Electrical characteristics of silicon differential photoreceivers

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Abstract. The volt-ampere curve of silicon differential photodiodes were measured. It was found that the current-voltage curve of the photodiodes of the main and additional channels had a similar shape, without revealing a significant dependence on the implantation dose of the additional channel. The main parameters of the equivalent circuits of photodiodes are determined. In the reverse branch, the dominant impact was exerted by the surface leakage conductivity with a differential resistance of about 10 GΩ. Measurements from minus 60 °C to 60 °C showed that when using amplifiers with an input impedance of about 10³ Ω, differential photoreceivers can be successfully used as selective short-wavelength and two-color ones.

1. Introduction
Silicon-based photoreceivers are widely used in optoelectronics. This is due to the highly developed and low-cost technology of silicon devices, as well as the ability of the material to efficiently record optical radiation in a wide spectral range from ultraviolet to infrared radiation. However, for the practical use of photoreceivers, it is often necessary to form the sensitivity in a certain, relatively narrow, spectral range. If it is necessary to provide spectral sensitivity only in the short-wavelength region of the spectrum, differential photoreceivers can be successfully used [1, 2]. The method of forming the spectral sensitivity of such photoreceivers is carried out by subtracting signals from nearby sensitive areas with different spectral characteristics. One of the channels should have a wide spectral range, while the second channel should have no sensitivity in some part of this range. Then the difference between the signals makes it possible to provide the photoreceiver with selective sensitivity in a narrow spectral range.

2. Photoreceivers structure and experimental technique
One of the channels to ensure high sensitivity in the UV region was formed by a shallow p-n junction obtained by phosphorus diffusion. The second channel was formed simultaneously with the first, on the same plate, using general technological operations, but with the addition of a high dose of arsenic at the final stage of the implantation process. This technique made it possible to create additional recombination centers in the near-surface region of the second channel and to reduce the sensitivity of the photodiode in the UV region. At the same time, the identity of deep layers provided similar spectral sensitivity in the long-wavelength region, where the processes of collection of photocarriers were determined by regions remote from the surface. The use of a differential amplifier made it possible to record only the short-wave, mainly UV part of the spectrum.
The most important requirement for differential photoreceivers is the identity of the electrical characteristics of the main and additional channels. In this regard, it seems relevant to study and compare the current-voltage characteristics of two channels of photoreceivers.

The volt-ampere characteristics were measured using the Agilent B1500A installation, which records voltages in the range from 0 to 200 V with an accuracy of 100 μV and currents ranging from 1 nA to 1 A with an accuracy of 50 fA. For temperature measurements, Microxact SPS-2800-TC probe installation was used, which allows setting the operating temperature in the range from minus 60°C to plus 200 °C, with an accuracy of maintaining 0.01 °C.

3. Results
The volt-ampere characteristics of the main and additional channels of a number of differential photodiodes differing in the dose of arsenic implantation were measured. For each technological series, the volt-ampere characteristics of the photodiodes of the main channel (1) and additional channel (2) had a similar form, without revealing a significant dependence on the doping dose of the additional channel. As an example, Figure 1 shows the direct branches of the volt-ampere characteristics in the region of low currents. As you can see, at voltages up to 0.5 U, an exponential dependence was observed, corresponding to the generally accepted form [3]

\[ I = I_0 \exp \left( \frac{eU}{\beta kT} \right) - 1 \]

with values of \( I_0 = 1.10^{-11} \) A, \( \beta = 1.11 \).

![Figure 1](image-url)  
**Figure 1.** Direct branches of volt-ampere characteristics in the region of low currents. 1 – main channel, 2 – additional channel.

The proximity of the dimensionless coefficient \( \beta \) to unity is usually associated with the dominant character of the injection current. As can be seen from the Figure 1, at low voltages, both the main and
additional channels had practically the same shape of the volt-ampere characteristics. At high voltages, the series residual resistance of the diodes began to affect, and the volt-ampere characteristic reached the linear section. For some samples in the region of high currents, there was a slight difference in the values of the residual resistance (Figure 2).

Sample 32-4 (500 µC / cm²)

**Figure 2.** Direct branches of volt-ampere characteristics in the area of big currents. 1 – main channel, 2 – additional channel.

Sample 34-4 (5000 µC / cm²)

**Figure 3.** Direct branches of the volt-ampere characteristics in the region of high currents for a sample with a high doping dose of the additional channel. 1 – main channel, 2 – additional channel.
So for the given example, the differential resistances were: \( R_1 = 9.4 \, \Omega \), \( R_2 = 11.2 \, \Omega \). We associate the observed discrepancy with the unequal value of the contact resistance due to the possible difference in the surface concentration of the near-contact layers. For a differential photoreceiver, as noted, it is desirable to have completely identical characteristics of both channels. However, it should be taken into account that the mode with zero, or small negative voltages at the p-n junction is preferable for the photodiode operation. In this case, the observed difference at large positive voltages is not significant. For samples of another technological series (No. 34), in the forward branch, almost complete coincidence of the volt-ampere characteristic was observed in the entire observed region, up to currents of the order of 100 mA (Figure 3). The residual resistance was \( R_1 = R_2 = 12.7 \, \Omega \). The dimensionless coefficient for this sample had a slightly larger value \( \beta = 1.33 – 1.45 \), which can be associated with more significant contribution of the recombination component of the current. Typical reverse current versus voltage dependences are shown in Figure 4.

