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FORMATION OF RADIATION-DISTURBED LAYER IN Al/SiO2/n-Si STRUCTURES IRRADIATED WITH HELIUM IONS WITH ENERGY 5 MeV

V. Q. Nha[1], L. V. Thang[1], H. T. Thuy Linh[1], N. I. Gorbachuk[2], N. X. Cuong[3*]

[1] Hue University, Quang Tri Branch, Dien Bien Phu St., Dong Ha, Quang Tri, VietNam
[2] Belarusian State University, 4 Nezavisimosti Avenue, Minsk, Belarus
[3] School of Engineering and Technology, Hue University, 1 Dien Bien Phu St., Hue, VietNam

* Correspondence to N. X. Cuong <ngoxuancuong@hueuni.edu.vn>

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Abstract. This paper presents the change in the volt-farad characteristics of the Al/SiO$_2$/n-Si structure irradiated with helium ions with the energy of 5 MeV in the frequencies of 1, 10, 100, and 1000 kHz. The voltage dependence of the capacitance and the frequency dependence of the dissolution angle are measured on an LCR Agilent E4980A and Agilent 4285A meter. The hodograph of the irradiated structure shows that there is a formation of a quasi-continuous radiation-disturbed layer at a fluence of 10^{12} cm^{-2} with $U < -7$ V and 10^{13} cm^{-2} with $U < -20$ V, which enhances the speed of charged particles, thereby increasing the reverse current in the irradiated structure.

Keywords: SiO$_2$, MOS structure, irradiated, fluence, radiation-disturbed layer

1 Introduction

Over the past decades, the study of metal-oxide-semiconductor (MOS) structures has been of great importance to the development of integrated circuit technologies. The motivation behind the use of silicon dioxide has been the fabrication of stable and high-performance MOS devices and integrated circuits. The silicon dioxide that has an electrically isolated transistor gate from the silicon channel is a key material for the digital revolution with today's GHz microprocessors [1].

However, earlier attempts to fabricate MOS devices were unsuccessful because of the lack of controllable and stable surface [2]. Brown [3] and Garrett and Brattain [4] formulated the theoretical modeling of surface band bending and its consequences. This theoretical background leads to the identification of radiation-induced changes in MOS structures [5] by using capacitive spectroscopy. Especially, the irradiation by helium ions is one of the widely used methods to enhance high-speed semiconductor devices [6].

In this paper, we study the changes of volt-farad characteristics on Al/SiO$_2$/n-Si structures, such as CMOS structures by using the silicon dioxide, irradiated with helium ions that are provided by OAO "INTEGRAL" of Ruhr University (Bochum, Germany).

2 Experiment

Al/SiO$_2$/n-Si structures are manufactured at OAO "INTEGRAL". These structures are then irradiated with 5 MeV helium ions, which are produced by using the accelerator of Ruhr University (Bochum, Germany). The fluence of the irradiation varies from 10^{10} to 10^{13} cm^{-2}. The Al/SiO$_2$/n-Si structures

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are fabricated on the single-crystal n-type silicon sheets developed with the Czochralski method [7, 8]. The resistivity of silicon is 4.5 Ohm.cm. A 420-nm thick layer of silicon dioxide (SiO_2) is formed by thermal oxidizing at 950 °C for 225 minutes. Aluminum is deposited in the plane on the SiO_2 layer by thermal spraying. The area of the aluminum needle with a thickness of 0.7 μm is 1.85 × 1.85 mm^2. Bridges to the uneven side are also formed by A_l sputtering. The plates are divided into chips with an area of 2.5 × 2.5 mm^2.

The simplest experimental devices for measuring conductivity and capacitance in alternating current (AC) are usually based on the Wheatstone bridge circuit [9]. Within the present work, the digital devices based on AC bridge circuits or digital devices that operate on the principle of an ammeter-voltmeter are used [9, 10].

