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Nonlinearity of Diffusion Resistors at High-density Current

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The paper presents the results of an experimental study of the current dependence of the resistance of diffusion resistors (DR) produced by the "silicon with dielectric insulation" technology, with different geometric characteristics, in particular, length and thickness, with a current density of 10^5 A/cm^2. The analysis of the obtained results is carried out and three areas on the dependence of resistance on current $R(I)$ are determined. The first region is an ohmic plot, on which the resistance value of the diffusion resistor is linearly dependent on the current value. The second region of the curve $R(I)$ is characterized by the presence of strong nonlinearity, jumps and a sharp increase in the resistance of the DR, which happen due to the emergence of a high electric field in the DR. The third region on $R(I)$ is characterized by a decrease in the value of the current resistance: the thicker the DR, the lower the peak value of the resistance. It is shown that the change in the length and the decrease in the thickness of the diffusion resistors lead to a change in the length of the linear region on $R(I)$: the smaller the length, the lower the resistance of the sample and the longer the area of stable differential resistance. The region of the linearity of the diffusion resistor is determined on the basis of the differential resistance on the current dependence. The linearity of the resistance was defined as the region where the change in the differential resistance did not exceed 10 % of its value at some small electric field: the largest region of the linearity of the resistor is present in a specimen with a length of 2.4 μm and a thickness of 8.4 μm. The revealed characteristics of the behavior of the resistance of the diffusion resistor are due to the change in its physical characteristics as a result of significant self-heating.

Keywords: Diffusion resistor, Resistance, Nonlinearity, Self-heating.

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1. INTRODUCTION

Diffusion resistors are the most common type of resistors in semiconductor integrated circuits (ICs). They are manufactured in a single technological process with the base or emitter. The resistance of a diffusion resistor (DR) is the volume resistance determined by the thickness of a diffusion layer. It is determined by the geometrical dimensions of a resistive layer, which in turn is characterized by specific surface resistance ρ_S [ohm/square]. ρ_S is a constructive parameter of a DR that depends on technological factors (diffusion regimes). When creating ICs, the parameters of diffusion layers are optimized in order to obtain the best characteristics of *n-p-n*-type or *p-n-p*-type transistors. This explains why the parameters of the DR are improved not by varying technological regimes, but by matching the configuration and geometry of the DR. Phenomena associated with self-heating caused by the high-density current flowing through the DR are therefore investigated to determine limiting regimes for the operation of the DR depending on the geometrical parameters. At the same time, nonlinear phenomena in the DR are of interest when developing elements for functional electronics, considering the surface condition of the passivating dielectric layer. Quite a number of studies are devoted to the development of mathematical models for calculating the self-heating in semiconductor devices and the application of these models in computer simulation systems. However, systematic experimental studies of this phenomenon, particularly non-linear effects under extreme conditions, are only at the initial stage. In this work, we present the results of experimental investigations of the nonlinear behavior of resistance and the effects revealed in DRs at high density current.

2. EXPERIMENTAL

2.1 Work Motivation

For low-resistance resistors (tens of ohms), the shape and size of contacts were chosen in such a way that the resistance of the adjacent section was much lower than the resistance of the active zone of the DR.

DRs with a resistance from several hundred ohms to kiloohms have a one-strip design and the width of the adjacent area is equal to the width of the resistor. High-resistance resistors (60 kiloohms) have a meander shape (like snakes). The length of one-strip DRs does not exceed the active zone dimensions (0.5-1 mm) of the crystal. The width is limited by the window's minimal width under diffusion determined by photolithography properties (2.5-3 nm) and by lateral diffusion. Typical resistance values for DRs, which can be obtained for the given specific surface resistance ρ_S, are in the range of $4\,\rho_S < R < 10^4\rho_S$. The low boundary is limited by the resistance of adjacent area; the top boundary is limited by the available area for the DR.

