ISSN 1063-7826, Semiconductors, 2018, Vol. 52, No. 9, pp. 1114–1117. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © A.A. Shiryaev, V.M. Vorotyntsev, E.L. Shobolov, 2018, published in Fizika i Tekhnika Poluprovodnikov, 2018, Vol. 52, No. 9, pp. 990–994.

SURFACES, INTERFACES, AND THIN FILMS

Poole–Frenkel Effect and the Opportunity of Its Application for the Prediction of Radiation Charge Accumulation in Thermal Silicon Dioxide

A. A. Shiryaev[a]*, **V. M. Vorotyntsev**[b], **and E. L. Shobolov**[a]
[a] *Research and Development Center, Sedakov Measuring Systems Research Institute, Nizhny Novgorod, 603137 Russia*
[b] *Alekseev Nizhny Novgorod State Technical University, Nizhny Novgorod, 603950 Russia*
**e-mail: alsh92@rambler.ru*

Submitted November 7, 2017; accepted for publication November 29, 2017

Abstract—It is proposed that the Poole–Frenkel effect be applied to predict radiation-induced charge accumulation in thermal silicon dioxide. Various conduction mechanisms of thermal silicon dioxide are considered, the conditions of the appearance of the Poole–Frenkel effect in it are determined, and the characteristics of donor centers participating in Poole–Frenkel electrical conductivity are calculated. A donor center level at an energy of 2.34 eV below the conduction-band bottom is determined and the concentration of ionized donor centers of 1.0×10^9 cm^{-3} at 400 K and a field strength of 10 MV/cm is found. It is concluded that the Poole–Frenkel effect can be applied not for prediction of the absolute value of the radiation-induced charge but for comparison of the samples in terms of the ability to accumulate it.

DOI: 10.1134/S1063782618090166

1. INTRODUCTION

One of the main causes of limitation of the dose radiation stability of microcircuits based on a complementary metal–oxide–semiconductor (CMOS) structure fabricated using silicon-on-insulator (SOI—[1, 2]) structures, is the formation of a bottom parasitic *n*-type channel transistor at the bottom of a *p*-type pocket of the transistor structure at the "device layer–buried oxide" interface because of the radiation-induced accumulation of positive charge in the buried oxide. This process is caused by the presence of hole traps in the buried oxide, and the magnitude of the positive charge accumulated in the buried oxide under the effect of ionizing radiation (IR) is first and foremost determined by the concentration of hole traps present in the oxide (oxide imperfection) [3], which can greatly vary in the scope of a single production process [4]. In this context, in order to predict the radiation stability of microcircuits, to determine the requirements to the imperfection level of the buried oxide, and analyze its influence on the radiation stability of CMOS circuits, the development of methods for monitoring the parameters of these traps is necessary (their concentration, capture cross section, and spatial distribution).

The main method, which is used for these purposes (for example, [5–12]), includes measurement of the radiation-induced bias of the threshold voltage of the bottom parasitic transistor or the flat-band voltage of the SOI structure—quantities, which are directly determined by these trap parameters. However, the development of alternative methods, especially nondestructive, which do not use ionizing radiation, can open up new possibilities in the field of the quality control and provision of the radiation resistance of semiconductor devices. A review of such methods is given in [13]. Such a method can find application, for example, to increase the preciseness of modeling the radiation resistance of microcircuits [14], to optimize the fabrication process of SOI structures, to provide the application of special fabrication methods for preventing the formation of a parasitic channel [15, 16], and the rejection of SOI structures.

The Poole–Frenkel conduction mechanism observed in silicon dioxide, under which the current density is determined by the concentration and energy position of donor centers, is mentioned in [17–19]. These observations were random and were not directed at predicting radiation-induced charge accumulation in the buried oxide of SOI structures. In this context, the purpose of this publication is the analysis of conditions for the appearance of the Poole–Frenkel effect in thermal silicon dioxide and the possibility of its application for the prediction of the radiation accumulation of charge.

