

UDC 621.315.5:621.383
EDN: ZWKOUQ

PACS: 85.30.-z, 85.60.-q

The effect of defects in oxide layers on the performance of silicon photodiodes

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Received 6.11.2025; revised 18.11.2025; accepted 11.12.2025

The mechanism of leakage current formation in p^+-n junctions of photodiodes in the presence of local defects is investigated. The patterns of formation of local defects in dielectric layers are considered in order to determine the conditions that reduce their density. On n -type monocrystalline silicon (Cz-Si) wafers with a diameter of 100 mm and a resistivity of 4–5 ohms.cm and orientation (100) were used to produce elements with a pad size of $1.4 \times 1.4 \text{ mm}^2$. The manufacturing process cycle included the operations of oxidation in $\text{H}_2\text{O} + \text{HCl}$ vapors, photolithography, coralling (precipitation) of boron from BN, boron diffusion and phosphorus diffusion in various modes. Both liquid sources POCl_3 and PCL_3 and solid sources – aluminum metaphosphate (MFA) (Al_2O_3 , $3\text{P}_2\text{O}_5$) plates were used as a diffusant source during phosphorus diffusion. It has been established that the current-voltage characteristic of silicon photodiodes with anomalous "soft" characteristics is determined by the tunneling current flow mechanism. The use of optimal gettering modes leads to a sharp decrease in the number of photosensitive elements with anomalous current-voltage characteristic.

Keywords: silicon photodiodes; monocrystalline silicon; defects; current-voltage characteristics.

DOI: 10.51368/2949-561X-2025-6-5-10

Introduction

The cycle of manufacturing silicon photodiodes typically involves the diffusion of high concentrations of boron and phosphorus to form p – n junctions and doped regions. The process of phosphorus diffusion often leads to the formation of local defects in the dielectric layers acting as a protective mask [1–3]. These defects can lead to the formation of local n^+ -channels in p^+-n junctions and defects on the silicon surface causing leak currents ("soft" volt-ampere characteristics) resulting in the increase of photodiodes noise, including low-frequency ones with $1/f$ type spectrum.

Paper [4] considers the patterns of formations of these defects to determine conditions reducing their density.

The purpose of this paper is to study the mechanism of formation of leak points in p^+-n junctions of photodiodes if the specified defects are present.

Experiment

Photosensitive elements (FSE) with a pad size of $1.4 \times 1.4 \text{ mm}^2$ were manufactured on the n -type monocrystalline silicon (Cz-Si) plates with a diameter of 100 mm and specific resistance of 4–5 $\Omega \cdot \text{cm}$ and orientation (100). Process cycle of

manufacturing included the processes of oxidation in $\text{H}_2\text{O} + \text{HCl}$ vapors, photolithography, pre-depositon (precipitation) of boron from BN, boron and phosphorus diffusion in different modes.

Both liquid POCl_3 and PCL solid sources such as aluminum metaphosphate plates ($\text{Al}_2\text{O}_3/3\text{P}_2\text{O}_5$) were used as a diffusant source during phosphorus diffusion.

The concentration and distribution of local defects over the plate were determined on the manufactured samples using an optical microscope. Optical, atomic-force microscope and REM were used to determine the dimensions and shape of defects. The manufactured samples were used to measure volt-ampere characteristics (VAC) of PSE in the temperature range from -60°C to $+70^\circ\text{C}$ and reverse voltage from 0.01 V to 20 V.

Results

Part of the samples showed a significant increase of dark currents (I_d) with the increase of

reverse bias (“soft” VAC). To determine the causes of this phenomenon, measurements of VAC were carried out on such PSE in the temperature range from -60°C to $+70^\circ\text{C}$ and reverse voltage from 0.01 V to 20 V, the results are shown in fig. 1. The obtained results show a weakening of the temperature dependence of the dark current with the increase of reverse voltage and its near absence with large leak currents (voltage 20 V).

To determine the nature of the I_d except for reverse voltage, the VAC was plotted in I_d/V coordinates from $V^{-1/2}$ (fig. 2) which demonstrated a transition from the area with dependence $I_d \sim V^{1/2}$ characteristic of the generating current, to an area with exponential current increase.

