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Microdefects influence on leakage currents and noise of silicon photodiodes

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Microdefects causing leakage currents and noise in the p^+-n junctions of silicon photodiodes were investigated. It was established that the tunnel component of dark currents is caused by local defects in the oxide and impurity precipitates in the space charge region of the $p-n$ junction. The tunnel currents leads to the generation of noise with a wide spectrum, including "burst" noise.

Keywords: silicon photodiode, microdefects, tunnel currents, current-voltage characteristics.

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Introduction

One of the main requirements for photodiodes (PhDs) used in photoreceiving devices is a low noise level, which requires reducing dark currents and excluding excess noise in the low-frequency range.

The manufacturing cycle of silicon photodiodes includes a number of thermal operations (oxidation, boron and phosphorus diffusion, low-temperature annealing), during which the samples are contaminated with metal impurities, and local defects form in the oxide, as well as oxygen and impurity precipitates in the silicon bulk. [1–3]. The specified defects can lead to the formation of local n^+ -channels in p^+-n junctions and defects on the silicon surface and in its bulk causing leakage currents – “soft” current-voltage characteristics [4], which results in an increase in photodiode noise, including low-frequency noise with a $1/f$ type spectrum.

The study [5] established that the reason for “soft” current-voltage characteristics is the

occurrence of a tunnel current in the strong electric field of local defects.

1. Experiment

Photosensitive elements (PSEs) with a pad size of $1.4 \times 1.4 \text{ mm}^2$ were manufactured on n -type monocrystalline silicon (Cz-Si) wafers with a diameter of 100 mm, a resistivity of 4–5 $\Omega \cdot \text{cm}$ and a (100) orientation without swirl defects.

The manufacturing process cycle of manufacturing included oxidation in $\text{H}_2\text{O} + \text{HCl}$ vapors, photolithography, the pre-deposition (precipitation) of boron from boron nitride (BN) sources, boron and phosphorus diffusion (drive-in) in different modes.

The concentration and distribution of local defects across the wafers with the fabricated PSE were analyzed using selective etching and an optical microscopy, and the distribution of the charge carrier lifetime was also determined. The current-voltage characteristics of the PSEs were

measured on the manufactured samples in the range of reverse voltages from 0.01 V to 90 V, and the noise was measured in the frequency range from 10 to 12.000 Hz.

2. Results

2.1 Current-voltage characteristics

Since the defects of the oxide layers [2] seen in an optical microscope have a different diameters (5–10 μm) and depths, not all of them are electrically active, which makes it difficult to compare the spatial distributions of PSEs with a “soft” IVC and defects on the wafer. Only a qualitative relationship was observed between the spatial distributions of such as PSEs and the defect density.

Therefore, to find the dependence of tunnel currents on the oxide defect density, the distribution of the threshold voltage U_t was

determined for PSEs with a different number of observed defects (N) (Fig. 1) through an array of 350 PSEs. The threshold value was taken as the value at which the dark current I_d exceeded 10^{-7} A.

The observed correlation of N and the U_t value confirms the relationship between them.

At the same time, the comparison of the spatial distributions of dark currents at voltages of 0.01, 1, and 5 V shows the existence of areas in which a correlation is observed between tunnel currents and currents at low voltages (Fig. 2). This relationship is confirmed by an increase in the proportion of PSEs with a dark current $I_d < 10^{-11}$ A at 0.01 V among elements with a high threshold value (Fig. 3).

The qualitative correlation between the values of N , U_t and I_d shows the relationship between them and, respectively, between the number of defects N and the value of the dark current I_d .