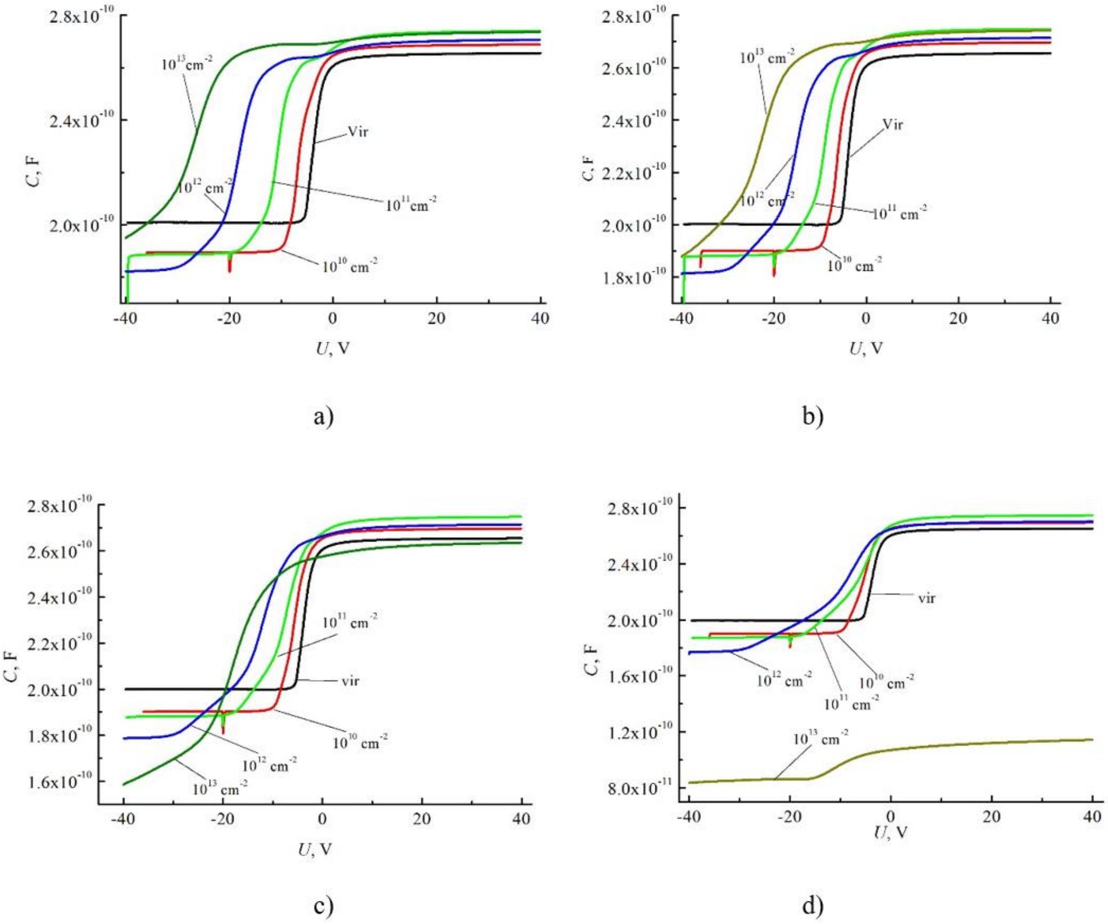
In this study, the frequency dependence measurements of the actual impedance and the virtual impedance are measured with the Agilent E4980A meter in frequency under 20 Hz and Agilent 4285A precision LCR meter in the frequency range from 20 Hz to 30 MHz. The sinusoidal voltage amplitude does not exceed 40 mV. 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 $Al/SiO_2/n\text{-}Si$ structure. The voltage changing from negative to positive in the experiment is used to change the thickness of the space charge region. The concentration of holes injected into an n-base is changed by changing the current through the structure between 0 and 40 mA. The measurements were performed at ambient temperature.

