Modification of Diazoquinone-Novolac Photoresist Films by the Implantation of Antimony Ions

S. D. Brinkevich, D. I. Brinkevich, and V. S. Prosolovich

Belarusian State University, Minsk, 220013 Belarus

*e-mail: Brinkevich@bsu.by

**e-mail: prosolovich@bsu.by

Received May 20, 2020; revised May 20, 2020; accepted May 26, 2020

Abstract—In this paper, we study the radiation-induced processes occurring during the implantation of antimony ions into films of the positive diazoquinone-novolac (DQN) FP9120 photoresist (PR) on silicon by the Fourier-transform infrared (FTIR) spectroscopy of the frustrated total internal reflection (TIR). Ion implantation (II) is found to lead to the appearance in the frustrated TIR spectrum of a band at 2331 cm⁻¹ caused by the O=C=O stretching vibrations. The violation of adhesion at the PR/silicon interface manifests itself in the appearance of a 610 cm⁻¹ band related to the absorption of the Si lattice. The formation of new C–O–C bonds because of the ether cross links of ketene with the OH group of novolac resin is found.

Keywords: frustrated total internal reflection spectrum, diazoquinone-novolac photoresist, implantation, adhesion, silicon

INTRODUCTION

At present, lithography is one of the main processes in the general production cycle of a wide class of semiconductor devices and integrated circuits. Diazoquinone-novolac (DQN) resists are widely used as masks in submicron and nanolithography [1–4]. One of the main methods for the formation of doped regions in modern electronics is ion implantation (II). It allows accurately controlling the dopant concentration and is characterized by the versatility and flexibility of the process. The interaction of DQN resists with ultraviolet, X-ray, and visible radiation has been studied in sufficient detail, while the processes induced by ion irradiation remain poorly understood, despite the fact that they can have a significant effect on the quality of the created devices [4–6].

During the II of polymers, radiation-induced processes were previously shown to occur both in the region of the ion path and outside it [5, 7–9]. For example, the radiation hardening of DQN resist films behind the layer of antimony ions implantation was discovered in [5]. However, the mechanism of the radiation-induced processes responsible for the change in the physicomехanical properties of DQN resists behind the layer of II was not established.

For the thin film studies, the FTIR spectroscopy of the frustrated total internal reflection (TIR) that allows obtaining qualitative and quantitative information on the composition and structure of complex organic compounds and their mixtures in the solid aggregation state is widely used [10]. Note that the frustrated TIR method was not used earlier to study DQN photoresist (PR) films on the surface of monocrystalline silicon wafers. In this study, we used the FTIR spectrometry of the frustrated TIR in order to establish the mechanisms of the radiation-induced modification of the physicomехanical properties of DQN PR films upon implantation of antimony ions.

EXPERIMENTAL

A positive FP9120 PR is a composite of light-sensitive α-naphthoquinone-diazide and phenol-formaldehyde resin. PR films with a thickness of 1.8 μm were deposited on the surface of p-type silicon wafers (ρ = 10 Ω cm) with the (111) orientation by the centrifugation method at the angular velocity of υ = 2900 rpm [11]. Before the formation of the PR film, the silicon wafers were subjected to the standard cycle of surface cleaning in organic and inorganic solvents and washing in deionized water. After applying the PR to the operating side of the plate, it was dried for 50–55 min at 88°C. The thickness of the PR films was monitored using a Dectak profilimeter.

Implantation with Sb⁺ antimony ions was carried out with an energy of 60 keV in the dose range of Φ = 1 × 10¹⁵–5 × 10¹⁶ cm⁻² at an ion current density of j = 4 μA/cm² in a residual vacuum not worse than 10⁻⁵ mm Hg using the Vezuvi-6 ion-beam accelerator. The frustrated-TIR spectra of the PR-silicon struc-
RESULTS AND DISCUSSION

The FTIR spectra of the initial and implanted films of the DQN FP9120 PR on silicon are shown in Fig. 1. When analyzing the experimental data, we need to take into account that, in the process of recording the IR spectra of the frustrated-TIR, the penetration depth $d_{\text{eff}}$ of the light beam into the sample depends on the wavelength, the refractive indices of the prism $n_2$ and the sample $n_1$, and the incidence angle $\alpha$ and is calculated by the following formula [10]:

$$d_{\text{eff}} = \frac{(n_1/n_2)^2 \lambda \cos \alpha}{\pi \left[ 1 - \left( \frac{n_1}{n_2} \right)^2 \right] \sin^2 \alpha - \left( \frac{n_1}{n_2} \right)^2].$$