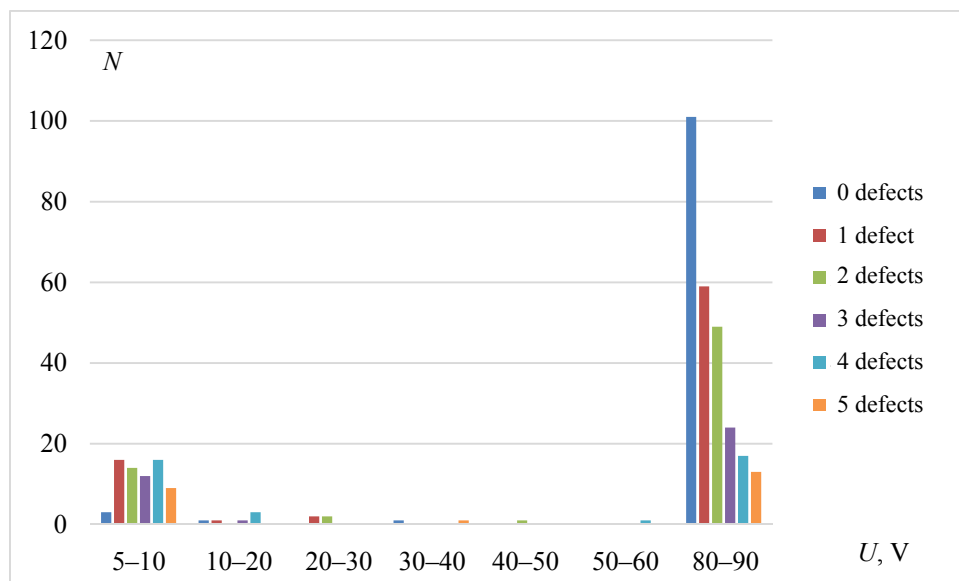


Fig. 1. Histogram of PSE distribution by the threshold voltage value for a different number of defects on one element

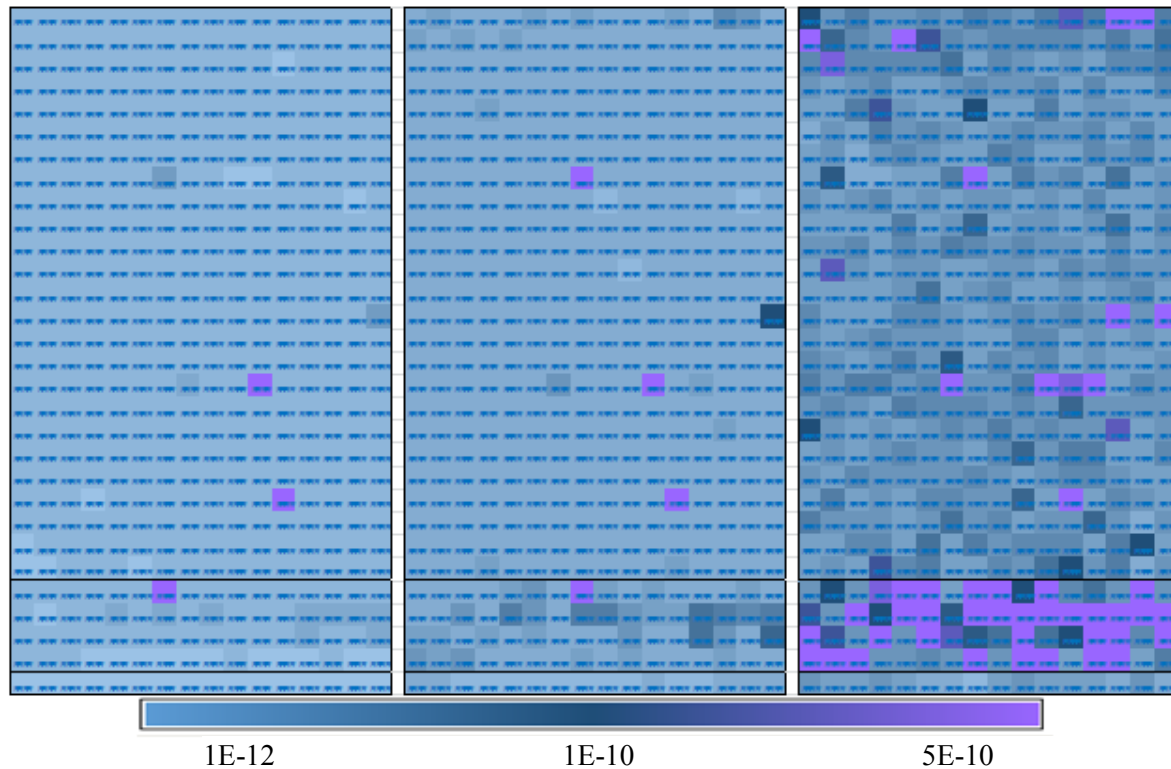


Fig. 2. Distribution of dark currents over the wafer area at voltages of 0.01 V, 1 V, and 5 V.

