Semiconductors, 2022, Vol. 56, No. 10

# Application of RIE-technology to control responsivity of 4*H*-SiC photodiodes

© A.V. Afanasev[1], V.V. Zabrodskiy[2], V.A. Ilyin[1], V.V. Luchinin[1], A.V. Nikolaev[2],
A.V. Serkov[1], V.V. Trushlyakova[1], D.A. Chigirev[1]

[1] St. Petersburg State Electrotechnical University „LETI",
197022 St. Petersburg, Russia,
[2] Ioffe Institute,
194021 St. Petersburg, Russia
E-mail: a_afanasjev@mail.ru

*Received June 30, 2022*
*Revised August 3, 2022*
*Accepted August 12, 2022*

The possibility to increase the responsivity of 4*H*-SiC $p^+-n-n^+$-photodiodes by varying the thickness of the $p^+$-epilayer has been studied. It is shown that the thinning of the upper epilayer by RIE with the use of metal contacts as a mask makes it possible to control both the maximum responsivity and the spectral dependence of the responsivity of photodiodes and does not lead to degradation of dark electrical characteristics.

**Keywords:** 4*H*-SiC, $p^+-n-n^+$-photodiode, UV-range, $p^+$-epilayer, reactive ion etching RIE, responsivity.

DOI: 10.21883/SC.2022.10.54908.9926

## 1. Introduction

Interest in effective photo converters operating in the ultraviolet (UV) range is constantly growing. The high demand for devices of this class for a wide range of applications in the aerospace, military, medical and biological fields formed the direction „UV photoelectronics" [1] at the beginning of the 2000s. A special position in this segment is occupied by the photodetectors (PDs) made on the basis of wide-band semiconductors (nitrides of group III metals, silicon carbide and diamond), which, thanks to the fundamental parameters of the material, provide the possibility of „visible-blind" radiation detection [2]. Hexagonal silicon carbide polytypes (especially 4*H*) are successfully used to solve this problem. Based on 4*H*-SiC, photodiodes with a Schottky barrier are manufactured, both in the vertical [3,4] and planar [5] versions, as well as the most popular $p-n$photodiodes [6] and avalanche (APD) photodiodes [7]. It is known that one of the most important areas of research and development is the search for optimal design options for the PDs, which would provide an optimal combination of low dark currents, high photosensitivity (quantum yield) and [8] performance. Ensuring high sensitivity (especially in the short-wave UV-region) will be determined by the properties of the external photodetector layer (usually $p^+$) and, first of all, its thickness [9], which should be minimal, as well as the presence or absence of no anti-reflective coating [10]. The results of our preliminary studies showed that 4*H*-SiC photodiodes made on the basis of epitaxial structures with ultrathin ($< 0.1$ microns) external $p^+$-layers were characterized by large ($> 10^{-8}$ A) by reverse currents. Apparently, this is a consequence of high-temperature annealing — a necessary operation for the formation of low-resistance contacts to the *p*- and *n*-regions of 4*H*-SiC [11]. As a result of such heat treatment, extended intermetallic regions of high conductivity are formed, penetrating through a thin $p^+$-layer. This leads to the disappearance of $p-n$ transitions in the local areas of the device and, as a consequence, to the linear VAC (volt-ampere characteristic). Therefore, the thickness of the $p^+$-layer should be $\geq 0.4$ microns [12]. One of the possible ways to solve this problem may be the local thinning-out of photodetector regions while maintaining the initial thickness of the $p^+$-layers located under ohmic contacts. It should be noted that due to the exceptional chemical resistance of silicon carbide, the only possible technological method of etching it is the technology of reactive ion-plasma etching [13].

In this paper, we investigated the possibility of increasing the sensitivity of $p^+-n$-photodiodes based on 4*H*-SiC by varying the thickness of photodetector $p^+$-regions by the Reactive Ion-Plasma Etching Mode (RIPEM) using metal contacts (Ni/Al) as a mask. The application of this technology requires experimental verification, since along with the obvious effect of reducing the thickness of the $p^+$-epislayer, the effect of micro-masking the surface of the 4*H*-SiC with metal particles of the mask is manifested during etching. As a result of plasma treatment of the near-surface region, an array of micron-sized cusps with a surface density of up to $10^8$ cm$^{-2}$ [14]. The presence of such a surface can both increase the sensitivity of the photodetector by reducing the reflection coefficient, and reduce it by increasing the surface centers of recombination and diffuse light scattering.

