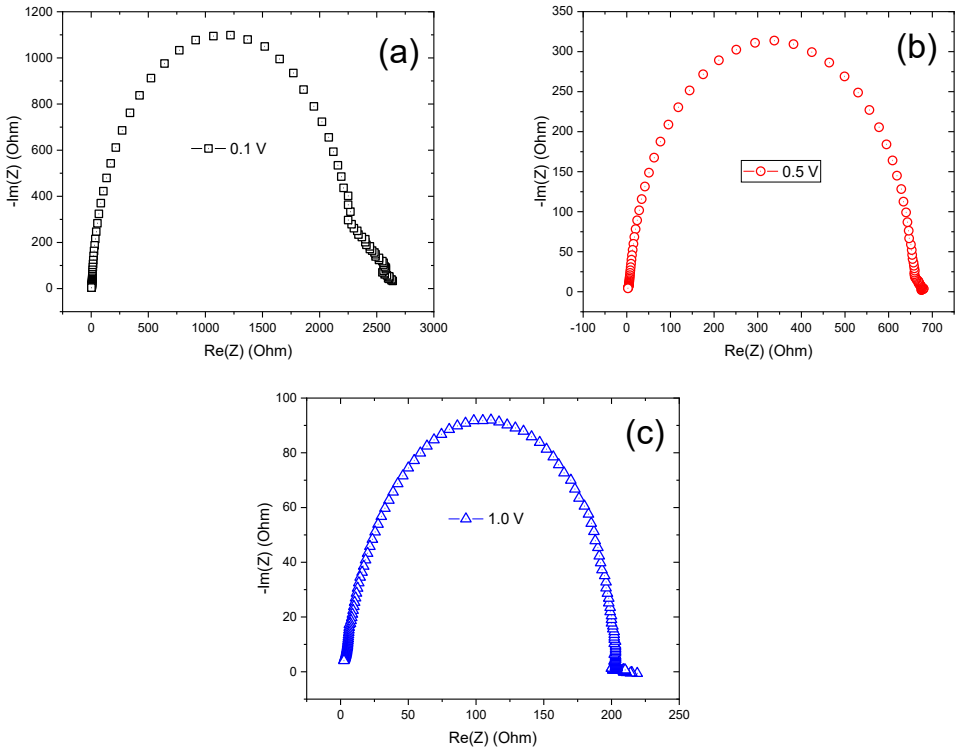

Fig. 2. Impedance hodographs (Nyquist plots) of the Ag-SiO_2-Si-SiO_2-Ag structure at excitation electric field amplitudes of U = 0.1 V (a), 0.5 V (b), and 1.0 V (c).

The observed changes in the impedance of the investigated Ag-SiO_2-Si-SiO_2-Ag structure can be explained based on the physical processes in the highly-doped silicon, the thin layers of native oxide, and the interface under the influence of the electric field.

The small value of the high-frequency series resistance, R_S (the high-frequency intercept of the hodograph with the *Re(Z)* axis), is attributed to the low bulk resistance of the highly-doped n+-silicon (resistivity ρ = 0.003 Ohm·cm), the resistance of the Ag metal contacts, and the connecting wires. The relative stability of R_S under different AC excitation amplitudes is expected, since it is primarily determined by the bulk resistance of the highly-doped silicon substrate and the ohmic metallic contacts. Due to the high carrier concentration in the n^+-Si, the bulk conductivity remains constant and is not significantly modulated by the applied electric field in the studied voltage range, unlike the barrier resistance.

The presence of a single dominant semicircle on the Nyquist plot may indicate a single primary relaxation process in the investigated frequency range. This semicircle can be associated with a parallel connection of a resistance (R_P) and a capacitive element, which reflects the charge transport efficiency (tunneling resistance) and the dielectric charge storage capability (oxide capacitance) of the ultrathin SiO_2 layers and the Si(n^+)-SiO_2 interfaces.

The key feature of the obtained results is the strong dependence of the semicircle diameter, R_P (which corresponds to the low-frequency value of *Re(Z)* minus R_S), on the applied excitation signal amplitude. The significant decrease in R_P (from ~ 2600 Ohm at U = 0.1 V to ~ 200 Ohm at U = 1.0 V) indicates a substantial increase in the efficiency of charge transport through the Ag-SiO_2-Si structure. Considering the use of highly-doped n^+-silicon (high carrier concentration) and the presence of very thin native SiO_2 oxide layers (usually several nanometers), the most probable mechanism explaining such behavior is the quantum-mechanical tunneling of charge carriers through the SiO_2 dielectric barriers [7, 8]. With an increase in the applied voltage, the electric field in the oxide layers increases, which leads to an exponential increase in the probability of electron tunneling (e.g., by direct tunneling or Fowler-Nordheim tunneling mechanisms). This effectively reduces the resistance of the dielectric layers. Although the applied voltage also modulates the Space-Charge Region (SCR) in silicon at the SiO_2 interface, for highly-doped n^+-Si, this region is extremely thin, and its modulation likely cannot significantly impact the large changes in R_P compared to the tunneling effect [8].