The maximum resistance of a DR is about 60 kiloohms if the area destined for the resistor is not very large (up to 15 % of the crystal). The reproducibility of nominal values of the resistance is as a rule 15-20 % and depends on the resistor's width. Deviations from nominal values for resistors located in one crystal are caused by technological inaccuracies, they have the same sign, and, as a result, the ratio of resistances remains highly accurate.

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For the same reason, the temperature coefficient (TCR) of their ratio is small compared to the TCR for one resistor [(1.5-3) × 10^{-4} 1/°C]. This feature of DRs is taken into account when designing semiconductor ICs.

Field-emitter resistors of small nominal (3-100 ohms with TCR = (1-2) × 10^{-4} 1/°C) are formed using appropriate doping and diffusion conditions. The isolation of individual elements in an IC can be realized by a *p-n* junction or a dielectric layer in the structure manufactured by “silicon with dielectric isolation” (SDI) technology. Diffusion resistors, like other resistive elements, are characterized by the following parameters: value range of nominal resistances, permissible deviation of resistance, TCR, appropriate power dissipation and maximum applied voltage [1]. It is also important to take into account the maximum heat dissipation when developing DRs. The excessive dissipated power, which is caused by the self-heating of a DR during operation, leads to nonlinear *I-V* dependence because the resistance of a DR depends largely on temperature. Therefore, this requires the use of relatively wide diffusion strips in ICs, which allows to dissipate the higher power. It should be noted that the limit value of the dissipative ability depends on the dissipative properties of the heat-radiating elements of the structure which are sealed in semiconductor ICs [1].

The size of ICs is reduced significantly by the microminiaturization of all components in ICs. However, the value of the flowing current remains the same. This leads to an increase in current density. Therefore, the investigations of DRs at high densities of flowing currents are relevant and interesting for developers of IC elements. The purpose of this work is to investigate the resistance of DRs of various sizes as a function of the voltage at high current densities.

The significant nonlinearity of the resistance of SDI structures suggests the possibility of using them as a basis to create highly sensitive sensors, where a surface potential changes as a result of interaction with analyte gas molecules or a liquid medium. The presence of a neutral oxide layer on the surface protects DRs against a potentially aggressive external environment, while at the same time facilitating the transfer of the surface potential to the volume of the semiconductor. Local self-heating can be limited in space by scaling and in time by the application of a pulsed mode of operation. The sensitivity of the SDI current structure to the charge state of the surface may be realized by a change in the spatial distribution of the thermal fields in a semiconductor under the influence of the redistribution of the surface potential.

2.2 Materials and Methods

The DRs manufactured by SDI-based technology [2] were taken as experimental samples (see Fig. 1). SDI technology allowed a bridge to be created from the monocrystalline silicon in a “pocket” from a dielectric SiO_2 layer placed in a matrix of polycrystalline silicon, as shown in Fig. 1. Current was supplied through an n^+-n-n^+ structure with metallic contacts to n^+ areas. The area of energy release (10^{-7}-10^{-6} cm^2) between the contacting areas of metallization was part of the semiconductor and it was covered with a silicon dioxide layer. The main parameter characterizing this area is the ohmic resistance $R = V / I$, where V is the bias voltage, I is the current flowing through the DR. The value of R for various SDI structures changes from a few ohms to tens of ohms and is determined by SDI structure geometry: the length L, width W and thickness H_1.