Fig. 3 shows VAC in the area of “soft” characteristics at two temperatures (-60°C and 25°C) confirming exponential dependence of current on voltage and its weak dependence on temperature.

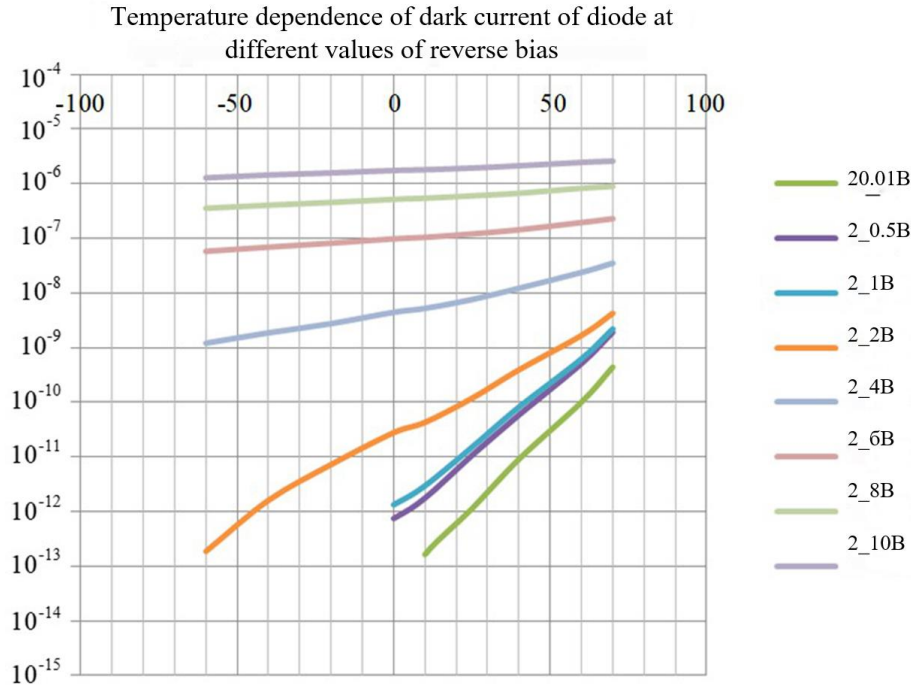


Fig. 1. Temperature dependencies of the current at different bias voltages

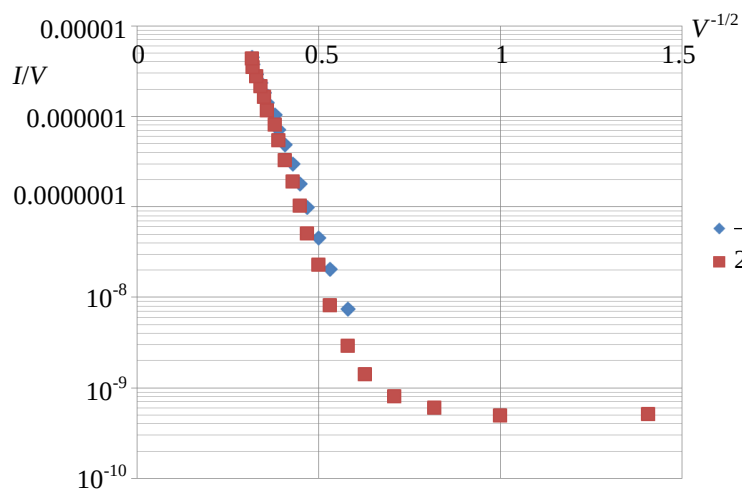
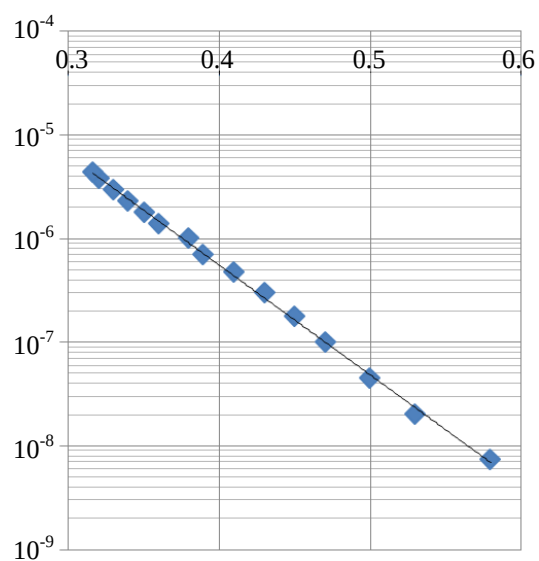
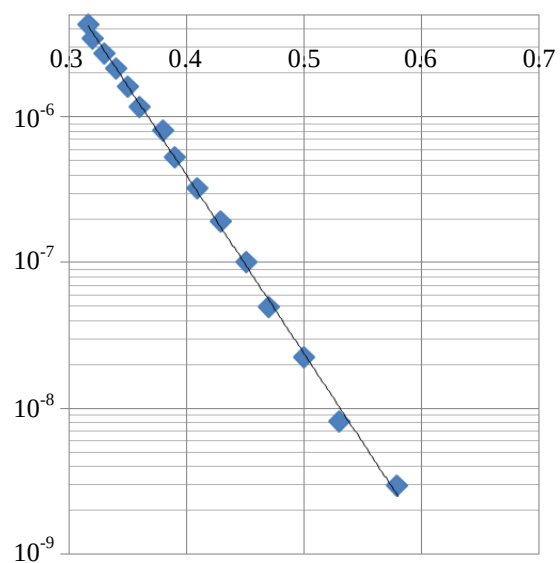


