Influence of Peripheral Effects on the Electro Physical Properties of Schottky Diodes

T. H. Ismayilov, A. R. Aslanova

Abstract* – In Cu-nSi Shottky diode (SD) with different diameters additional electric field (AEF) arising due to the limitation of the contact surface with free surfaces of the contacting materials significantly influence on its electrophysical properties. In SD at the active participation of AEF formed a effective potential barrier height. In SD at the active participation of AEF formed a effective potential barrier height. Forward and initial reverse I-V characteristics SD are determined by the current flowing through as periphery of contact surface as its rest surface and is well described by the thermionic emission theory, as in the idealized homogeneous SD. In a forward and primary reverse bias with increasing diameter SD of 6μm to 100 μm effective potential barrier height and the contact resistance increased, but the ideality factor and proportionality coefficient remain virtually unchanged. STM images SD and their I-V characteristics show that, the contribution of peripheral current to total current of SD increases with increasing reverse voltage. The second section of the reverse I-V characteristics SD, which consists only of peripheral current is represented by a straight line in a semi-logarithmic scale. The potential barrier height, a dimensionless coefficient, the contact resistance, the area and the width of the periphery of the contact surface different from that for of the first initial portion I-V characteristics SD.

***Index Terms* – contact metal – semiconductor, inhomogeneous Schottky barrier, peripheral current Schottky diode, additional electric field, semiconductor converters, limitation of contact surface.**

I. INTRODUCTION

Schottky diodes (SD) are widely used in modern electronic devices at the same time their properties are studied in detail. As a result of intensive research multifunction capabilities of real SD revealed all sorts of deviations of parameters and characteristics of the relevant data arising from the fundamental theories and energy models idealized SD [1]-[3]. Progress has been made in eliminating these shortcomings by constructive - technological methods. Numerous designs have been developed SD eliminating mainly negative influence of so-called edge effects [3]- [15]. In [4], was investigated the influence of the width of the metal film on the surface of the SiO_2 dielectric from the contact edge on the breakdown voltage Al-nSi SD with different diameters (20 - 130 μm) and width (5 - 50 μm) Al film from the periphery of the contact. It was found that with increasing width of the Al film from 5 μm to 15 μm, the breakdown voltage of SD increases from 50V to 90V, and a further increase in the width of the film breakdown voltage does not change. n [5] it is shown that SD structure in which the metal electrode has a conical form forming an angle of about 3^{o} with a surface of silicon, the breakdown voltage is increased from 30V to 130V compared to metal cylindrical mold. Of certain interest is the results presented in [6], wherein the breakdown voltage increases as the SD using mesa structures with lateral MOS isolation. In SD with different designs, due to the limitation of the contact surface with free surfaces of metals and semiconductors arise an additional electric field (AEF) [2], [16]- [23]. In [16], the results of direct measurements of AEF by atomic force microscopy (AFM) on the surface of Au - nGaAs SD c rectangular contact surface. It is shown that under the influence of AEF around the perimeter of the contact forms an extended region (aureole) with potential differing from the potential of the free surface of the nGaAs. Aureole width reaches about 30 μm along a straight metal edge due to the large contact area. This is well illustrated in [17], where it was shown that a decrease in the contact-diameter SD of from 100 μm to 5 μm width of the aureole decreases from 23 μm to 4 μm. The AFM images of relief of Au - nGaAs Shottky diodes with 50 μm in diameter where the single round contact of gold is precisely visible are presented in the Fig.1*a* . The AFM images of distribution of the contact potential difference (CPD) between an edge of a needle cantilever (probe) and surface Au - nGaAs Shottky diode with 50 μm in diameter are presented in Fig.1*b*. It is visible, that CPD on the metal is much less than CPD on free surface of nGaAs outside the contact. In the process of removing from the contact perimeter CPD value gradually increases from minimal, equal to CPD of metal surfaces, up to maximal, equal to the free surface CPD of the semiconductor. Thus, due to action of AEF around the round contacts is observed the transitive area (aureole) with difference width with CPD, distinct from CPD of a free surface of the semiconductor. In the narrow SD the AEF almost completely covers the near-contact region of the semiconductor and is actively involved in electronic processes. Was designed Au - nGaAs SD with AEF converter the light energy into electrical energy, where a light current is greater than the dark current more than 1000 times [18]. Meanwhile, in a similar SD without AEF the light current exceeds the dark current about 10 times. In [19], [20] found that the I-V characteristic of the Au-nGaAs SD with AEF have ideality factor close to unity and the reverse current in the SD is virtually absent at initial approximately 3-4 voltage.