## 2. Experiment procedure

4*H*-SiC photodiodes were manufactured on the basis of epitaxial $p^+-n-n^+$structures obtained by CVD on 150 mm

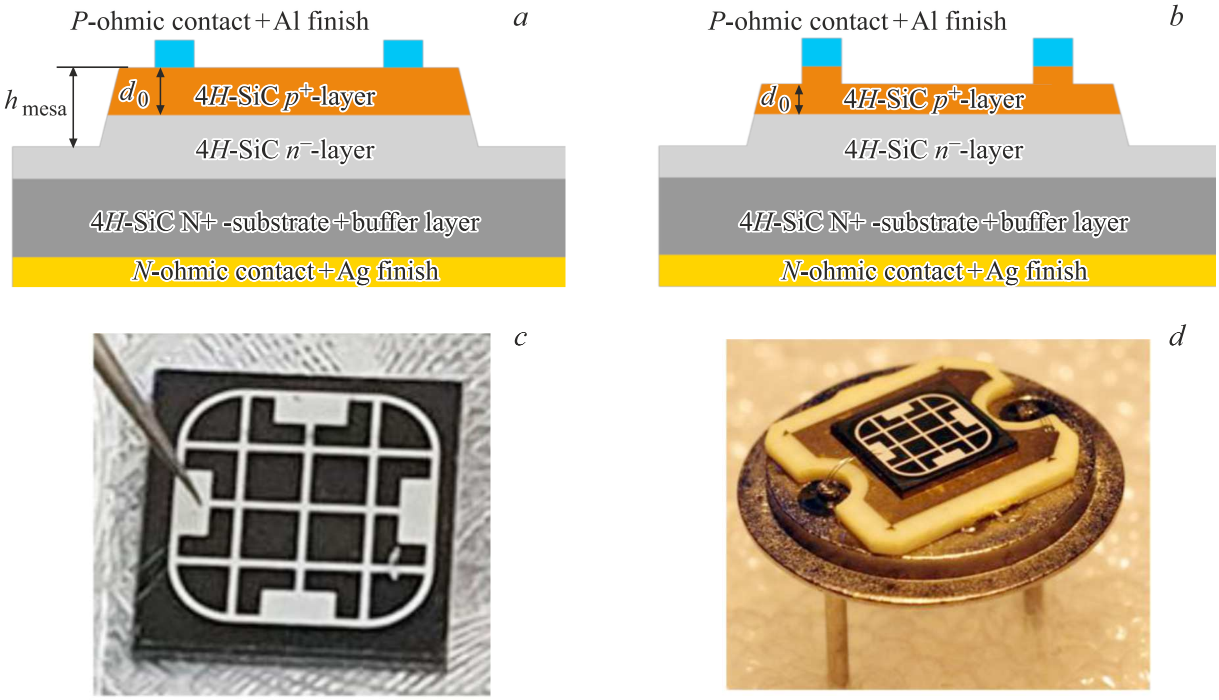

**Figure 1.** Mesaepitaxial $4H$-SiC photodiode chip: initial structure (*a*); after the RIPEM (*b*); top view (*c*); in a housing prepared for measurements of spectral characteristics (*d*). (Colored version of the figure is presented in electronic version of the article).

$n^+$-substrates. The drift $n$-region had a thickness of 12 microns and a concentration of uncompensated donors $N_d - N_a < 5 \cdot 10^{14}\,\text{cm}^{-3}$. The upper $p^+$-layer was alloyed with aluminum to the level of $N_a - N_d > 5 \cdot 10^{19}\,\text{cm}^{-3}$ (Fig. 1, *a*). Based on the published calculated and experimental data [8–10], in order to ensure a sufficiently high initial sensitivity and exclude volumetric leaks in the diode structure, the thickness of the $p^+$-layer $d_0$ was chosen to be 2 microns.