Fig. 2. Current dependence on voltage at temperatures of $-60\text{ }^{\circ}\text{C}$ and $25\text{ }^{\circ}\text{C}$ in the voltage range of $0.4\text{--}10\text{ V}$



a)



b)

Fig. 3. Tunneling current dependence on voltage at temperatures of $-60\text{ }^{\circ}\text{C}$ and $25\text{ }^{\circ}\text{C}$ in the voltage range of $3\text{--}10\text{ V}$

Discussion of the results

Obtained dependencies of dark current on reverse voltage in the area of exponential growth indicate a tunneling mechanism of current flow.

Indeed, a known expression for the tunneling current is as follows [5]:

$$I = AE^2 \exp(-B/E) \quad (1)$$

where E is the electric field strength; A , B – coefficients poorly depending on the electric field.

Dependence of the electric field in the sharp p^+-n -junction E on the voltage V if there are local areas with increased field voltage, can be represented as follows [6]:

$$E = \beta E_{\max} = \beta \left(\frac{2qN_d}{\epsilon_s} \right) (V_b + V)^{1/2} \quad (2)$$

where V_b is inbuilt potential, N_d – concentration of charge carriers in the n -area, $E_{\max}$ – maximum field strength in a homogeneous area of the spatial charge, β – coefficient considering local field changes due to the defect, ϵ_s – dielectric constant.

Considering (1, 2), current dependence on voltage can be expressed as follows:

$$\ln \left(\frac{I}{V} \right) = \ln a - b(V_b + V)^{-1/2} \quad (3)$$

where [5]:

$$a = \frac{(2m^*)^{1/2} q^3 E V}{4\pi^2 \left(\frac{h}{\pi} \right)^2 E_g^{1/2}}, \quad (4a)$$

$$b = \frac{4(2m^*)^{1/2} E_g^{3/2}}{3q \left(\frac{h}{\pi} \right) \beta \left(\frac{2qN_d}{\epsilon_s} \right)^{1/2} (V_b + V)^{1/2}} \quad (4b)$$

where m^* – effective electron mass; E_g – band gap of silicone.

Experimental data shown in fig. 3 confirm with a high degree of certainty the presence of specified dependence between current value and applied voltage at values β in expression (4b) equal to 184.6 and 211.8 for temperatures -60°C

and 25°C , respectively. Obtained values β according to (2) lead to electric field values in the defective region $(3.1\text{--}3.6) \times 10^6 \text{ V/cm}$ at $V = 1 \text{ V}$ and $(0.98\text{--}1.15) \times 10^7 \text{ V/cm}$ at 10 V which significantly exceeds the field strength during avalanche breakdown in silicone ($\sim 5 \times 10^5 \text{ V/cm}$) and complies with literature data for tunnel breakdown [5, 6]. An additional argument confirming the tunneling mechanism of current flow is its weak temperature dependence with a negative temperature coefficient ($dI/dT < 0$) (fig. 1).