Under the conditions of our experiment, the prism’s material is diamond ($n_2 = 2.42$) [12], the incidence angle is 40°, and the refractive index of the PR is $n_1 = 1.52$ [11]. Therefore, according to formula (1), the penetration depth of radiation in the PR film is $d_{\text{eff}} \approx 0.45 \lambda$. Thus, the effective beam penetration depth at wave numbers of less than 2000 cm$^{-1}$ exceeds the geometric thickness of the studied films. In this case, the radiation is partially reflected from the silicon substrate; this reflection from the resist/silicon interface must be taken into account when analyzing the experimental results.

Fig. 1. Frustrated-TIR spectra of (1) initial and (2) Sb$^+$-implanted with a dose of $5 \times 10^{16}$ cm$^{-2}$ FP9120 films on silicon.

Fig. 2. Frustrated-TIR spectra of the (1) initial and implanted Sb$^+$ with doses of (2) $1 \times 10^{16}$ cm$^{-2}$ and (3) $5 \times 10^{16}$ cm$^{-2}$ FP9120 films in the region of double cumulative bonds.

Under the conditions of our experiment, the absorption $\nu = 400$ to 4000 cm$^{-1}$ were recorded at room temperature using an ALPHA IR Fourier spectrophotometer (Bruker Optik GmbH). The resolution was not worse than 2 cm$^{-1}$ and the number of scans was 24. The background was corrected before each measurement.

The main reason for the appearance of the 2331 cm$^{-1}$ band in the spectrum of implanted resist films is most likely the radiation-induced decomposition of the residual solvents containing an acetate fragment, for example, butyl acetate and 2-methoxyethyl acetate. These substances are included in the formulation of solutions of the DQN resists. Since their boiling points are 126 and 145°C, respectively, they are not completely removed from thin films during drying.
The rigid structure of the phenol-formaldehyde resin network can retain small amounts of solvents even under a high vacuum during II.

It was shown in [8] that radiation-induced transformations in the bulk of the DQN resist occur as a result of the energy transfer (in the form of the electronic excitation of particles) along the polymer’s macromolecules from the ion thermolization region. Being aliphatic compounds, solvents are significantly less resistant to degradation processes than phenol-formaldehyde resin. One of the decomposition mechanisms of these acetates will be the destruction of the \(-\text{C}–\text{O}–\) bond, followed by the rapid elimination of \(\text{CO}_2\) according to the following scheme:

\[
\begin{align*}
\text{H}_3\text{C}–\text{C}=\text{O}–\text{O}–\text{CH}_3 & \xrightarrow{+\text{M}^*} \text{H}_3\text{C}–\text{C}=\text{O}^*–\text{O}–\text{CH}_3 \\
\text{R} & = \text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 \\
\text{R} + \text{M}^* & \rightarrow \text{H}_3\text{C}–\text{C}=\text{O}–\text{R} \\
\text{H}_3\text{C}–\text{C}=\text{O}–\text{R} & \rightarrow \text{H}_3\text{C}–\text{C}=\text{O}–\cdot\text{CH}_3 + \text{CO}_2
\end{align*}
\]

Under the irradiation of organic esters, including acetates, \(\text{CO}_2\) is one of the main products of radiolysis [15]. The fact that we register \(\text{CO}_2\) as a product of the DQN resist radiolysis can be related to both the low diffusion rate of this gaseous compound in the polymer bulk and with the formation of a kind of crust near the film surface in the region of the ions’ path (due to the thermolization of \(\text{Sb}^+\) ions). The crust is composed of a tightly cross-linked polymer compound that reduces the removal of \(\text{CO}_2\) and other volatile products from the film under high-vacuum conditions under ionizing radiation.

A broad structured band with several weakly pronounced maxima in the wavenumber range of 590 to 610 cm\(^{-1}\) and a low-intensity band at \(~510\) cm\(^{-1}\) appear in the low-energy region after the implantation of \(\text{Sb}^+\) (Fig. 3). The intensity of these bands did not change significantly with an increase in the implantation dose (curves 2, 3, Fig. 3). Similar bands with a significantly higher intensity are observed in the frustrated-TIR spectrum of the silicon substrate (curve 4 in Fig. 3) and are related to the Si’s lattice absorption [16].