3 Results and discussion

Fig. 1 shows the volt-farad characteristics of the source structure (vir) and the structures irradiated with helium ions. It can be seen that there is a change not only in the flat bands' voltage but also in the volt-farad characteristic on the irradiated structures. The voltage of the flat regions is shifted to the negative area, which is related to the local charges accumulation in the dielectric [11, 12]. The changes in the C–V characteristics can be related to the charge trapping in the bulk of the oxide layer and in the silicon-oxide interface and how the charge trapped can be sensed and actuated [13]. The change in capacitance according to the U voltage of the irradiated structures increases significantly (compared with the source structure). This is due to the influence of local charges on the surface state [5]. Compared with the source structure, the volt-farad characteristics of irradiated structures have a smaller capacitance value in the reverse region.

In Fig. 1, when the measurements are performed at the frequency from 1 kHz to 1 MHz with fluence 10^{10} cm^{-2}, the reverse capacitance of inversion region is observed at voltage $-40\text{ V} < U < -10\text{ V}$ and the depletion region at voltage $-10\text{ V} < U < 0\text{ V}$; similarly, with fluence 10^{11} cm^{-2}, the inversion region is observed at voltage $-40\text{ V} < U < -20\text{ V}$ and the depletion region at voltage $-20\text{ V} < U < 0\text{ V}$; with fluences 10^{12} cm^{-2}, the inversion region is observed at voltage $-40\text{ V} < U < -30\text{ V}$ and depletion region at voltage $-30\text{ V} < U < 0\text{ V}$.

Fig. 1d with fluence 10^{13} cm^{-2} at frequency 1 MHz shows a sharp decrease of capacitance in both cases with reversible and forward voltage. The change in the C–V characteristic of the structures after irradiation [11, 12, 14] might be because the capture of a positive charge by a trap in the oxide increases the density of surface states, resulting in radiation defects in the silicon layer adjacent to SiO_2 [15]. The increase in capacitance via decreasing frequencies is attributed to the existence of the surface states [16]. These capacitance change characteristics could be consistently interpreted by the voltage-driven oxygen ion migration between metal and the semiconductor layers that can alter the dielectric permittivity and induce the gate depletion [17].



a)

b)

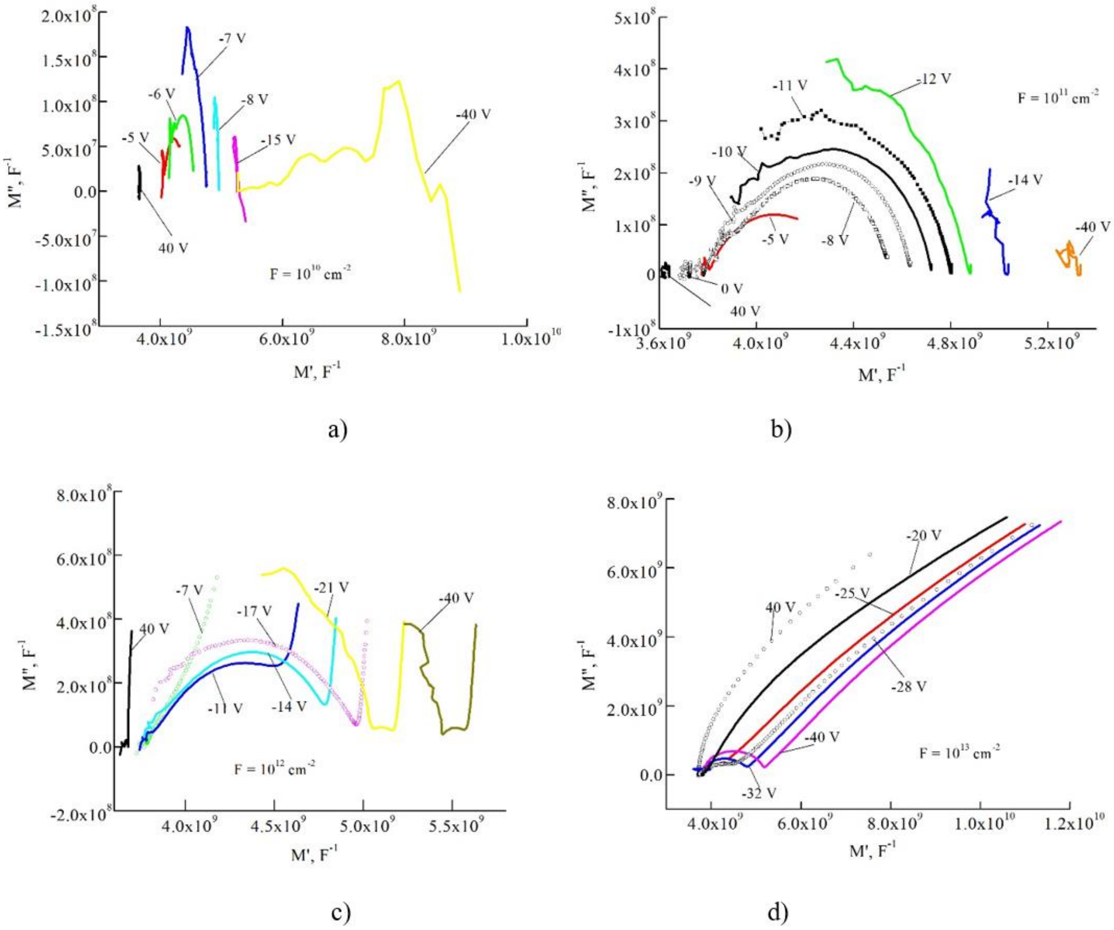
c)