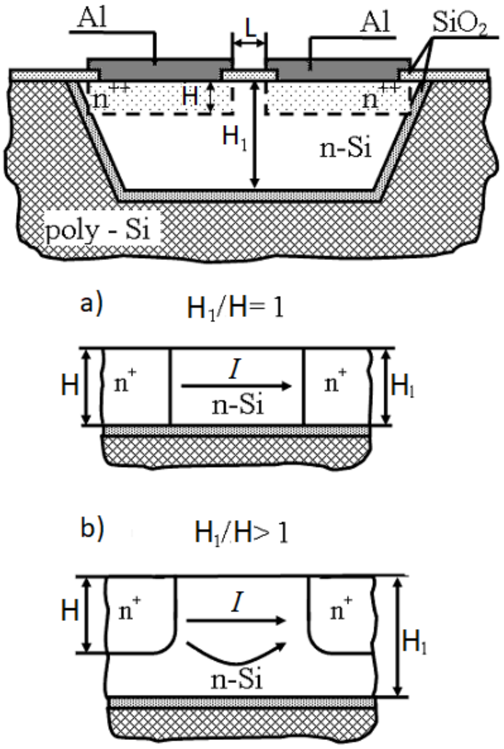

Fig. 1 – General view of DR design produced on the basis of SDI technology: a – parallel current flow, b – non-parallel current flow. L is the geometric length of n channel (distance between the edges of windows in the oxide). H_1 is the "pocket" depth. H is the sub-alloying depth. Sample parameters: H = 5 μm, H_1 = 2.8 μm to 10.5 μm, area is equal to 10^{-7} cm^2 to 10^{-6} cm^2, volume is equal to 10^{-11} cm^3 to 10^{-9} cm^3, L = 2.4; 5.6 and 8 μm

DRs were separated from the substrate by a SiO_2 layer (2.5 μm thick). The n area in the “pocket” was fabricated from monocrystalline silicon with n-type conductivity and a resistivity of ρ = 1.0 ohm × cm. However, because of technological processes, the resistivity decreased to ρ = 0.7 ohm × cm, which corresponds to the impurity concentration $n = 6.4 \times 10^{15}$ cm^{-3}. The n^+ areas were obtained by the thermal diffusion of phosphorus into “pockets” to a depth of H = 5 μm. The resistance ρs of these areas was 1.4 ohm/square, which corresponds to the concentration of impurities of $n^+ = 11 \times 10^{19}$ cm^{-3}. This led to sub-alloying under the oxide edge to the depth of 2.8 μm. Characteristics of investigated samples are given in Table 1. Here, V_{max} is the maximum voltage applied to the sample during the measurements, and I_{max} is the maximum current flowing through the sample.

During the measurements, a constant current mode was used at each point.

3. EXPERIMENTAL RESULTS

Fig. 2 shows the dependences of resistance versus current for DRs of different lengths (L = 2.4; 5.6 and

8.0 μm) and 9.8 μm thick. These samples (N2, N3, N4 structures, respectively) satisfy the ratio $H_1/H = 1.97$. Fig. 3 shows the resistance dependence on the current for DRs of different thicknesses ($H_1 = 8.4$; 9.8 and 11.9 μm) and $L = 8$ μm. For these samples (N5, N6, N7 structures), the ratio H_1/H is 1.68; 1.97; 2.38, respectively. Three sections can be distinguished in the *R-I* curves presented in these figures.

Table 1 – Characteristics of samples investigated

Sample	Thickness H_1 [μm]	Length L [μm]	I_{max} [A]	V_{max} [V]	R [Ohm]
N2	9.8	2.4	0.36	4.06	5.85
N3	9.8	5.6	0.35	4.37	6.70
N4	9.8	8.0	0.27	4.07	9.35
N5	8.4	8.0	0.30	3.93	14.27
N6	9.8	8.0	0.27	4.07	9.63
N7	11.9	8.0	0.20	4.06	11.31