The decrease in the amplitude of the maxima on the frequency dependencies of *Im(Z)* (**Fig. 1b**) and their shift toward the higher frequency region with increasing AC excitation signal amplitude also aligns with the described model. The relaxation frequency, f_{PEAK}, which corresponds to the apex of the semicircle on the Nyquist plot or the maximum on the *Im(Z)* curve, is approximately determined by $f_{PEAK}/(2\pi \cdot R_P \cdot C_{EFF})$, where C_{EFF} is the effective capacitance of the structure (mainly determined by the capacitance of the SiO_2 layers). Since R_P sharply decreases with increasing voltage, while C_{EFF} changes much less, f_{PEAK} increases. The decrease in the *Im(Z)* peak height is also a consequence of the decrease in R_P. According to the interpretation proposed above, the total impedance of the Ag-SiO_2-Si-SiO_2-Ag structure will consist of the interface impedance and the bulk silicon resistance:

$$Z_{total}(\omega) = Z_{int}(\omega) + R_{Si}, \quad (1)$$

where $Z_{int}(\omega)$ is the complex interface impedance, and R_{Si} is the real-valued bulk resistance of silicon.

The interface impedance ($Z_{int}(\omega)$) is the most complex component, as it describes the characteristics of the Ag-SiO_2-Si(n^+) structure. The presence of a thin SiO_2 dielectric

layer introduces capacitive and tunneling effects, which are particularly noticeable during AC impedance measurements [11]. The interface impedance model (Z_{int}) is represented as a parallel combination of elements that model physical processes such as the oxide layer capacitance (C_{OX}) and the tunneling resistance through the oxide (R_{tun}), and a series combination of the SCR (Space-Charge Region) impedance element in silicon (Z_{SC}). Let's consider this in more detail.

The capacitance of the thin SiO_2 layer is defined as:

$$C_{OX} = \frac{\varepsilon_{OX}\varepsilon_0 S}{d_{OX}}, \tag{2}$$

ε_{OX} – the dielectric permittivity of SiO_2 (~ 3.9), ε_0 – the electric constant, S – the contact area, d_{OX} – the oxide thickness (a few nm). Due to the small thickness of d_{OX}, this capacitance will be quite significant [12, 13].

Since the SiO_2 layer is very thin (several nanometers), electrons can tunnel through it [14]. This process provides a conductive path characterized by a tunneling resistance (R_{tun}), which is effectively parallel to C_{OX}. It is the presence of this tunneling current that ensures the DC conductivity of the contact. As established in theory and confirmed by our voltage-dependence results, R_{tun} is strongly dependent on the electric field, oxide thickness, and barrier height.

An SCR is formed in the silicon under the oxide. For n^+-silicon, this region will be very thin. Depending on the applied voltage and the metal work function, the silicon under the oxide can be in a state of accumulation or weak depletion. In n^+-silicon, where the carrier concentration is very high, the SCR capacitance C_{SC} is usually very large (especially in the accumulation regime). For the studied silicon with ρ = 0.003 Ohm·cm (corresponding to a doping concentration of $N \approx 10^{19}$ cm^{-3}), the estimated bulk and SCR resistance is less than 10^{-3} Ohm, which is negligible compared to the interface resistance (10^2 - 10^3 Ohm). Similarly, due to the extremely thin depletion width in degenerate semiconductors, the SCR capacitance C_{SC} is sufficiently large compared to the oxide capacitance C_{OX}, making the contribution of the SCR to the total impedance negligible.

Since the capacitance C_{SC} is very large and the resistance R_{SC} is small, the SCR impedance (Z_{SC}) can be negligible compared to the impedance of the oxide layer (Z_{OX}), especially at non-high frequencies. In this case, the interface impedance can be approximately described only by the oxide components:

$$Z_{int}(\omega) \approx Z_{OX}(\omega) = \left(\frac{1}{R_{tun}} + j\omega C_{OX}\right)^{-1}. \tag{3}$$

Then the impedance model is defined as:

$$Z_{total}(\omega) = R_{Si} + \frac{R_{tun}}{1 + j\omega R_{tun} C_{OX}}. \tag{4}$$

Thus, according to the physical interpretation, the equivalent circuit of the impedance is a series connection of a resistor with a parallel *RC* circuit.