d)

Fig. 1. Volt-farad characteristics of Al/SiO_2/n-Si structure. The measurements were performed at frequencies 1 kHz (a),10 kHz (b), 100 kHz (c), and 1 MHz (d)

Fig. 2 shows the hodograph proportional to the complex electrical module $M = \omega C_0 Z = M/C_0 = \omega(-Z'' + i\,Z')$ for the structures that are irradiated with heavy ions. The voltage values are also shown in this Fig.. Obviously, the hodograph fundamental changes are obtained with fluence $F = 10^{12}\div10^{13}$ cm^{-2}. At this fluence, the hodograph is divided into two semi-circles. While at $F = 10^{10}$ cm^{-2} and 10^{11} cm^{-2}, the hodograph has only one semi-circle (Fig. 2a and Fig. 2b). At $F = 10^{12}$ cm^{-2}, the hodograph has two semi-circles (Fig. 2c) with voltage $U < -7$ V; similarly, for $F = 10^{13}$ cm^{-2}, the hodograph has two semi-circles (Fig. 2d) with voltage $U < -20$ V.

From the hodographs presented in the literature [7, 11, 17-19], the presence of multiple semi-circles is a sign of multilayer structure. Therefore, we are able to claim that the Al/SiO_2/n-Si structure irradiated with ions $F = 10^{12}\div10^{13}$ cm^{-2} at reversed voltage has a multilayer structure. This structure includes a space charge region and a quasi-continuous radiation-disturbed layer. If a circle with low frequency is determined with a space charge region, the remaining circle corresponding to the high frequency forms a highly resistive quasi-continuous radiation-disturbed layer.



a)

b)

c)

d)

Fig. 2. Hodograph of structures irradiated by helium ions with fluence $F = 10^{10}$ cm^{-2} (a); $F = 10^{11}$ cm^{-2} (b); $F = 10^{12}$ cm^{-2} (c) và $F = 10^{13}$ cm^{-2} (d)

4 Conclusion

In the present paper, we analyze the electrical characteristics of Al/SiO$_2$/n-Si structures irradiated with helium ions, including volt-farad characteristics at frequency 1 kHz–1 MHz and the hodograph with fluence 10^{10}–10^{13} cm^{-3}. In the inversion region, the decrease in capacitance occurs most clearly, and there is a formation of a highly resistive quasi-continuous radiation-disturbed layer with fluence 10^{12} cm^{-2} with $U < -7$ V and 10^{13} cm^{-2} with $U < -20$ V. This formation will speed up the charged particles, thereby increasing the reverse current. Therefore, the considered structures can be applied to fabricate integrated circuits. These structures are also suitable for high-power radio frequency circuit applications.