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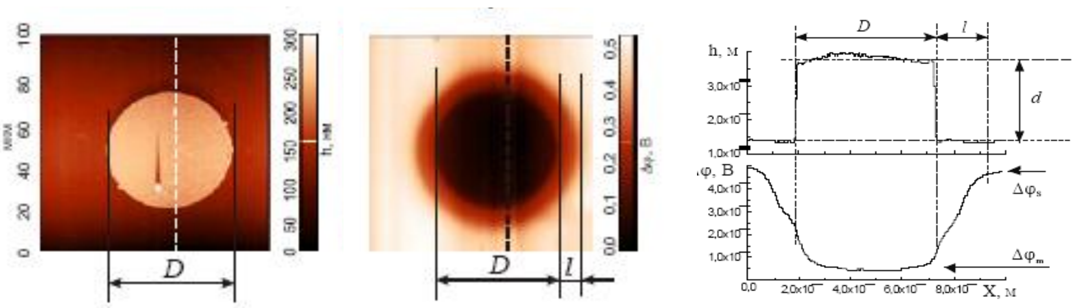
Prof. T. H. Ismayilov, Department of Physics, Baku State University, Azerbaijan.

Dr. A. R. Aslanova, Department of Physics, Baku State University, Azerbaijan.



a) **b)** **c)**

Fig. 1. Two-dimensional AFM topography image (*a*), the potential (*b*), the contour cross-section (*c*) of the space h (x) and the potential Δφ (x) surface of Au-nGaAs SD in diameter D=50 µm.

Was developed more perfect design Trench MOS Barrier Schottky diode (TMBS diode), in which AEF completely concentrated in the contact region of the semiconductor [7]-[15] , [23]-. Under the influence AEF the TMBS diode have low forward voltage, high speed switching, low leakage current at reverse bias and high breakdown voltage compared to conventional planar SD. In the a number of works [17], [24] was established certain correlation between the potential barrier height and the geometrical dimensions of the contact surface SD. In [17] show that in the SD form of a gold film on the surface of the n- and p-type GaAs, reducing the diameter of the contact leads to a decrease in the potential barrier height Au-nGaAs SD and increase of the same parameter for Au -pGaAs SD. In Al-nSi SD [24] found that when S> 100 mm^2 basic parameters (the potential barrier height, the ideality factor, the specific capacitance at U = 0, etc.) is practically independent of the size SD. At S <100 mm^2, with a decrease in contact area from 100 mm^2 to 1 mm^2, the barrier height is reduced from 0.72 eV to 0.53 eV. It is clear that in the SD with different sizes, the character of the influence of the AEF also becomes depended on the size and shape of the contact surface. Unfortunately, these features of real SD in the literature are poorly understood. This paper presents the results of studies of electrophysical properties of Cu-nSi Schottky diodes, depending on the effect of AEF, arising due to the limitation of the contact surface with free surfaces of the contacting materials.

II. THE EXPERIMENTAL PROCEDURES

The semiconductor substrates used in this work were n-type Si single crystals, with a (111) surface orientation and 1 Ω cm resistivity. Before making contacts, the Si wafer was degreased for 5 min in boiling trichloroethylene, acetone and ethanol, consecutively. The wafer was chemically cleaned using the RCA cleaning procedure (i.e. a 10 min boil in NH_3 H_2O_2 $6H_2O$ followed by a 10 min boil in HCl H_2O_2 $6H_2O$) with the final dip in diluted HF for 30 s and then rinsed in deionized water and dried by high purity nitrogen. The Schottky contacts in diameters 6, 10, 20, 60 and 1000 µm were formed on the planar faces by evaporating Cu with a thickness of 300 nm vacuum system in the pressure of $1{\cdot}10^{-6}$ Torr. Metal layer thickness as well as deposition rates were monitored with the help of a digital quartz crystal thickness monitor. The deposition rates were 1–4 A^0/s. Immediately after surface cleaning, high purity aluminum metal with a thickness of 300 nm was thermally evaporated from the tungsten filament onto the whole back surface of the wafer in the pressure of $1{\cdot}\ 10^{-5}$ Torr. Then, a low resistivity Ohmic contact was followed by a temperature treatment at 500 ^{0}C for 3 min in N_2 atmosphere. Static I-V characteristics SD were measured at room temperature on a traditional experimental set. Potential barrier height, ideality factor and the specific contact resistance of SD were determined by the standard method I-V characteristic. Peripheral parameters SD with peripheral contact length L were determined by peripheral current density J_L. According to [3], averaged linear density of peripheral currents SD with different diameters were determined by the formula:

$$J_L = \frac{NI - I_e}{NL - L_e} \tag{1}$$

Here, I - current flowing through SD with peripheral contact length L; L_e- periphery length SD contact with a reference diameter of 1000 µm, through which flows a current I_e; N - number of SD with a current I and peripheral length L, which is equal to the total area identical to the area of reference SD with diameter of 1000 µm. The areas S_L and width h_L of the peripheral contact surface SD with different diameters, which flow through respective peripheral currents I_L are determined by the formulas [3]:

$$S_L = \frac{S_O}{I_{LO}} I_L \qquad \text{и} \qquad h_L = \frac{S_L}{L} \tag{2}$$

Here, S_O – the area contact surface SD with diameters of 6 µm , through which flows the current I_{LO}. Atomic force microscopy (AFM) measurements were carried out using DualScope ™ DS 95-200 / 50.

III. RESULTS AND DISCUSSION

STM current images of SD in forward and reverse biases. For studding the current transport mechanism through the patches in MSC contact with different voltage , we performed current images of schottky contact using STM mode of SPM system in forward and reverse biases. The results are given in Fig.2. In forward bias the applied voltage varied in range from 0 up 0.7V and for reverse bias voltage change from 0 to -3.0 V.

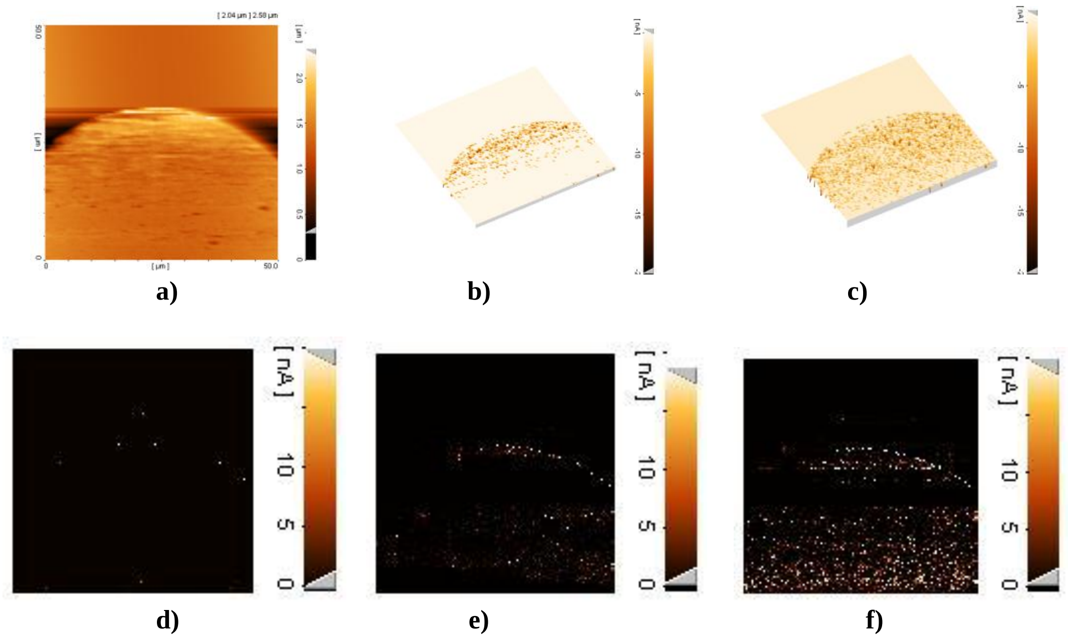


Fig. 2. AFM image of contact surface Cu–nSi DS with 100μm diameter (*a*), current image in forward biases for 0.1V (*b*), 0.3 V (*c*) and in reverse biases for -0.5 V(*d*), -1.0V (*e*), -3.0V (*f*).

In forward bias, gradually with increasing applied voltage current passes from all patches. In the forward bias, the additional electric fields are directed with the main electrical fields which amplify or strengthen the electric field but this strengthening have little effect on the total electric field. But the main effect of additional electric fields will be in the reverse bias. In the reverse bias, at first with gradually increasing applied voltage the current begin flow in the periphery of the contact at the voltage 1 V and by increasing the voltage the current goes on the all contact surface. With increasing the voltage, the external field overcome to the additional electrical field and neutralize its effect. With this action, the current flows uniformly through the entire contact. In Fig.2 we can see set of images that shown current flow in the forward and reverse biases in the Cu - nSi contact with 100 μm diameter.