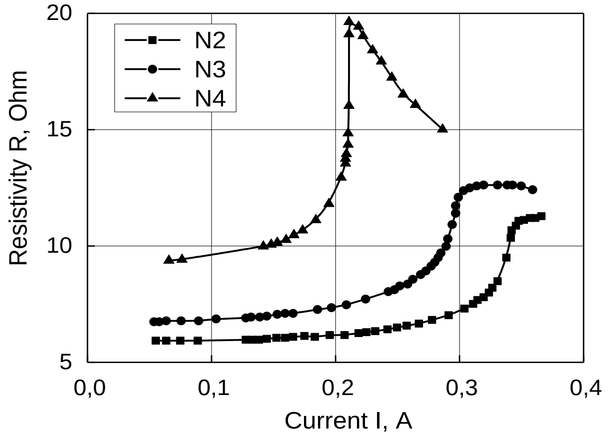

Fig. 2 – The resistance dependence on current in structures N2, N3, N4 with the thickness $H_1 = 9.8$ μm and different lengths $L = 2.4$; 5.6 and 8.0 μm, respectively

In the first section, the resistance of the samples is only slightly dependent on the current. The change in the length L of the DRs leads to changes in the resistance and the extent of the linear section. The smaller the length L, the lower the resistance of the sample and the longer the linear section of *R-I* curves.

R-I dependences of samples with the same length obtained for different thicknesses (see Fig. 3) demonstrate that the linear section length increases monotonically with increasing thickness of DR. However, the resistance in this section of the curves behaves more complexly. The minimum resistance was found for a sample with an intermediate thickness ($H_1 = 9.8$ μm), while a sample with minimum thickness ($H_1 = 9.8$ μm) showed the maximum resistance. This corresponds to simple geometric considerations. Perhaps the described anomalous behavior of the DR resistance may be explained by the different influence of heat sink conditions:

$$R = \rho_S \times L/W, \qquad (1)$$

where W is the width of the resistor, and ρ_S decreases with increasing thickness H_1 according to the law determined by the doping profile of the DR structure.

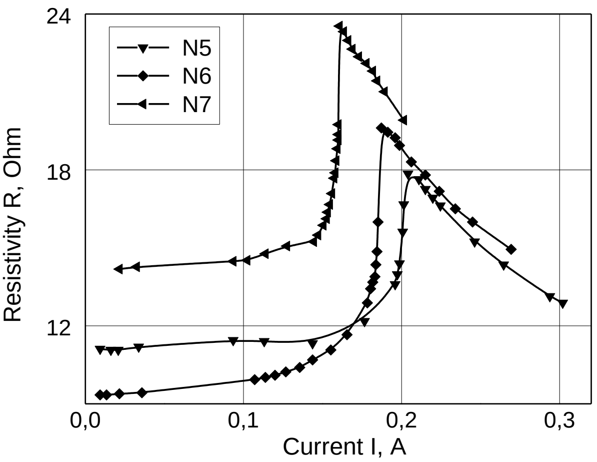

Fig. 3 – The resistance dependence on current in structures N5, N6, N7 with $L = 8$ μm and different thicknesses $H_1 = 11.9$; 9.8 and 8.4 μm, respectively

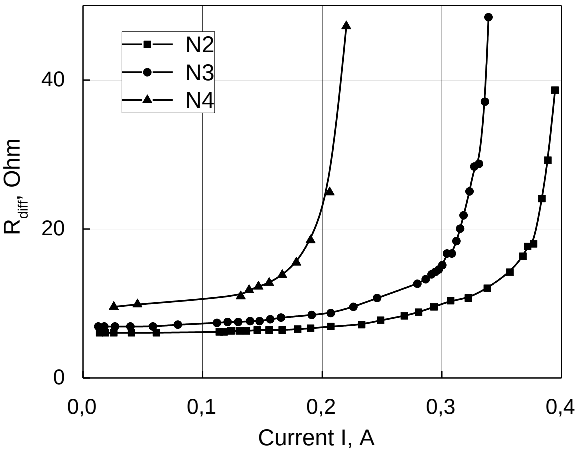

Fig. 4 – The differential resistance dependence on current in N2, N3, N4 structures with different lengths $L = 2.4$; 5.6 and 8 μm, respectively

The second section of the *R-I* curves is characterized by a strong superlinearity. When the sharp increase in resistance is observed, the current decreases with increasing length L and decreasing thickness H_1.