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References

1. Hsu C, Shih W, Lin Y, Hsu H, Hsu H, Huang Y, et al. Improved linearity and reliability in GaN metal–oxide–semiconductor high-electron-mobility

pISSN 1859-1388
eISSN 2615-9678

transistors using nanolaminate La $2O_3/SiO_2$ gate dielectric. Japanese Journal of Applied Physics. 2016;55(4S):04EG04.

2. Bentarzi H. Transport in Metal-Oxide-Semiconductor Structures. Berlin (DE): Springer-Verlag Berlin; 2011.
3. Brown WL. n-Type Surface Conductivity on p-Type Germanium. Physical Review 1953;91(3):518-527.
4. Garrett C, Brattain WH. Physical Theory of Semiconductor Surfaces. Physical Review B. 1955;99:376-87.
5. Mogeb K, Fraser D, Fichtner W. SBIS technology. In 2 books. Book 2. Moscow: Edition of literature on new technology; 1986. (in Russian)
6. Kozlovski V, Abrosimova V. Radiation Defect Engineering. International Journal of High Speed Electronics and Systems. 2005;15(01):1-253.
7. Shimura F. Semiconductor silicon crystal technology. California (US): Academic Press; 2012. 434 p.
8. Shimura F. Single-Crystal Silicon: Growth and Properties. Surveys in High Energy Physics. 2007:7-13.
9. Poklonski NA, Gorbachuk N. I. Fundamentals of impedance spectroscopy of composites: lecture course. Minsk: BSU; 2005. (in Russian)
10. Grafov BM, Ukshe EA. Electrochemical circuits alternating current. Moscow: Science; 1973. (in Russian)
11. Sze SM. Semiconductor Devices: Physics and Technology. 2nd Ed. New York: Wiley; 2008.
12. Nicollian EH, Goetzberger A. The Si-SiO_2 interface-electrical properties as Determined by the metal-Insulator-Silicon Conductance Technique. The Bell System Technical. 1967;46(6):1055-1133.
13. DomInguez-Pumar M, Bheesayagari CR, Gorreta S, Lopez-Rodriguez G, Martin I, Blokhina E, et al. Charge trapping control in MOS capacitors. IEEE transactions on industrial electronics. 2016;64(4): 3023-3029.
14. Barsoukov E, Macdonald JR. Impedance spectroscopy: theory experiment and applications. 2nd ed. New Jersey: Wiley-Interscience; 2005. 608 p.
15. Poklonski NA, Gorbachuk NI, Shpakovski SV, Lastovskyi CB, Wieck A. Influence of radiation defects on the electrical losses in the silicon diodes, irradiated by electrons. Semiconductor Physics and Technology. 2010;397-401. (in Russian)
16. Erdal MO, Kocyigit A, Yildirim M. The rate of Cu doped TiO_2 interlayer effects on the electrical characteristics of Al/Cu:TiO_2/n-Si (MOS) capacitors depend on frequency and voltage. Microelectronics Reliability. 2020;106:113591.
17. Park D, Kim M, Beom K, Cho SY, Kang CJ, Yoon TS. Reversible capacitance changes in the MOS capacitor with an ITO/CeO_2/p-Si structure. Journal of Alloys and Compounds. 2019;786:655-61.
18. Poklonski NA, Gorbachuk NI, Nha VQ, Krasitskaya YuA, Shpakovski SV, filipenia VA, et al. Impedance of silicon diodes irradiated with helium ions with energies of 4–9 MeV. Actual problems of solid state physics (FTT-2013): Proceedings of the international scientific conference. Minsk: Kovcheg; 2013. p. 285-287.
19. Poklonski NA, Gorbachuk NI, Shpakovski SV, Filipenia VA, Nha VQ, Krasitskaya Yu. A, et al., editors. The formation of a continuous radiation-disturbed layer in silicon diodes irradiated with bismuth ions with an energy of 700 MeV. Materials and structures of modern electronics: collection of scientific papers of the V international scientific conference. Minsk: BSU; 2012.