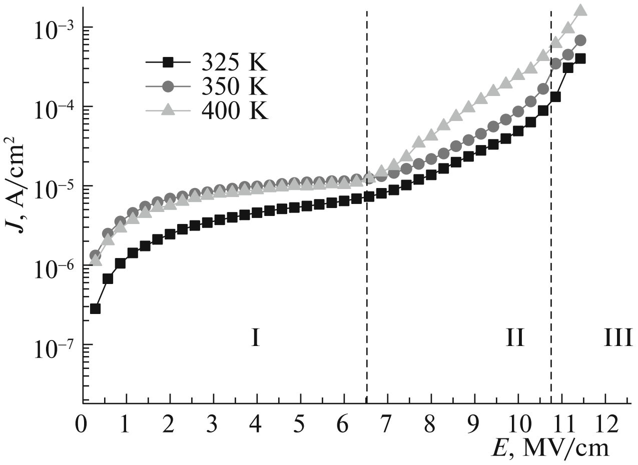

Fig. 1. Dependences of the current density on the electric-field strength of the undergate insulator at various temperatures.

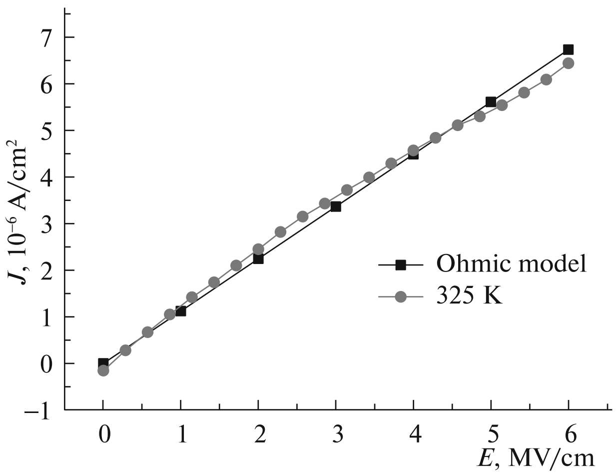

Fig. 2. Measured and model (ohmic) dependences of the current density on the electric-field strength of the undergate insulator at 325 K.

2. EXPERIMENTAL

The samples under study were n-channel MOS transistors with an area and thickness of the undergate insulator of 80 × 6 μm² and 35 nm, respectively. The current–voltage (I–V) characteristics of the undergate insulator were measured with the help of a parametric analyzer of semiconductor devices and a probe system. The gate was grounded, and a voltage from 0 to 40 V with a step of 1 and 0.1 V was supplied to the substrate. The I–V characteristics were measured at 325, 350, and 400 K.

3. EXPERIMENTAL RESULTS

Figure 1 shows the dependences of the current density J of the undergate insulator on the electric-field strength E of the insulator found on the basis of measured I–V characteristics. It is seen that the curves can be divided into three segments apparently associated with three different conduction mechanisms.

The dependence $J(E)$ is linear in the range from 0 to 6 MV/cm (Fig. 2), injecting contacts are absent, and the insulator thickness is too large for direct tunneling; therefore, we can assume that the insulator conductivity is described by the Ohm law in this range, while other mechanisms of conduction [20] do not manifest themselves.

The ohmic dependence, which is shown in Fig. 2, is described by the following formula:

$$J = nq\mu E, \tag{1}$$

where q is the elementary charge, μ is the electron mobility in the insulator, n is the electron concentration in the conduction band of the insulator, and E is the electric-field strength in the undergate insulator. The magnitude of n is determined by the following formula:

$$n = N_C \exp\left(-\frac{E_C - E_F}{kT}\right), \tag{2}$$

where N_C is the density of quantum states in the conduction band of the insulator, E_C is the conduction-band bottom of the insulator, E_F is the Fermi level in the insulator, k is the Boltzmann constant, and T is the temperature.

The hole conduction component is not taken into account in formula (1) because it is negligibly small (the hole mobility in silicon dioxide is smaller than the electron mobility by six orders of magnitude).

The Poole–Frenkel mechanism was proposed as the conduction mechanism for segment II of the curves shown in Fig. 1 because, according to [17, 20], it was observed in silicon dioxide in approximately this strength range.