![Figure 4. Reverse branches of volt-ampere characteristics. 1 – main channel, 2 – additional channel.](image)

The characteristics of the main and additional channels were similar, but slightly different numerically. As can be seen from the data obtained, the reverse current did not experience saturation. The currents at low voltages significantly exceeded the values of \( I_0 \approx 10 \, pA \) (at \( U = 1.9 \, V \) and \( I_1 = 117 \, pA \), \( I_2 = 206 \, pA \)). This could indicate the presence of excess currents. The diode current at small biases can be represented as the sum of a number of terms:

\[
I(U) = I_d(U) + I_{gr}(U) + G_s U.
\]

Here: \( I_d \), \( I_{gr} \) diffuse and generation-recombination components of the diode current; \( G_s \) – leakage conductivity. Although V. Stafeev in [4] showed that the additivity of ideal diode current and leakage current is not strictly fulfilled, nevertheless, the above formula can be useful as giving a certain approximation to the actual processes occurring in a semiconductor device. Then, taking into account the ohmic nature of the change current in the initial section, we can assume the dominant influence of the surface leakage conductivity. For a quantitative characterization, it is useful to estimate the surface leakage resistance, which for the sample under consideration was: \( R_{d1} = 16.10^9 \, \Omega \) and \( R_{d2} = 9.910^9 \, \Omega \). Usually, the resistance for the main channel was somewhat larger than the resistance of the additional
(ion-doped) channel. The volt-ampere characteristics for a number of other samples of technological series 32 and 34 are given in the table 1.

| Sample number | Dose, As µC/cm² | Channel | $R_{ph}$, Ω | $I_{rev}$, (U=1.9 V), pA | $R_s$, GΩ | β |
|---------------|-----------------|---------|-------------|---------------------------|----------|---|
| 32-1          | 200             | 1       | 9.95        | 123                       | 16.7     | 1.02 |
|               |                 | 2       | 12.4        | 141                       | 15.0     |     |
| 32-2          | 300             | 1       | 8.2         | 146                       | 10.3     | 1.14 |
|               |                 | 2       | 11.5        | 222                       | 7.6      |     |
| 32-3          | 400             | 1       | 9.9         | 98                        | 13.6     | 1.04 |
|               |                 | 2       | 11.2        | 152                       | 12.7     |     |
| 32-4          | 500             | 1       | 9.4         | 117                       | 18       | 1.11 |
|               |                 | 2       | 11.4        | 206                       | 8.2      |     |
| 32-5          | 700             | 1       | 8.8         | 92                        | 16.0     | 1.09 |
|               |                 | 2       | 11.2        | 376                       | 5.5      |     |
| 32-6          | 1000            | 1       | 29.7        | 190                       | 10.5     | 1.1  |
|               |                 | 2       | 41.3        | 259                       | 6.9      |     |
| 34-1          | 2000            | 1       | 12.2        | 152                       | 14.2     | 1.45 |
|               |                 | 2       | 12.2        | 232                       | 6.2      |     |
| 34-4          | 5000            | 1       | 12.7        | 145                       | 12.1     | 1.33 |
|               |                 | 2       | 12.7        | 256                       | 7.2      |     |

The temperature dependences of the characteristics of devices are of great practical importance. For photodetectors, the most popular are the reverse branches of the volt-ampere characteristic. Figure 5 shows the volt-ampere characteristics measured for sample 32-4 in the temperature range from minus 60 °C to plus 60 °C. As you can see, at voltage of about 3 V, regardless of the temperature, the pattern of increasing the current changed. At low voltages, the dependence is close to linear, and then the characteristic entered a plateau section.

Analysis of the temperature change in the reverse current both in the first, ohmic section (at a voltage of 1 V) and in the second, flat section (at voltage over 3 V) led to similar dependences of the form:

$$I = I_0 \exp\left(-\frac{\Delta E}{kT}\right)$$

The activation energies had a close value $\Delta E = 0.61$ eV, and the values of the pre-exponential factors were $I_0 = 6.7$ A for $U = 1$ V and $I_0 = 24$ A for $U = 4$ V (Figure 6).
Figure 5. Reverse branches volt-ampere characteristics at different temperatures. Sample 32-4, dose 500 µC/cm², main channel.

Figure 6. Temperature dependences of reverse current at voltages: 1 V (1), 4 V (2).
A convenient characteristic in relation to the ohmic section may be the value of the differential resistance. Figure 7 shows as an example the temperature dependence of the differential resistance for one of the samples. The result can be described by dependency:

\[ R = R_0 \exp \left( \frac{\Delta E}{kT} \right) \]

The activation energy was \( \Delta E = 0.55 \) eV, \( R_0 = 0.62 \) Ом.

**Figure 7.** Differential resistance versus temperature. Sample 32-4, dose 500 \( \mu \)C/cm\(^2\), main channel.

### 4. Conclusion

The results obtained in this work make it possible to compose mathematical models of the electrical characteristics of the main and additional channels of differential photoreceiver, which are necessary for the practical use of devices. The measured values of the differential resistances showed some difference for different channels. However, their absolute values were many orders of magnitude higher than the dynamic resistance of the input stages of the preamplifiers \( R_{in} \approx 10^3 \) Ω in the entire investigated temperature range, which makes it possible to reliably record and compare the photocurrents of the main and additional channels.

Thus, differential photoreceiver can be successfully used both selective and two-color in a wide range of operating temperatures.

### References

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