The samples were made in the form of mesodiodes, where the area of the photodetector region was $12\,\text{mm}^2$. Mesa height $h_{\text{mesa}} = 3.1-3.3$ The microns were obtained by the RIPEM method (Fig. 1, *a*). Fig. 2 shows a SEM image of the photodiode cleaved facet, which was used to determine $d_0$ and $h_{\text{mesa}}$. Nickel ohmic contacts to the $n^+$-substrate and Ni/Al contacts with a mesh topology to the $p^+$-layer were manufactured using the technology described in [11]. The final metallization from the $n^+$-side of the substrate and $p^+$-layer was formed by applying Ag and Al films, respectively, with a thickness of 1 microns.

After dividing the plate into chips of $4.3 \times 4.3$ mm in size and measuring the dark VAC photodiodes (samples of group 1), $p^+$-regions were thinned-out by the RIPEM method using an aluminum metallization layer as a mask (Fig. 1, *b*).

The RIPEM process $4H$-SiC was implemented on the ICP installation „Caroline-15“.

The Reactive Ion-Plasma Etching Mode (RIPEM) in the SF environment ${}_6-\text{O}_2-$Ar was selected to provide the etching rate of $p^+$-layer $0 \leq 0.2$ microns/min. Further studies were carried out on groups of photodiode structures, where etching times varied in the range of $0-10$ min (see table).

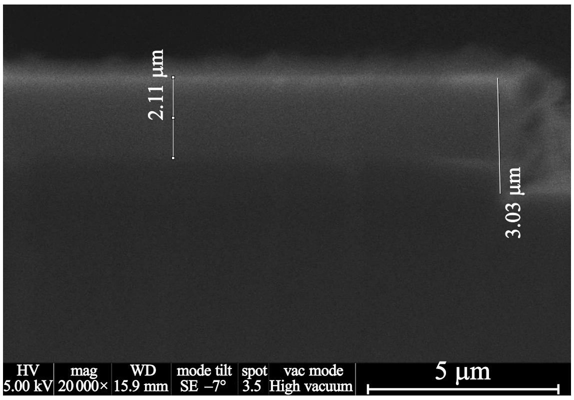

**Figure 2.** The SEM image of a $4H$-SiC photodiode cleaved facet in the mesa region.

Studies of the sensitivity of samples by comparison were carried out in photogenerator mode in the wavelength range $220-400$ nm. A deuterium gas discharge lamp DDS-30 was used as a UV radiation source. The monochromator SF-16 provided the choice of wavelength. The photocurrent was recorded by the picoamperemeter „Keithley 6485“. A silicon photodiode was used as a secondary sensitivity standard, calibrated in VNIIOFI (Moscow). The sensitivity and External Quantum Yield (EQY) of the test sample were determined in accordance with the expressions:

$$S(\lambda)_{\text{SiC}} = S(\lambda)_{\text{Si}} \times \left(I(\lambda)_{\text{SiC}} - Id_{\text{SiC}}\right)/\left(I(\lambda)_{\text{Si}} - Id_{\text{Si}}\right), \quad (1)$$

$$EQY(\lambda)_{\text{SiC}} = \left(S(\lambda)_{\text{SiC}} \cdot h \cdot c\right)/(\lambda \cdot q), \quad (2)$$

where $\lambda$ — wavelength, $I(\lambda)_{\text{SiC}}$ — current recorded from the sample during UV irradiation, $Id_{\text{SiC}}$ — dark current of the sample, $I(\lambda)_{\text{Si}}$ — current recorded by the calibrated photodiode under UV radiation, $Id_{\text{Si}}$ — dark current of the calibrated photodiode, $S(\lambda)_{\text{Si}}$ — absolute sensitivity of the calibrated photodiode, $S(\lambda)_{\text{SiC}}$ — measured absolute sensitivity of the sample, $EQY(\lambda)_{\text{SiC}}$ — calculated EQY of the sample, $q$ — electron charge, $h$ — Planck's constant, $c$ — the speed of light.