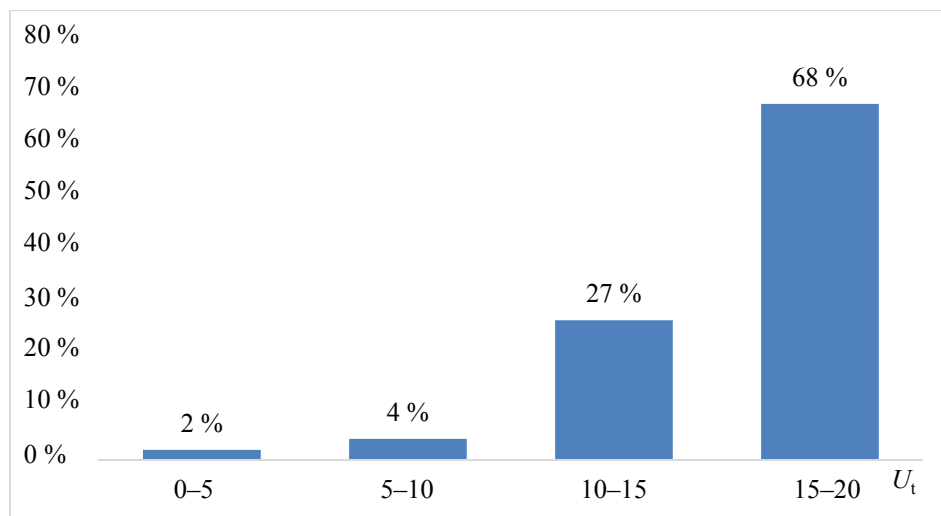


Fig. 3. Dependence of the PSE proportion with a current $I_d < 10^{-11}$ A on the threshold value

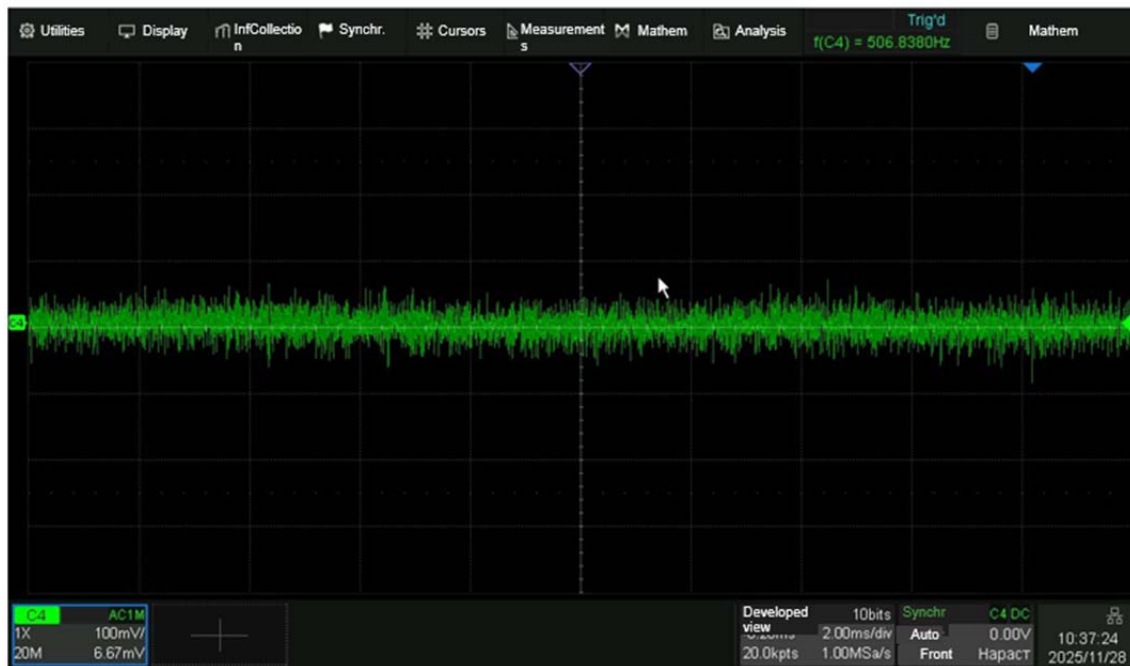
2.2. Noise

Measurements of noise and noise spectral density in the frequency band 100–12000 Hz at various reverse voltages were carried out on PSEs with a “soft” IVC. Fig. 4 shows the oscillograms of the noise voltage at bias voltages of 1 V (a) and 10 V (b). At a voltage of 10 V, which corresponds to the area of exponential growth of the tunnel current, a large number of noise