The third section of the *R-I* curve is characterized by cessation of growth and a reduction in the resistance of the samples with increasing current. There is a more significant decrease in resistance in samples of maximum length and in samples with a shorter length. The decrease in resistance is insignificant for sample N3 and completely absent for sample N2.

For a more detailed study of the features of the nonlinear behavior of the samples, the dependence of the differential resistance on the current was obtained in the section where their values are positive (Fig. 4 and Fig. 5).

For comparison, Fig. 6 shows the differential resistance R_{diff} of the measured samples from Fig. 4 and Fig. 5 normalized to $R_{diff}(0)$ corresponding to zero current. These values were determined by extrapolation. The linear section of the resistance was defined as the section where the change in the differential resistance did not exceed 20 % of the value in the vicinity of the zero current (dashed line in Fig. 6).

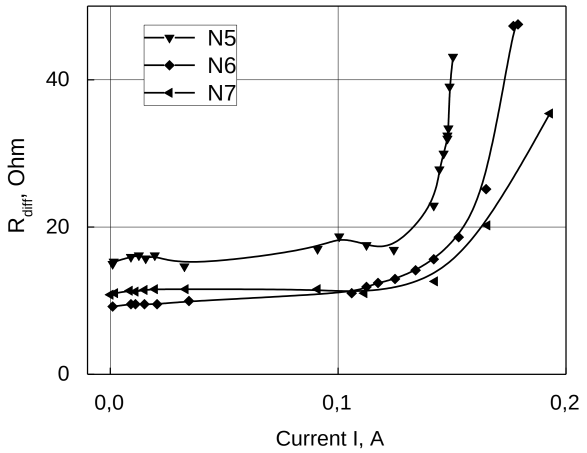

Fig. 5 – The differential resistance dependence on current in structures N5, N6, N7 with $L = 8$ μm and different thicknesses $H_1 = 11.9$; 9.8 and 8.4 μm, respectively

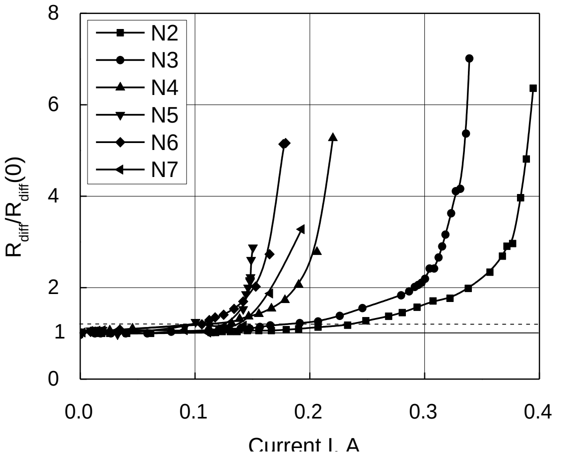

Fig. 6 – The normalized values of differential resistances as a function of current for all measured samples

As follows from Fig. 6, the most extended linear section in samples with short length: for sample N2 ($L = 2.4$ μm) nonlinearity starts at 0.24 A, and for sample N3 ($L = 5.6$ μm) – at 0.18 A. At the same time, samples of length 8.0 μm (N4-N7) show approximately the same extent of the linear section (up to 0.10-0.13 A) with a weak dependence on the thickness H_1.

4. DISCUSSION

The analysis of the results shows that the experimental values of DR resistance are about the same as the estimated values (within 10 % margin of error). According to the theoretical formula (1), an increase in the length and a reduction in the thickness lead to an increase in the DR resistance in the linear section. By measuring the DR resistance, we determined the resistivity and the concentration of charge carriers $n = 5 \times 10^{15}$ cm^{-3} [3].

In the first linear region of the *R-I* curve, the resistance was determined by the dopant concentration and mobility. The dependence on the longitudinal electric field is small and can therefore be neglected. The weak growth of resistance in this region can be explained by the weak dependence of the mobility on temperature $\mu \sim T^{-3/2}$ and by weak self-heating.