## 3. Experimental results

Dark volt-ampere characteristics of photodiode $4H$-SiC-chips — before (sample 1) and after (samples 3 and 5) the RIPEM, were measured using a picoamperemeter „Keithley 6487". In all cases, for direct branches of the VAC, the exponential growth of the current in the range $10^{-11}-10^{-2}$ A was proportional to $\exp(t/CNT)$ with a coefficient value of $H$ close to 2 (Fig. 3), which is characteristic of the recombination mechanism of carrier transport in sharp asymmetric 4h-Zy$N-N$transitions [13]. For samples of all types, the values of reverse currents at voltages up to $-5$ V did not exceed 20 pA (Fig. 3), which is acceptable for large-area photodetector structures without passivation of the lateral surface of the mesa, designed to operate in photogenerator mode.

The thicknesses of $p^+$-layers (Fig. 1, *b*) after the RIPEM were determined by the Atomic Force Microscopy (AFM). From Fig. 4 it can be seen that the spent mode of „soft" etching $4H$-SiC allows for a material removal rate $0.15-0.16$ microns/min.

Photodiode chips of the sample groups were used for spectral measurements 1, 3, 5, which were placed in metal-glass cases on subcrystalline boards and boiled (Fig. 1, *d*). Fig. 4 shows the spectral dependences of the current sensitivity and the external quantum output of the manufactured samples, as well as photodiodes with a Schottky barrier based on Cr-$4H$-SiC [15]. For photodiodes based on $p^+-n$ transitions, as the $p^+$-layer is refined, there is an obvious tendency to increase the sensitivity and EQY. As follows from the data shown in Fig. 5, with a decrease in the thickness of the upper layer of the photodiode from 2 to 0.45 microns, the sensitivity and EQY values in the maximum region (from 0.091 A/W to 0.156 A/W and from 0.38 electrons/photon to 0.64 electrons/photon, respectively), as well as the short-wave region increase very significantly. It should be noted that the values of the maximum sensitivity and the corresponding wavelengths practically coincide with the results of calculations in [9,10]. Attention is drawn to the fact that even at $d = 0.45$ microns in the absence of anti-reflective coatings at a wavelength of 295 nm, the maximum values of sensitivity and EQY are equal to 0.156 A/W and 0.64 electrons/ photons, respectively, which is not inferior to known analogues.

Distribution of photodiodes into groups depending on the time of the RIPEM

| № Sample groups | RIPEM time of $p^+$-layer, min |
|---|---|
| 1 | 0 |
| 2 | 3 |
| 3 | 5 |
| 4 | 7 |
| 5 | 10 |

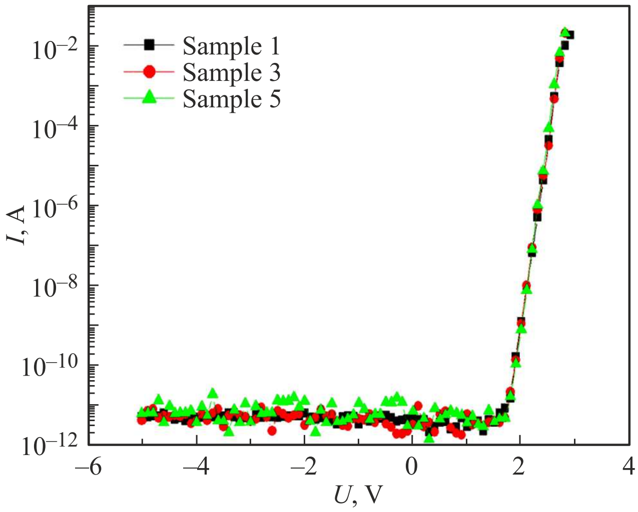

**Figure 3.** The dark VAC $4H$-SiC photodiode chips (sample groups 1, 3, 5). (Colored version of the figure is presented in electronic version of the article).