The appearance in the frustrated-TIR spectrum of a band in the wavenumber range of 590 to 610 cm\(^{-1}\) and a low-intensity band at \(~510\) cm\(^{-1}\) is due to the following circumstances. As noted above, the effective penetration depth of radiation into the PR film is \(d_{\text{eff}} \sim 0.45 \lambda\). In the wavenumber range of 500 to 700 cm\(^{-1}\), \(d_{\text{eff}}\) \(~16\) μm, which is almost an order of magnitude larger than the thickness of the PR film. Thus, the radiation in the indicated range is reflected from the resist/silicon interface, which causes the appearance of a band in the wavenumber range of 590 to 610 cm\(^{-1}\) in the frustrated-TIR spectrum of the PR film. Its manifestation after the introduction of \(\text{Sb}^+\) ions is related to the deterioration in the adhesion of the PR film to silicon. A sharp decrease in adhesion (up to detachment) after the implantation of \(\text{Sb}^+\) into the FP9120 PR film on silicon was noted earlier in [5]. However, a reflection enhancement in the antimony-implanted films of a DQN resist on silicon was found in [17]. These experimental data confirm the assumption made above that the bands in the wavenumber range of 590 to 610 cm\(^{-1}\) and at \(~510\) cm\(^{-1}\) are due to the radiation reflection from silicon. Note that the enhancement of the reflection from the resist/silicon interface upon \(\text{Sb}^+\) implantation also causes a decrease in the background absorption by 15–20% in comparison to the unirradiated film in the wavenumber range of 400 to 1200 cm\(^{-1}\) (Fig. 1).

The deterioration of the adhesion of the PR film to silicon is also indicated by the disappearance, after implantation, of the maximum of the frustrated TIR band at \(~1070\) cm\(^{-1}\), which was observed in the initial samples on the low-energy wing of the band with the maximum at 1100 cm\(^{-1}\) (Fig. 4). At a dose of \(1 \times 10^{15}\) cm\(^{-2}\), its intensity decreases, and at \(\Phi \geq 5 \times 10^{15}\) cm\(^{-2}\), it does not manifest itself at all. Note that the band with the maximum at 1070 cm\(^{-1}\) is the most intense IR absorption band in tetraethoxysilane and is caused by the asymmetric stretching vibrations of the Si–O–C

---

**Fig. 3.** Frustrated-TIR spectra of the (1) initial and implanted \(\text{Sb}^+\) with doses of (2) \(1 \times 10^{15}\) cm\(^{-2}\) and (3) \(5 \times 10^{16}\) cm\(^{-2}\) FP9120 films and (4) silicon substrate.
According to [8], this group ensures the adhesion of the FP9120 film to silicon.

In our opinion, a number of factors can lead to a decrease in the adhesion of the DQN resist to a silicon wafer, including a change in the polymer density due to the crosslinking of macromolecules in the bulk, film deformation due to the compound formation in the Sb+-ion thermolization zone, and the accumulation of gaseous and highly volatile radiolysis products at the polymer–silicon interface.

The intensity of the band in the wavenumber range of 1150 to 1230 cm$^{-1}$ caused by the stretching vibrations of the C–O bonds in the phenoxyl group (СОН) decreases upon implantation of the Sb$^+$ ions (Fig. 4).

In the initial samples, this is a broad structured band with three pronounced maxima: at ~1150, ~1170, and ~1200 cm$^{-1}$. Its intensity is higher than the intensity of the 1100 cm$^{-1}$ band. Upon implantation, at $\Phi = 1 \times 10^{15}$ cm$^{-2}$, the maximum disappears first at ~1150 cm$^{-1}$ and then at 1200 cm$^{-1}$. The intensity of the band in the wavenumber range of 1150 to 1200 cm$^{-1}$ becomes lower than the intensity of the band at 1100 cm$^{-1}$ (curve 2 in Fig. 4). The band loses its structure and appears at $\Phi = 5 \times 10^{16}$ cm$^{-2}$ in the spectra as an inflection on the high-energy shoulder of the band at 1100 cm$^{-1}$.