Using expression (4a) and experimentally obtained dependencies of tunneling current on voltage (fig. 3):

$$I/V = 0.0095 \exp(-24.37V^{-1/2}) \text{ at } -60^\circ\text{C}, \quad (5a)$$

$$I/V = 0.031 \exp(-28.18V^{-1/2}) \text{ at } 25^\circ\text{C}, \quad (5b)$$

It is possible to determine the ratio of tunneling current to its density J_t and, respectively, the area of the emitting area A_t from the ratio $A_t = I/J_t$. Obtained values $A_t = 350\text{--}650 \text{ A}$ indicate the presence of local current flows making up to $5 \times 10^{-10}\text{--}2 \times 10^{-9}$ of the area of the p - n junction at temperatures of -60°C and 25°C , respectively.

Since the distribution of PSE with “soft” characteristics over the area of plates is random, it may be caused by local defects, such as oxide or the silicone surface defects formed by phosphorus diffusion [6]. The location of defects causing tunneling currents near the surface is confirmed by the fact that in the considered range of reverse voltages the width of the spatial charge area of the p^+-n junction with high field strength does not exceed 5 microns. Penetration defects of the specified type may result in tunnel breakdown of parasitic p^+-n^+ junctions due to a high concentration of alloying admixtures, as well as formation of local defect areas on the silicate surface (fig. 4) containing impurities of oxygen, carbon [6] and heavy metals (impurity precipitates) around which the electric field strength increases.

The influence of local defects on the formation of PSE with abnormal “soft” VAC is confirmed by a correlation between the number of PSE with low density of defects on the plate ($< 5 \text{ cm}^{-2}$) detected using an optical microscope (N_{def}) and the number of PSE with low dark

currents (N_{pse}) (fig. 5). The data are specified for 100 plates from different batches, each of which contains 70 lines of 16 PSE. Consequently, an important task is to reduce the density of oxide

defects which is achieved by the optimization of phosphorous diffusion modes and improvement of the quality of the oxide formed before diffusion [1, 4].