emissions with an amplitude of up to 400 mV were observed against the background of a noise track with an amplitude of up to 50 mV. At the same time, a section of the oscillogram with two states characteristic of “explosive” (random telegraph) noise was observed in some PSEs [5, 6].

Fig. 5 shows the corresponding frequency dependences of the spectral noise density at

voltages of 1 V (a) and 10 V (b), showing a sharp increase in the noise spectral density at a voltage of 10 V, which is especially significant at a frequency of 1 kHz.



a)

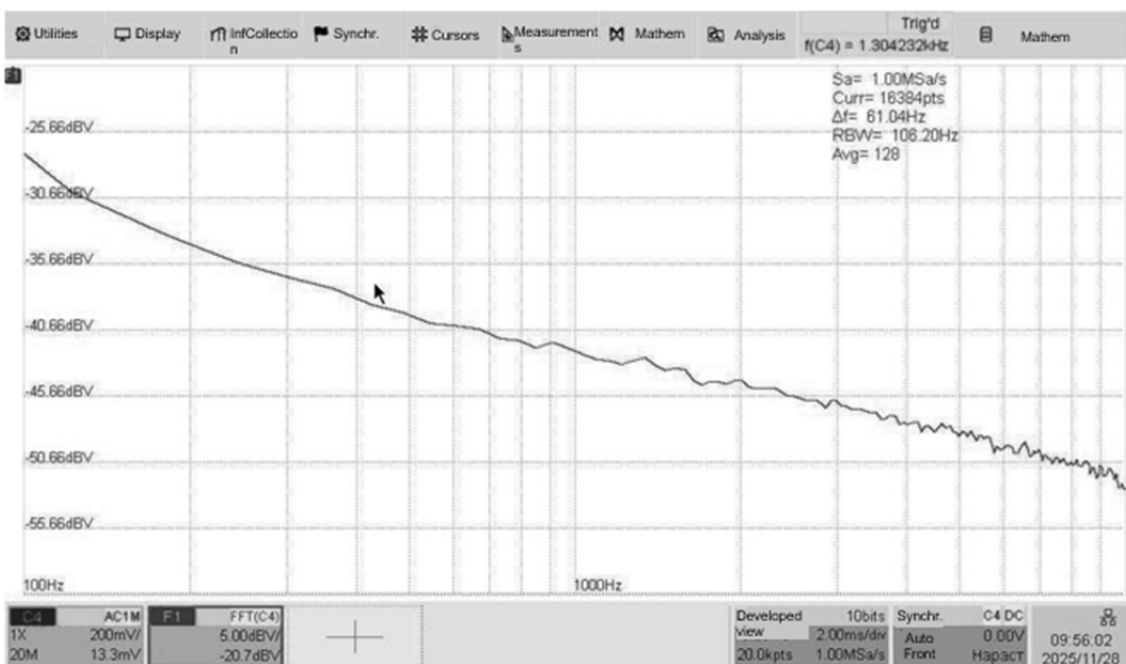


b)

Fig. 4. Noise voltage oscillograms at voltages of 1 V and 10 V



a)



b)

Fig. 5. Dependence of the spectral noise density on frequency at voltages of 1 and 10 V

Discussion of the results

Studies [3, 7] established the influence of oxygen precipitates on the lifetime of charge carriers in silicon, as well as on the dark currents and photosensitivity of photodiodes made on silicon with a circular distribution of oxygen concentration over the wafer area [8].

In this work, silicon without swirl defects was used, with a more uniform distribution of

oxygen, which resulted in a more uniform distribution of the charge carrier lifetime (range of 10-12%) and microdefects (etching pits) over the wafer area and, respectively, a random distribution of PSEs with a “soft” IVC.