This behavior of the frustrated-TIR bands in the wavenumber range of 1050–1230 cm$^{-1}$ indicates the interaction, during the implantation of ketene, with the OH group of the resin with the formation of ether crosslinks according to reaction (3). However, the oxidation of phenols to quinones can also produce a similar effect, as a result of which the C–OH group is converted to C=O. However, the latter mechanism is unlikely, since after implantation, no significant absorption enhancement in the region of ~1715 to 1730 cm$^{-1}$ caused by the C=O vibrations in the aromatic compounds [13, 14] was observed (Fig. 1).

Note that ketene is formed upon II from the photosensitive component of the resist, ortho-naphthoquinone diazide [8]. The formation of ether crosslinks by reaction (3) should lead to an increase in the microhardness and brittleness of the resistive film, as was observed in [5]. As a result of ether crosslinks, C–O–C bonds are formed, the stretching vibrations of which cause a band with the maximum at 1100 cm$^{-1}$. Furthermore, C–O–C bonds can be also formed during the recombination of radicals on the phenol-formaldehyde polymer [8]. All this leads to the dominance of the band at 1100 cm$^{-1}$ in relation to the band at ~1170 cm$^{-1}$ caused by the vibrations of the C–O bonds.

The progress of reaction (3) is also indicated by a decrease in the intensity of the band in the wavenumber range of 3000 to 3700 cm$^{-1}$ upon the Sb$^+$ implantation caused by the stretching vibrations of the bound O–H groups, the shift of its maximum to the high-energy region, and the appearance of an inflection on its high-energy shoulder at ~3600 cm$^{-1}$ (Fig. 5).

Upon implantation, the removal of formaldehyde CH$_2$=O from the film, which did not react with phenol during the synthesis of the resist polymer base, was observed. This was manifested as the disappearance of the band with the maximum at ~1650 cm$^{-1}$ (Fig. 6) caused by the stretching vibrations of the C=O bonds and the weak band at ~1130 cm$^{-1}$ (Fig. 4) related to the in-plane bending vibrations. Both of these bands are observed in the formaldehyde spectra [13, 19]. The removal of CH$_2$=O is due to its high reactive capability with respect to electrons, hydrogen atoms, and most organic radicals formed in the polymer during ionizing radiation.

The frustrated-TIR spectra of polymers in the wavenumber range of 1475 to 1650 cm$^{-1}$ exhibit absorption bands due to the vibrations of the carbon skeleton of the aromatic ring [13, 14]. They are superimposed by the valence symmetric (1475–1525 cm$^{-1}$) and asymmetric (1620–1760 cm$^{-1}$) vibrations of the C=O bonds. In the same region, the vibrations of double C=C bonds are observed [14]. The position of the C=C and C=O bands is affected by a number of factors, among which the main ones are the electronic
effects of the nearest substituents, conjugation with multiple bonds and aromatic rings, and the presence of inter- and intramolecular bonds [13, 21, 22].

The implantation of Sb+ ions leads to an increase in the intensity of integral absorption in the considered range of wavenumbers during the simultaneous broadening of the absorption bands and smoothing (up to disappearance) of the local maxima (Fig. 6). This may be due to several processes occurring during the interaction of the PR components upon the implantation of Sb+ ions. In particular, the transformation (change in the composition) of the nearest substituents of the aromatic rings and C=O bonds, the strengthening of inter- and intramolecular bonds (cross-linking) [5], and an increase in the number of conjugated multiple bonds [23] can be observed. As noted above, each of these factors leads to a change in the vibration frequency of the aromatic ring skeleton and double bonds. Thus, the band of stretching vibrations of C=O bonds in the aromatic compounds, in particular in benzaldehyde [20, 21] and α-naphthoquinone diazide, is observed at 1700−1715 cm$^{-1}$. When conjugated with C=C bonds, the maximum of the band of these vibrations shifts to the wavenumber range of 1600 to 1650 cm$^{-1}$ [14]. The participation of the C=O group in intermolecular hydrogen bonds also leads to a decrease in the frequency of its stretching vibrations by 40−60 cm$^{-1}$ [20, 22]. In complex aromatic esters, in contrast, the maximum of the stretching vibration band of the C=O group shifts to 1715–1735 cm$^{-1}$ [14]. According to [23], upon implantation of the FP9120 PR, quinoid structures are formed, for which the maximum of the absorption band should be in the range of 1645 to 1690 cm$^{-1}$ [14] depending on the presence of the conjugated bonds. The combined effect of these factors should lead to a broadening of the vibration bands and smoothing of their maxima, as was experimentally observed.