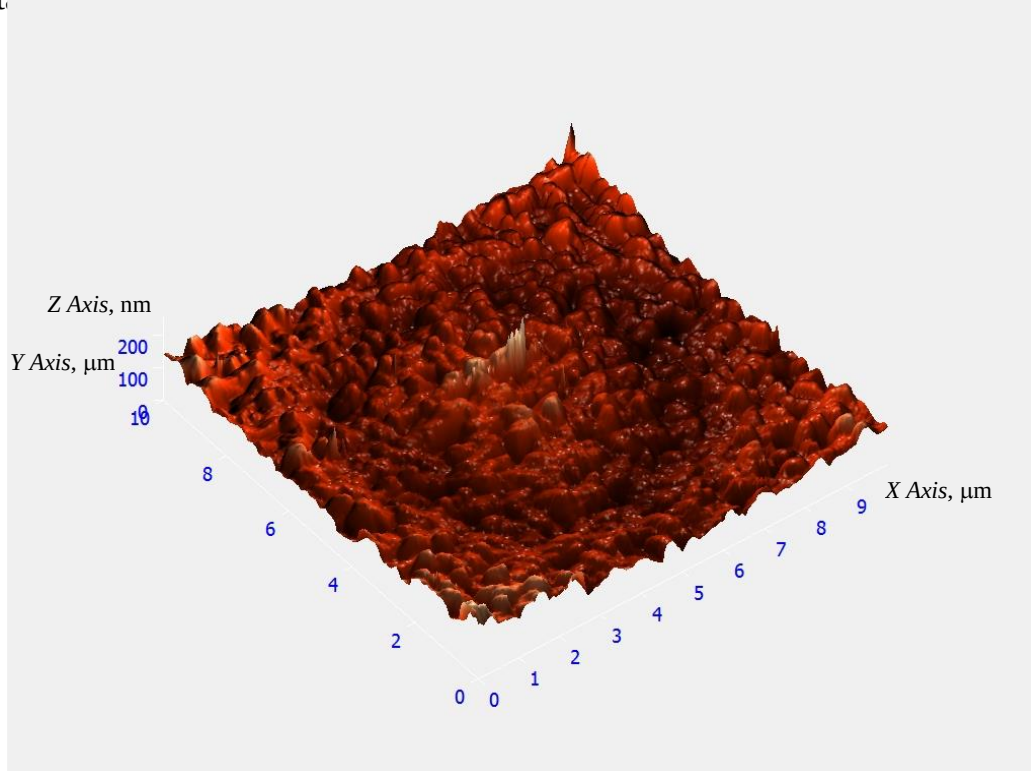


Fig. 4. Image of defect in silicone and atomic-force microscope

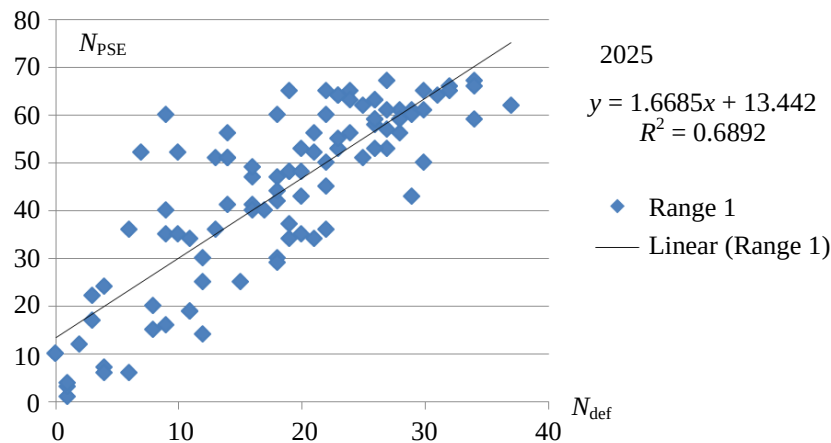


Fig. 5. Dependence of the number of PSE with $I_d < 1 \times 10^{-11}$ A at 10 mV on the number of PSE with density of defects less than 5 cm^{-2}

The formation of impurity precipitates near defects is more obvious out of two considered reasons of tunneling currents occurrence. Obviously, thermal operations following the phosphorous diffusion cannot remove the formed n^+ -channel. At the same time, the selection of optimal modes of the subsequent gettering operation resulting in the removal of

contaminating impurities from silicone volume, including impurity precipitates, makes it possible to almost practically exclude the formation of PSE with abnormal characteristics.

Repeated carrying out of the impurity gettering operation on plates containing PSE with “soft” characteristics also leads to the reduction of such elements.

Conclusions

1. It is established that voltage-current characteristic (VAC) of silicone photodiodes with abnormal “soft” characteristics is determined by tunneling mechanism of current flow.

2. The cause of tunneling currents are local areas with a small area and electric field strength

of $3 \times 10^6 - 10^7$ V/cm. The reason of occurrence of such areas can be impurity precipitates formed on the silicone surface during the formation of defects in the oxide.

3. Use of optimal modes of impurity gettering leads to sharp decrease in the number of photosensitive elements with abnormal VAC.

REFERENCES

1. Blackstone S., Henry W., Jastrzebski L. and Fisher A. W., Journal of Electrochemical Society **3**, 667–668 (1982).
2. Storch W., Mohr U., Elstner L. and Leihkauf R., Phys. Stat. Sol. (a) **132**, K109 (1992).
3. Miyashita M., Fukui H., Kubota A., Samata S., Hiratsuka H. and Matsushita Y., International Conference on Solid State Devices and Materials. Yokohama, 1991, pp. 568–570.
4. Boltar K. O., Vildyaeva M. A., Irodov N. A., Klimanov E. A., Lyalikov A. V., Malygin V. A., Molchanov D. S., Makarova E. A., Applied Physics, № 2, 39 (2025).
5. Zi S., Physics of Semiconductor Devices. Moscow, Mir, 1984.
6. Busta H. H. and Waggener H. A., Journal of Electrochemical Society **124** (9), 1424–1429 (1977).

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