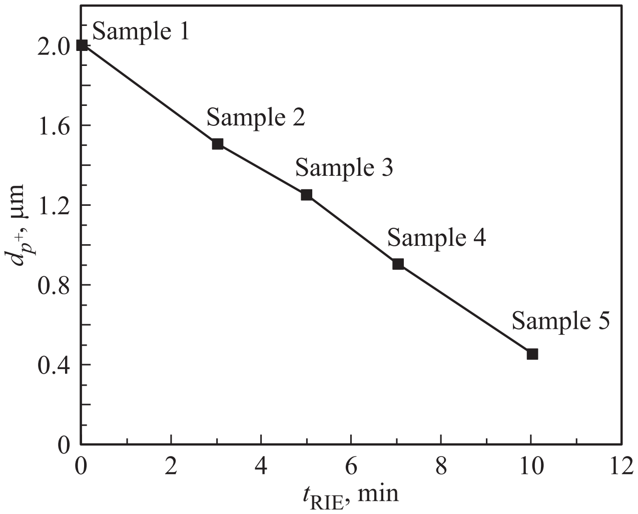

**Figure 4.** Thicknesses of $p^+$-layers measured by the AFM method after etching with different times.

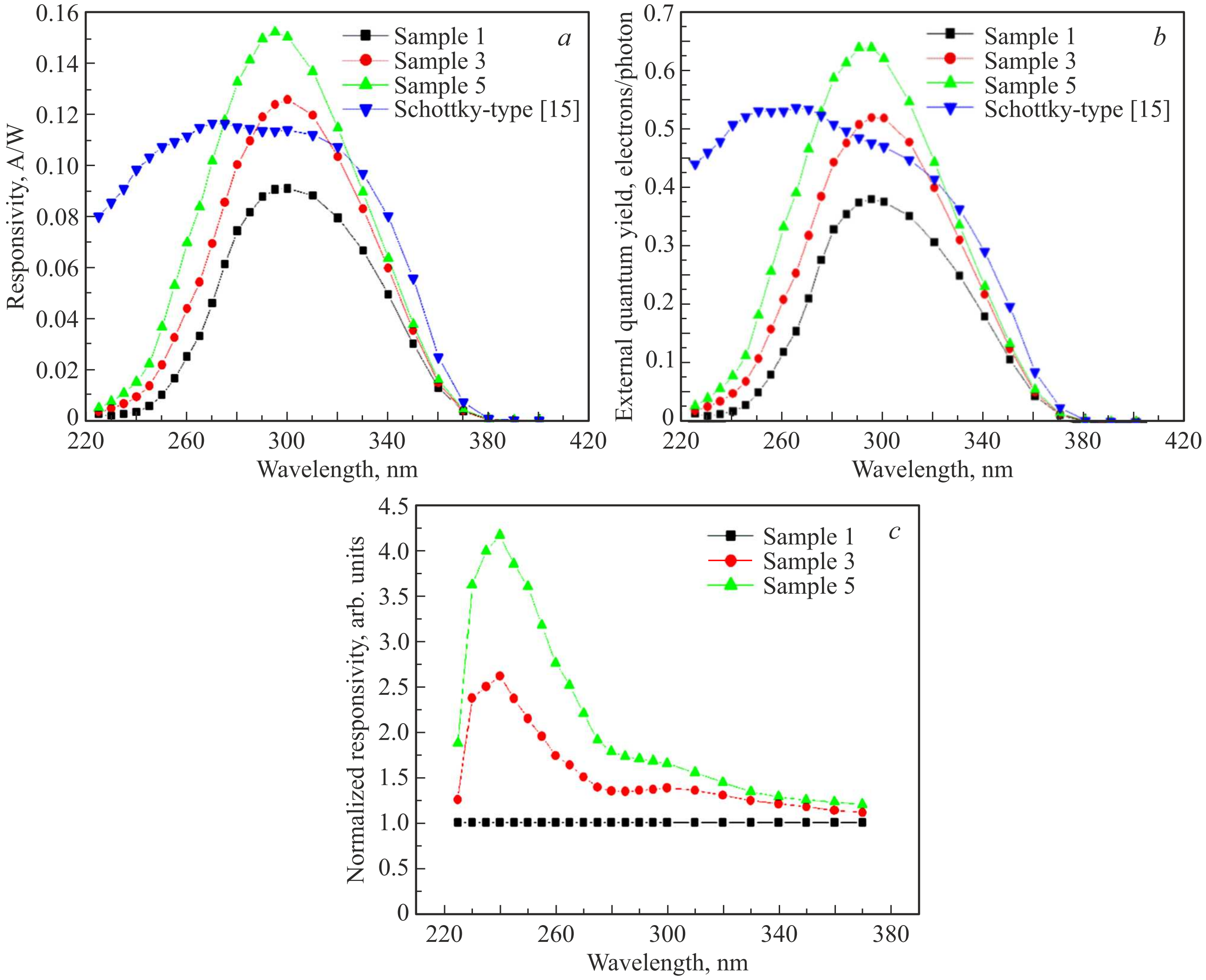

**Figure 5.** Spectral dependences of sensitivity (*a*), external quantum output (*b*) and sample-normalized 1 sensitivity (*c*) 4*H*-SiC photodiodes.