Similar conclusions can be drawn about the bands with the maxima at ~1500 and 1600 cm$^{-1}$ caused by the vibrations of the carbon skeleton of the aromatic ring.

Note that, upon implantation, a redistribution of the intensity of the bands at 2960 cm$^{-1}$ (−CH$_3$ methyl group) and 2930 cm$^{-1}$ (−CH$_2$− methylene group) is observed in favor of the latter. In this case, the band at 2930 cm$^{-1}$ becomes dominant. This redistribution of the bands’ intensity is most likely related to the abstraction of the hydrogen atom from the terminal methyl groups of the phenol-formaldehyde resin during radiolysis with the formation of thermodynamically stable carbon-centered radicals Ar−CH$_3$• of the tolyl type. Their subsequent recombination with the formation of new C−C and C−O bonds leads to an increase in the intensity of the band responsible for the vibrations of the methylene groups.

**CONCLUSIONS**

Thus, it is established that the implantation of Sb+ leads to the appearance in the frustrated-TIR spectrum of the films of the positive FP9120 DQN PR of the band at 2331 cm$^{-1}$ caused by the stretching vibrations of O=−C=O. Violation of adhesion at the PR/silicon interface promotes the appearance of the band at 610 cm$^{-1}$ related to the Si’s lattice absorption. The formation of C−O−C bonds because of the ether cross links of ketene with the OH group of novolac resin was found. Removal of unreacted formaldehyde was also observed during implantation. The interaction of the PR components during the implantation of Sb+ leads to a change in the vibration frequencies of the aromatic ring skeleton and double (C=O, C=C) bonds. This
manifests itself in the frustrated-TIR spectrum as an increase in the intensity of the integral absorption in the wavenumber range of 1475 to 1700 cm$^{-1}$ with the simultaneous broadening and smoothing of the local maxima in this range.

REFERENCES

1. Martins, J.S., Borges, D.G.A.L., Machado, R.C., Carpanez, A.G., Grazul, R.M., Zappa, F., Melo, W.S., Rocco, M.L.M., Pinho, R.R., and Lima, C.R.A., Evaluation of chemical kinetics in positive photoresists using laser desorption ionization, *Eur. Polym. J.*, 2014, vol. 59, pp. 1–7.

2. Debmalya, R., Gandhi, A., Basu, P.K., Eswaran, S.V., and Raghunathan, P., Optimization of monomer content and degree of linearity in lithographically interesting novolac copolymers using NMR spectroscopy, *Microelectron. Eng.*, 2003, vol. 70, no. 1, pp. 58–72.

3. Lebedev, V.I., Kotomina, V.E., Zelentsov, S.V., Leono, E.S., and Sidorenko, K.V., The influence of intermolecular hydrogen bonds on photoresist mask properties, *Vestn. Nizhegor. Univ., Khim.*, 2014, no. 4 (1), pp. 178–182.

4. Moreau, W.M., *Semiconductor Lithography: Principles, Practices and Materials*, New York, London: Plenum, 1988.

5. Brinkevich, D.I., Brinkevich, S.D., Vabishchevich, N.V., Ozdhaev, V.B., and Prosolovich, V.S., Ion implantation of positive photoresists, *Russ. Microelectron.*, 2014, vol. 43, no. 3, pp. 194–200.

6. Vasilevich, V.P., Kisel’, A.M., Medvedeva, A.B., Pleshanovich, V.I., and Rodionov, Yu.A., *Khimicheskaya obrabotka v tekhnom IMS* (Chemical Processing in Integrated Circuit Technology), Polotsk: Polots. Gos. Univ., 2001.

7. Kharchenko, A.A., Brinkevich, D.I., Brinkevich, S.D., Lukashevich, M.G., and Ozdhaev, V.B., Modification of the subsurface layers of polyimide films upon boron-ion implantation, *J. Surf. Invest.: X-ray, Synchrotron Neutron Tech.*, 2015, vol. 9, no. 1, pp. 87–91.

8. Vabishchevich, S.A., Brinkevich, S.D., Brinkevich, D.I., and Prosolovich, V.S., Adhesion of diazoquinone-novolac photoresist films implanted with boron and phosphorus ions to single-crystal silicon, *High Energy Chem.*, 2020, vol. 54, no. 1, pp. 46–50.