Since the distribution of PSEs with “soft” characteristics over the area of the wafers is random, the reason for their occurrence may be local defects, such as defects in the oxide and on the silicon surface formed by phosphorus

diffusion [2]. The location of defects causing tunnel currents near the surface is confirmed by the fact that in the considered range of reverse voltages, the width of the space charge region of the p^+-n junction with a high field strength does not exceed 5–7 microns. Deep defects of the specified type may lead to a tunnel breakdown of parasitic p^+-n^+ junctions due to a high concentration of alloying admixtures, as well as the formation of local defects on the silicon surface containing impurities of oxygen, carbon, and heavy metals (impurity precipitates). A tunnel breakdown of p^+-n^+ junctions results in an IVC with a sharp breakdown at voltages of 6–7 V.

Consequently, an important task is to reduce the density of oxide defects, which is achieved by optimizing the phosphorous diffusion modes and improving of the quality of the oxide formed before diffusion [1, 2].

Another reason for the occurrence of tunnel currents can be impurity precipitates, including oxygen ones, in the space charge region of $p-n$ junctions [9, 10], resulting in a “soft” IVC with increasing currents at voltages exceeding 10 V. By selecting the optimal modes of the gettering operation, leading to the removal of heavy metal impurities from silicon, including from impurity precipitates, it is possible to significantly reduce the number of PSEs with such characteristics.

Repeated impurity gettering on wafers containing PSEs with “soft” characteristics also leads to a reduction in the number of such elements.

The dependence of the spectral noise density on the value of the reverse voltage at 1 V and 10 V at frequencies of 100 Hz and 1 kHz shows a significantly weaker dependence on the current for low-frequency noise, which may indicate different noise generation mechanisms: at low frequencies, the $1/f$ type prevails, caused the trapping of the surface states at the Si-SiO₂ boundary, while at high frequencies “explosive” (RTN) noise, having a wide range, dominates. Since there are known works [11, 12], linking the occurrence of RTN in $p-n$ junctions with the modulation of the current flowing through impurity precipitates, these data can also confirm the model of tunnel current generation in the precipitate electric field.

The expression for the electric field in the area of the precipitate can be written as follows [9]:

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

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

Using the experimentally obtained values of the coefficient $\beta = 100$ –200 for different samples, it is possible to estimate the shape of the defects. Large values of β indicate that the defect is elongated along the applied field. This allows the defect’s electric field to be analyzed using the potential solution for a conducting prolate hemispheroid (with semi-axes c and b) oriented along a uniform electric field E_0 [13]. The expression for the electric field on the surface of the hemispheroid in the direction of the major axis is written as follows:

$$E = E_0 \frac{1}{\left(\frac{1}{2} \ln \frac{\eta_0 + 1}{\eta_0 - 1} - 1 \right) (\eta_0^2 - 1)}, \quad (2)$$

where $\eta_0 = c / (c^2 - b^2)^{1/2}$, and E_0 is the field of the space charge region of the $p-n$ junction.

From expression (2) and the given values of β we obtain the ratio of the semi-axes $c/b = 10$ –20. Assuming b to be half the diameter of the defect and using $b = 200$ –300 Å [2], we obtain the defect size in the field direction to be 0.2–0.6 μm . A variation of c/b values results in a corresponding variation in the values of threshold voltages of the tunnel current.

Thus, another reason for “soft” VAC and increased PSE noise is elongated impurity precipitates in the space charge region of the junction, for the removal of which it is necessary to use optimal modes of gettering metal impurities.

Conclusions

1. The current-voltage characteristics of silicon photodiodes with leakage currents are determined by the presence of a tunnel component of the current. The value of the dark current at low voltages (0.01 V) depends on the

voltage at the start of the sharp increase in the tunnel current (threshold voltage).

2. There is a correlation between the threshold voltage, the value of the dark current, and the number of oxide defects.

3. The presence of tunnel currents results in different type of noise. In some cases, “burst” (random telegraph) noise is observed at high tunnel currents.

4. The cause of the tunnel currents is local defects with a small area in the oxide, which results in the formation of parasitic p^+-n^+ -junctions, and impurity precipitates in the space charge region of the $p-n$ -junction that are elongated in the direction of the electric field.

5. An improvement of dielectric quality and the use of optimal impurity gettering lead to a sharp decrease in the number of photosensitive elements with a tunnel currents.

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