In the case of the Poole–Frenkel conduction mechanism [20, 21], the dependence of the current density of the insulator on the electric-field strength in it is established by the following formula:

$$J = q\mu E N_D(T, E), \tag{3}$$

where q is the elementary charge, μ is the electron mobility in the insulator (20 cm²/(V s) in the case of thermal silicon dioxide [22]), and $N_D(T, E)$ is the concentration of ionized donor centers in the insulator, which depends on the temperature T and field strength E in accordance with the following formula:

$$N_D = N_C \exp\left(-\frac{q\varphi - \sqrt{\dfrac{q^3 E}{\pi\varepsilon_0\varepsilon}}}{kT}\right), \tag{4}$$

where N_C is the density of quantum states in the conduction band of the insulator (~1.5×10^{23} cm^{-3} in the

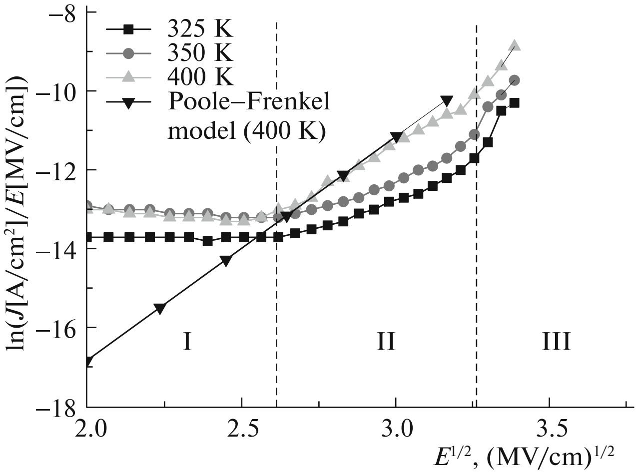

Fig. 3. Dependences of $\ln(J/E)$ on $E^{1/2}$ recalculated from the measured $I–V$ characteristics of the undergate insulator at various temperatures and the same dependence modeled according to formulas (3) and (4) for a temperature of 400 K.

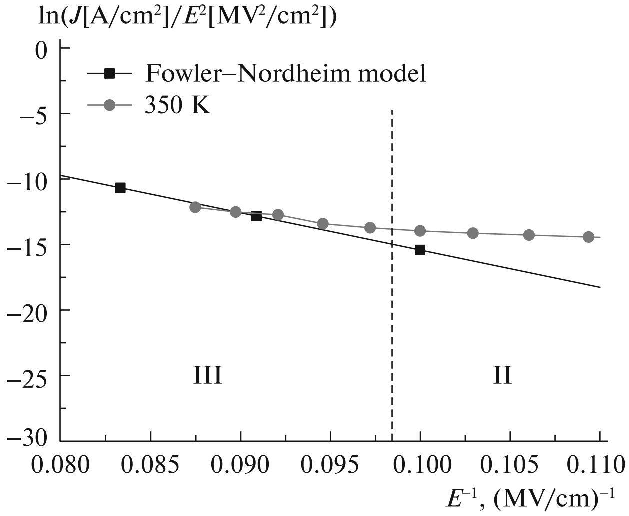

Fig. 4. Dependence of $\ln(J/E^2)$ on E^{-1} calculated from the measured $I–V$ characteristic of the undergate insulator at 350 K and the same dependence modeled according to the Fowler–Nordheim formula (5).

case of thermal silicon dioxide [23]), φ is the level of donor centers in the insulator (relative to the conduction-band bottom), ε_0 is the electric constant, ε is the relative insulator permittivity, and k is the Boltzmann constant.

Formulas (3) and (4) were derived based on the data [20, 21] allowing for the following admission: in addition to centers that provide the ohmic conduction mechanism in an insulator (at small E), only donor centers with the energy level φ are present, which provide Poole–Frenkel conduction in the definite range of E.

Figure 3 shows the dependences of $\ln(J/E)$ on $E^{1/2}$ calculated from the measured $I–V$ characteristics of the undergate insulator and the same dependence modeled according to formulas (3) and (4) for 400 K. It should be noted that the best coincidence was attained for such concentrations of ionized centers N_D, which correspond to a level of 2.34 eV. Herewith, the maximal N_D concentration found at a strength of 10 MV/cm and a temperature of 400 K was 1.0×10^9 cm^{-3}.