It is expected that the subsequent thinning-out of $d$ to a thickness of $0.10-0.15$ microns will significantly increase the short-wave sensitivity of receivers of this type, which can be comparable to photodiodes based on the Schottky barrier. At the same time, it is necessary to additionally investigate the possible influence of the surface layer formed as a result of the RIPEM with a length of several tens of nanometers, which can have both a positive and negative effect on sensitivity in the wavelength range of $< 290$ nm.

## 4. Conclusion

As a result of the research, it is shown that the thinning-out of the upper $p^+$-layer of the mesaepitaxial 4*H*-SiC photodiode of the type $p^+-n-n^+$ by the RIPEM method using as a mask the metal of the contacts allows you to control the sensitivity, EQY and their spectral dependencies. At the same time, there is no noticeable deterioration of the dark VAC photodiodes. It seems interesting to investigate the influence of the parameters of arrays of micron-sized points (density, linear dimensions, shape) on the photoelectric properties and performance of 4*H*-SiC photodiodes.

### Conflict of interest

The authors declare that they have no conflict of interest.

## References

[1] T.V. Blank, Yu.A. Gol'dberg. FTP, **37**, 1025 (2003). (in Russian).

[2] A. Sciuto, M. Mazzillo, S. Di Franco, F. Roccaforte, G. D'Arrigo. IEEE Photonics J., **7**, 6801906 (2015).

[3] T.V. Blank, Yu.A. Goldberg, E.V. Kalinina, O.V. Konstantinov. ZhTF, **78**, 86 (2008) (in Russian).

[4] A.V. Afanasyev, V.A. Ilyin, N.M. Korovkina, A.Yu. Savenko. Pis'ma ZhTF, **31**, 1 (2005). (in Russian).

[5] Z. Wu, X. Xin, Feng Yan, Jian Hui Zhao. Mater. Sci. Forum, **457-460**, 1491 (2004).

[6] IFW Optronics, GmbH — www.ifw-optronics.de

[7] M. Zhang, K. Wang, H. Jiang, R. Hong, Z. Wu. Electron. Lett., **52**, 1474 (2016).

[8] H.Y. Cha, P.M. Sandvik. Jpn. J. Appl. Phys., **47**, 423 (2008).

[9] Y. Hou, C. Sun, J. Wu, R. Hong, J. Cai, X. Chen, D. Lin, Z. Wu. Electron. Lett., **55**, 216 (2019).

[10] C. Matthus, A. Burenkov, T. Erlbacher. Mater. Sci. Forum, **897**, 622 (2017).

[11] A.V. Afanasyev, V.A. Ilyin, V.V. Luchinin, A.V. Serkov, D.A. Chigirev. FTP, **56**, 606 (2022). (in Russian).

[12] A.V. Afanasyev, V.A. Ilyin, S.A. Reshanov, A.A. Romanov, K.A. Sergushichev, A.V. Serkov, D.A. Chigirev. Nano- i mikrosistemnaya tekhnika, 18 (5), 331 (2016). (in Russian).

[13] T. Kimoto, J.A. Cooper. *Fundamentals of silicon carbide technology: growth, characterization, devices and applications* (Singapore, John Wiley & Sons, Inc., 2014).

[14] A.V. Afanasyev, B.V. Ivanov, V.A. Ilyin, A.F. Kardo-Sysoev, M.A. Kuznetsova, V.V. Luchinin. Mater. Sci. Forum, **740-742**, 1010 (2013).

[15] E.V. Kalinina, G.N. Violina, V.P. Belik, A.V. Nikolaev, V.V. Zabrodsky. Pis'ma ZhTF, **42**, 73 (2016). (in Russian).