The second region of the *R-I* curve is associated with the appearance of a local high field in the DR [3]. This region is a thermal gradient drift domain (TGD domain) [4]. This domain is formed by inhomogeneous Joule self-heating combined with the presence of bipolar conductivity arising from the thermal generation of electron-hole pairs at a sufficiently high temperature. The temperature can be estimated using the method described in [5]). The results show that even at 0.1 A, self-heating causes the temperature to reach the value of 700 °C, which exceeds the intrinsic temperature for silicon with a doping level of $N = 5 \times 10^{15}$ cm^{-3} ($T_i = 350$ K) [1]. Under the same heat sink conditions, shorter and thinner samples are heated up less. This reflects that the shorter and thinner the DR is, the larger the linear section of the resistor. This was also registered in the experiment (see Fig. 6).

A further increase in current leads to an increase in the DR temperature and a transition to the third section, in which the voltage drop in the DR in some approximation does not depend on the current. This is due to the fact that self-heating to higher temperatures results in the filling of high-field space with carriers generated by the heat and in the destruction of the TGD domain. In Fig. 2 and Fig. 3, we can see that the DR resistance in this case begins to decrease almost linearly.

A subsequent increase in current causes the DR to heat up to a temperature where the breakdown current occurs between the contacts.

5. CONCLUSIONS

As a result of the work, the electrical parameters of "silicon structures with dielectric insulation" with different geometric characteristics were investigated and important parameters such as the size of the linear part of the *R*(*I*) curve were determined. The shorter and thinner the DR, the longer the region of the linearity of the curve *R*(*I*).

The nonlinear behavior of the *R*(*I*) dependence is revealed. The important parameters of the local effects of a strong electric field are determined. The shorter and thinner the DR, the wider the region of the linearity of the *R*(*I*) curves.

It was found that when the depth of pockets increases, their influence on the behavior of the *R*(*I*) curve gradually decreases and continues to disappear. The physical explanation of the revealed complex behavior of the *R*(*I*) dependence is proposed. It is shown that the detected effects are related to the formation of strong-field domains due to self-heating.

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Нелінійність дифузійних резисторів при струмі високої щільності

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У роботі представлено результати експериментального дослідження залежності опору дифузійних резисторів (ДР) від струму, виготовлених за технологією «кремній з діелектричною ізоляцією», з різними геометричними характеристиками, зокрема, довжиною та товщиною, при густині струму до 10^5 А/см^2. Проведено аналіз отриманих результатів і визначено три області на кривих залежності опору резистора від струму $R(I)$. Перша область – омічна ділянка, на якій значення опору дифузійного резистора лінійно залежить від струму. Друга область кривої $R(I)$ характеризується наявністю сильної нелінійності та стрибками і різким збільшенням опору ДР, що пов'язано із виникненням області високого електричного поля в ДР. Третя область залежності $R(I)$ характеризується зменшенням величини опору від струму. Чим товщим є ДР, тим менше пікове значення опору. Показано, що зміна довжини і зменшення товщини дифузійних резисторів призводять до зміни протяжності лінійної ділянки залежності $R(I)$. Чим менша довжина, тим менший опір зразка і тим довша ділянка сталого диференційного опору. Із залежності диференціального опору від струму визначено області лінійності опору дифузійного резистора. Область лінійності опору була визначена як область, де зміна диференціального опору не перевищувала 10 % від його значення при малому електричному полі: найбільша область лінійності резистора має місце в зразку довжиною 2.4 мкм та товщиною 8.4 мкм. Виявлені особливості поведінки опору дифузійного резистора пояснюються зміною його фізичних характеристик в результаті значного самонагрівання.

Ключові слова: Дифузійний резистор, Опір, Нелінійність, Самонагрівання.