Let us consider region III at $E > 10$ MV/cm ($E^{1/2} > 3.2$ (MV/cm)$^{1/2}$). According to the data [24], the Fowler–Nordheim tunneling conduction mechanism prevails in thermal silicon dioxide in strong electric fields ($E > 10$ MV/cm), at which the current density is defined by the following formula:

$$J = \frac{q^2E^2}{8\pi hq\varphi_B}\exp\left(-\frac{8\pi(2qm_T^*)^{1/2}}{3hE}\varphi_B^{3/2}\right), \qquad (5)$$

where h is Planck's constant, φ_B is the energy barrier between the substrate and the polysilicon gate (the upper capacitor plate), and m_T^* is the tunneling effective mass of electrons in the insulator. In our case, the experimental characteristics in the corresponding range of E ($E^{-1} < 0.1$ (MV/cm)$^{-1}$) are described by the Fowler–Nordheim model rather well as seen from Fig. 4. Taking into account the fact that the measured current density at $E > 10$ MV/cm is weakly temperature-dependent, we can conclude that indeed Fowler–Nordheim tunneling is observed. It should be noted that the best coincidence of the characteristics in Fig. 4 was attained at $\varphi_B = 3.45$ eV, which corresponds to the data in [20].

4. RESULTS AND DISCUSSION

Thus, the Poole–Frenkel effect in thermal silicon oxide with a thickness of 35 nm and an area of 80 × 6 μm is observed at an electric-field strength from 6 to 10 MV/cm over the entire studied temperature range (from 325 to 400 K). Herewith, we were able to acquire information on the energy position of hole traps in the insulator band gap and on the concentration of ionized hole traps depending on the temperature and strength.

There are various opinions in publications as to which centers in thermal SiO$_2$ are the main hole traps. For example, the authors of [25–27] assume that trivalent silicon and interstitial oxygen are the main traps, while those of [28, 29] assume it is an oxygen vacancy. In this study, we experimentally determined a level with the energy $\varphi = 2.34$ eV, which apparently corresponds to the upper level of the oxygen vacancy (E'_γ-center) [26].

In this study, the concentration of ionized donor centers participating in Poole–Frenkel conduction was ~10^9 cm^{-3} at a strength of 10 MV/cm and a temperature of 400 K. The authors of [27] mention that the concentration of E'-centers reaches saturation at 10^{18} cm^{-3} during the effect of γ radiation on thermal SiO$_2$. This indicates that only an insignificant part of the donor centers participate in Poole–Frenkel conduction. Therefore, the results of measuring Poole–Frenkel conduction cannot be used for prediction of the absolute value of the radiation-induced charge. Additional investigations should be performed in order to determine the possibility of the comparison of silicon-dioxide samples by the ability to accumulate the charge based on Poole–Frenkel conduction.

It is noteworthy that the method considered in this article can be considered nondestructive; however, we should take into account that if the Fowler–Nordheim mechanism participates in conduction, charge accumulation and the formation of new centers are possible in an insulator, and the formation of surface states at the insulator and semiconductor interface is possible [30].

5. CONCLUSIONS

In this article, the occurrence of the Poole–Frenkel effect in thermal silicon dioxide is shown, and it is proposed that it can be used to predict the accumulation of the radiation-induced charge in an insulator. It was established that the Poole–Frenkel conduction mechanism could be observed at a strength of 6–10 MV/cm and a temperature of 325–400 K. Herewith, we can determine the energy level and concentration of donor centers of silicon dioxide participating in conduction. The level with an energy of 2.34 eV relative to the conduction-band bottom of the insulator, which apparently refers to oxygen vacancies, was found. The maximal concentration of donor centers participating in conduction was 10^9 cm^{-3}.