However, the experimental results of impedance hodographs of the Ag-SiO_2-Si-SiO_2-Ag structure (**Fig. 2**) show a slightly deformed (depressed) character of the semicircles, indicating the necessity of replacing the capacitor with a Constant Phase Element (CPE) and requiring consideration of more complex models to explain the obtained results [15]. Detailed equivalent circuit modeling and parameter determination will be the subject of a future study.

CONCLUSION

The impedance spectroscopy study of Ag-SiO_2-Si-SiO_2-Ag structures with native oxide layers revealed a strong non-linear dependence of electrical properties on the AC signal amplitude. The following key results were obtained.

Increasing the excitation signal amplitude from 0.1 V to 1.0 V leads to a drastic reduction in the real component of impedance (*Re(Z)*) by more than 10 times. This confirms that charge transport is governed by field-enhanced tunneling through the ultra-thin SiO_2 barriers rather than by simple dielectric polarization.

The imaginary impedance component (*Im(Z)*) exhibits relaxation maxima that decrease in amplitude and shift toward higher frequencies with increasing electric field. This behavior indicates a reduction in the effective parallel resistance of the structure, consistent with the tunneling model.

The Nyquist plots appear as depressed semicircles, indicating a deviation from ideal Debye relaxation. This suggests a distribution of relaxation times caused by the inhomogeneity of the native oxide interface and necessitates the use of non-ideal circuit elements (CPE) for accurate modeling.

The results demonstrate that in MOS structures with ultra-thin (native) oxides, the “insulating” layer acts as a field-dependent tunneling resistor. Impedance spectroscopy proves to be an effective method for distinguishing between capacitive accumulation and tunneling leakage regimes in such highly doped semiconductor systems.

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COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no competing interests.

AUTHOR CONTRIBUTIONS

Conceptualization, [D.S., Y.S., A.L.]; methodology, [D.S., M.K.]; investigation, [D.S., M.K., R.L.]; writing – original draft preparation, [D.S., R.L.]; writing – review and editing, [D.S., M.K., A.L.]; visualization, [D.S., M.K., R.L., Y.S., A.L.].

All authors have read and agreed to the published version of the manuscript.

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ЕЛЕКТРИЧНИЙ ІМПЕДАНС СТРУКТУРИ МЕТАЛ-КРЕМНІЙ З ТОНКИМ ШАРОМ SiO_2

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АНОТАЦІЯ

Вступ. Структури метал-оксид-напівпровідник (МОН) на основі кремнію з діелектричним шаром SiO_2 широко використовуються в різноманітних пристроях сучасної електроніки. Тому дослідження електричних властивостей таких структур є актуальними. Особливу цінність при вивченні цих властивостей займає імпедансна спектроскопія, що дозволяє досліджувати механізми переносу заряду, властивості міжфазних границь та визначати параметри еквівалентних електричних схем заміщення.

Матеріали та методи. Досліджено зразки монокристалічного кремнію n-типу провідності з такими характеристиками: легуюча домішка – арсен, питомий опір – ρ = 0,003 Ом·см, товщина – 0,5 мм, площа – 30 мм^2. На поверхні такого зразка формувалася структура типу метал-напівпровідник-метал (Ag-SiO_2-Si-SiO_2-Ag).

Для дослідження частотних залежностей імпедансу сформованої структури було використано установку на основі RLC метра HIOKI IM3536.

Результати. Досліджено частотні залежності дійсної та уявної складових імпедансу в діапазоні частот від 4 Гц до 8 МГц структури Ag-SiO_2-Si-SiO_2-Ag за різних амплітуд збуджуючого електричного поля. Встановлено, що для всіх значень амплітуди сигналу збудження дійсна складова імпедансу *Re(Z)* зменшується зі збільшенням частоти та напруги зміщення. Частотні залежності уявної складової імпедансу *Im(Z)* демонструють наявність релаксаційних максимумів. Зі збільшенням амплітуди електричного поля величина цих максимумів значно зменшується. Спостережувані зміни імпедансу такої структури можуть бути пояснені на основі її багатошарової природи та властивостей високолегованого кремнію і тонких шарів природного оксиду кремнію.

Висновки. Дослідження структур Ag-SiO_2-Si-SiO_2-Ag з шарами природного оксиду за допомогою імпедансної спектроскопії виявило сильну нелінійну залежність електричних властивостей від амплітуди збуджуючого сигналу. Результати показують, що в МОН-структурах з надтонкими оксидними шарами, «ізоляційний» шар діє як полезалежний тунельний резистор. Імпедансна спектроскопія є ефективним методом для виявлення та розділення процесів ємнісного накопичення та тунельного витоку в таких сильно легованих напівпровідникових системах.

Ключові слова: кремній, імпедансна спектроскопія, МОН-структура, діаграма Найквіста.

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