9. Brinkevich, D.I., Kharchenko, A.A., Brinkevich, S.D., Lukashevich, M.G., Ozdhaev, V.B., Valeev, V.F., Nuzhdin, V.I., and Khaibullin, R.I., Radiation-induced modification of reflection spectra beyond the ion path region in polyimide films, *J. Surf. Invest.: X-ray, Synchrotron Neutron Tech.*, 2017, vol. 11, no. 4, pp. 801–806.

10. Becker, J., *Spektroskopie*, Wurzburg, Germany: Vogel Industrie Medien, 1997.

11. Brinkevich, D.I., Kharchenko, A.A., Prosolovich, V.S., Ozdhaev, V.B., Brinkevich, S.D., and Yankovskii, Yu.N., Reflection spectra modification of diazoquinone-novolak photoresist implanted with B and P ions, *Russ. Microelectron.*, 2019, vol. 48, no. 3, pp. 197–201.

12. *Fiziko-khimicheskie svoistva poluprovodnikovykh veshestv*. Spravochnik (Physicochemical Properties of Semiconductor Substances, The Handbook), Moscow: Nauka, 1979, p. 13.

13. Tarasevich, B.N., *IK spektry osnovnykh klassov organicheskikh soedinii*. Spravochnye materialy (IR Spectra of the Main Classes of Organic Compounds. Reference Materials), Moscow: MGU, 2012.

14. Pretsch, E., Bühlmann, F., and Affolter, C., *Structure Determination of Organic Compounds: Tables of Spectral Data*, Berlin Heidelberg: Springer, 2000.

15. Pikaev, A.K., *Sovremennaya radiaitsionnaya khimiya: Radioliz gazov i zhidkostei* (Modern Radiation Chemistry: Radiolysis of Gases and Liquids), Moscow: Nauka, 1986.

16. Pankove, J.I., *Optical Processes in Semiconductors*, Englewood Cliffs, NJ: Prentice-Hall, 1971.

17. Kharchenko, A.A., Brinkevich, D.I., Prosolovich, V.S., Brinkevich, S.D., Ozdhaev, V.B., and Yankovskii, Yu.N., Radiation-stimulated transformation of the reflectance spectra of diazoquinone-novolac photoresists films implanted with antimony ions, *J. Surf. Invest.: X-ray, Synchrotron Neutron Tech.*, 2020, vol. 14, no. 3, pp. 558–557.

18. Brinkevich, S.D., Grinyuk, E.V., Brinkevich, D.I., Sverdlow, R.L., Prosolovich, V.S., and Pyatitliskii, A.N., Mechanism of the adhesive Interaction of Diazquinone-Novolac Photoresist Films with Monocrystalline Silicon, *J. Appl. Spec.*, 2020, vol. 87, no. 4, pp. 647–651.

19. Poljansek, I., Sebenik, U., and Krajnc, M., Characterization of phenol-urea-formaldehyde resin by inline FTIR spectroscopy, *J. Appl. Polym. Sci.*, 2006, vol. 99, pp. 2016–2028.

20. Belkov, M.V., Brinkevich, S.D., Samovich, S.N., Skornyakov, I.V., Tolstorozhev, G.B., and Shadyro, O.I., Infrared spectra and structure of molecular complexes of aromatic acids, *J. Appl. Spectrosc.*, 2011, vol. 78, no. 6, pp. 794–801.

21. Tolstorozhev, G.B., Skornyakov, I.V., Bel’kov, M.V., Shadyro, O.I., Brinkevich, S.D., and Samovich, S.N., IR spectra of benzaldehyde and its derivatives in different aggregate states, *Opt. Spektrosk.*, 2012, vol. 113, no. 2, pp. 179–183.

22. Tolstorozhev, G.B., Skornyakov, I.V., Bel’kov, M.V., Shadyro, O.I., Brinkevich, S.D., and Samovich, S.N., Hydrogen bonds and antiviral activity of benzaldehyde derivatives, *J. Appl. Spectrosc.*, 2012, vol. 79, no. 4, pp. 645–650.

23. Oleshkevich, A.N., Lapchuk, N.M., Ozdhaev, V.B., Karpovich, I.A., Prosolovich, V.S., Brinkevich, D.I., and Brinkevich, S.D., Electronic conductivity in a P$^+$-ion implanted positive photoresist, *Russ. Microelectron.*, 2020, vol. 49, no. 1, pp. 55–61.

Translated by A. Ivanov