REFERENCES

1. G. K. Celler and S. Cristoloveanu, J. Appl. Phys. **93**, 4955 (2003).
2. A. L. Aseev, V. P. Popov, V. P. Volodin, and V. N. Maryutin, Nano-Mikrosist. Tekh. **9**, 23 (2002).
3. A. Yu. Nikiforov, V. A. Telets, and A. I. Chumakov, *Radiation Effects in CMOS IC* (Radio Svyaz', Moscow, 1994) [in Russian].
4. I. B. Yashanin, G. G. Davydov, A. Yu. Nikiforov, and Yu. M. Moskovskaya, Izv. Vyssh. Uchebn. Zaved., Elektron., No. 5 (97), 11 (2012).
5. T. Ouisse, S. Cristoloveanu, and G. Borel, IEEE Electron Dev. Lett. **12**, 312 (1991).
6. C. A. Pennise and H. A. Boesch, IEEE Trans. Nucl. Sci. **37**, 1990 (1990).
7. R. E. Stahlbush, G. J. Campisi, J. B. McKitterick, W. P. Maszara, P. Roitman, and G. A. Brown, IEEE Trans. Nucl. Sci. **39**, 2086 (1992).
8. R. E. Stahlbush, IEEE Trans. Nucl. Sci. **43**, 2627 (1996).
9. R. E. Stahlbush, IEEE Trans. Nucl. Sci. **44**, 2106 (1997).
10. O. P. Gus'kova, V. M. Vorotyntsev, E. L. Shobolov, and N. D. Abrosimova, Izv. Vyssh. Uchebn. Zaved., Mater. Elektron. Tekh., No. 4 (60), 28 (2012).
11. D. V. Nikolaev, I. V. Antonova, O. V. Naumova, V. P. Popov, and S. A. Smagulova, Semiconductors **37**, 426 (2003).
12. A. Yu. Askinazi, A. P. Baraban, V. A. Dmitriev, and L. V. Miloglyadova, Tech. Phys. Lett. **28**, 983 (2002).
13. A. A. Shiryaev, E. L. Shobolov, and V. A. Gerasimov, in *Proceedings of the 21st Nizhny Novgorod Session of Young Scientists, Technical Sciences*, Ed. by I. A. Zvereva (NGIEU, Knyaginino, 2016), p. 105.
14. K. O. Petrosyants, E. V. Orekhov, L. M. Samburskii, I. A. Kharitonov, and A. P. Yatmanov, Izv. Vyssh. Uchebn. Zaved., Elektron., No. 2 (82), 81 (2010).
15. O. P. Gus'kova, V. M. Vorotyntsev, N. D. Abrosimova, E. L. Shobolov, and M. N. Mineev, Inorg. Mater. **48**, 222 (2012).
16. A. V. Amirkhanov, S. I. Volkov, A. A. Glushko, L. A. Zinchenko, V. V. Makarchuk, and V. A. Shakhnov, Russ. Microelectron. **45**, 237 (2016).
17. S. Mayo, J. S. Suehle, and P. Roitman, J. Appl. Phys. **74**, 4113 (1993).
18. H. Krause and R. Grünler, Phys. Status Solidi **42**, 149 (1977).
19. S. K. Gupta, A. Azam, and J. Akhtar, Pramana J. Phys. **74**, 325 (2010).
20. F. C. Chiu, Adv. Mater. Sci. Eng. **2014**, 578168 (2014).
21. J. G. Simmons, J. Phys. D: Appl. Phys. **4**, 613 (1971).
22. G. I. Zebrev, *Radiation Effects in Silicon Integrated Schemes of High Integration Degree* (NIYaU MIFI, Moscow, 2010) [in Russian].
23. C. Sevik and C. Bulutay, J. Mater. Sci. **42**, 6555 (2007).
24. B. D. Salvo, G. Ghibaudo, G. Panabnakakis, B. Guillaumo, and G. Reimbold, Microelectron. Reliab. **39**, 797 (1999).
25. F. P. Korshunov, Yu. V. Bogatyrev, and V. A. Vavilov, *Effect of Radiation on Integrated Microcirquts* (Nauka Tekhnika, Minsk, 1986) [in Russian].
26. C. T. Sah, IEEE Trans. Nucl. Sci. **23**, 1563 (1976).
27. V. S. Pershenkov, V. D. Popov, and A. V. Shal'nov, *Surface Radiation Effects in Integrated Microcirquit Elements* (Energoatomizdat, Moscow, 1988) [in Russian].
28. S. T. Pantelides, Z. Y. Lu, C. Nicklaw, T. Bakos, S. N. Rashkeev, D. M. Fleetwood, and R. D. Schrimpf, J. Non-Cryst. Sol. **354**, 217 (2008).
29. K. I. Tapero, V. N. Ulimov, and A. M. Chlenov, *Radiation Effects in Silicon v Integrated Microcirquit for Space Application* (BINOM, Labor. Znanii, Moscow, 2014) [in Russian].
30. B. Balland, C. Plossu, and S. Bardy Balland, Thin Solid Films **148**, 149 (1987).

Translated by N. Korovin