Current flow in the Shottky diode. The current flow in the conventional flat SD made on the basis of the metal - Si structures is determined by the thermionic emission theory [1]. According to this theory, the potential barrier height Φ_{BO} of ideal SD, defined as the difference between the work function of the contacting metal surfaces and the electron affinity of the contacting surface of semiconductor is reduced under the influence of the image force and the maximum potential barrier height SD is at a distance x_m from the metal surface, where, $x_m \approx 1\text{-}2$ nm. Investigation of current flow in Cu–nSi DS with diameters 6, 10, 20, 60 and 100 μm in forward and reverse directions shows that the I–V characteristics, unlike I–V characteristics of ideal flat SD have some specific features. *Forward bias.* The typically forward I–V characteristics of Cu-nSi SD with different diameters and produced in same technological process are shown in Fig.4a, in the semi-logarithmic scale. The parameter of the curves is the diameter of the contact. It can be seen that the experimentally observed I–V characteristics all SD have the same character and are represented by straight lines on a semi-logarithmic scale, the same high-quality I–V characteristics ideal flat SD. According to the thermionic emission theory, when qU>> kT they described by the following formula [3]:

$$I_F = SAT^2 \exp\left(-\frac{\Phi_{BA} + \beta_f qU}{kT}\right)\exp\left(\frac{qU}{kT}\right) = = SAT^2 \exp\left(-\frac{\Phi_{BA}}{kT}\right)\exp\left(\frac{qU}{n_f kT}\right) = I_{OF}\exp\left(\frac{qU}{n_f kT}\right) \quad (3)$$

were,

$$I_{OF} = SAT^2 \exp\left(-\frac{\Phi_{BA}}{kT}\right) \quad \text{and} \quad n_f = \frac{1}{1-\beta_f}$$

$$\text{or} \quad \beta_f = \frac{n_f - 1}{n_f} \quad (4)$$

Here, S – the area of contact, A – the Richardson constant, T – the absolute temperature, k– the Boltzmann constant, q – the electron charge, Φ_{BA} – the effective potential barrier height, n_f – the ideality factor, β_f – the proportionality coefficient changes in the barrier height with voltage, U – the applied voltage.

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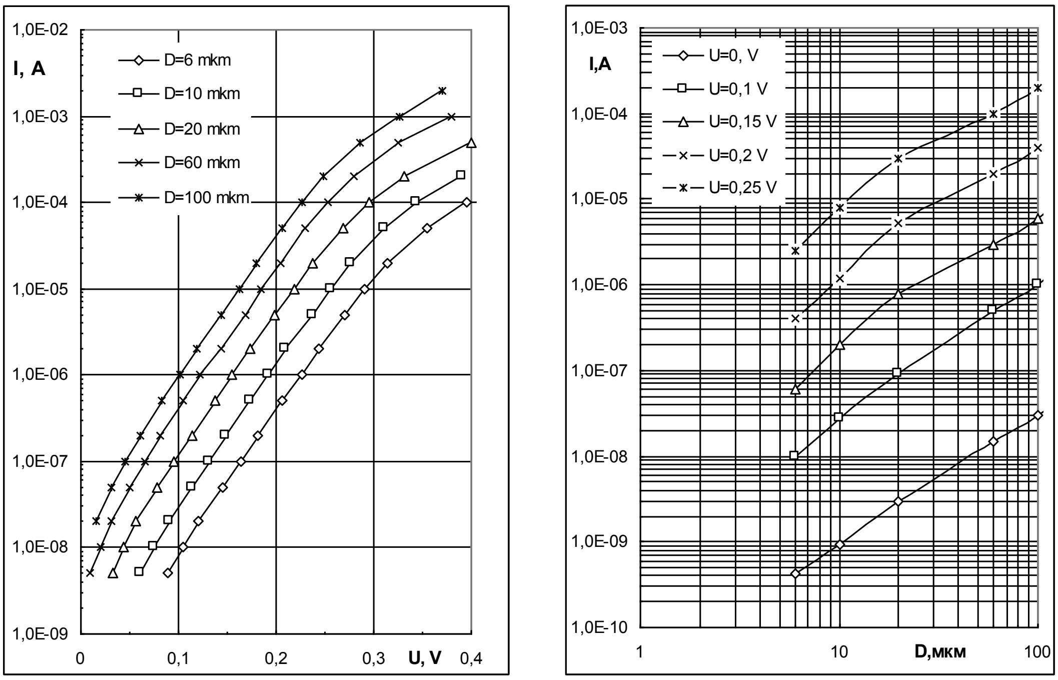


a) **b)**

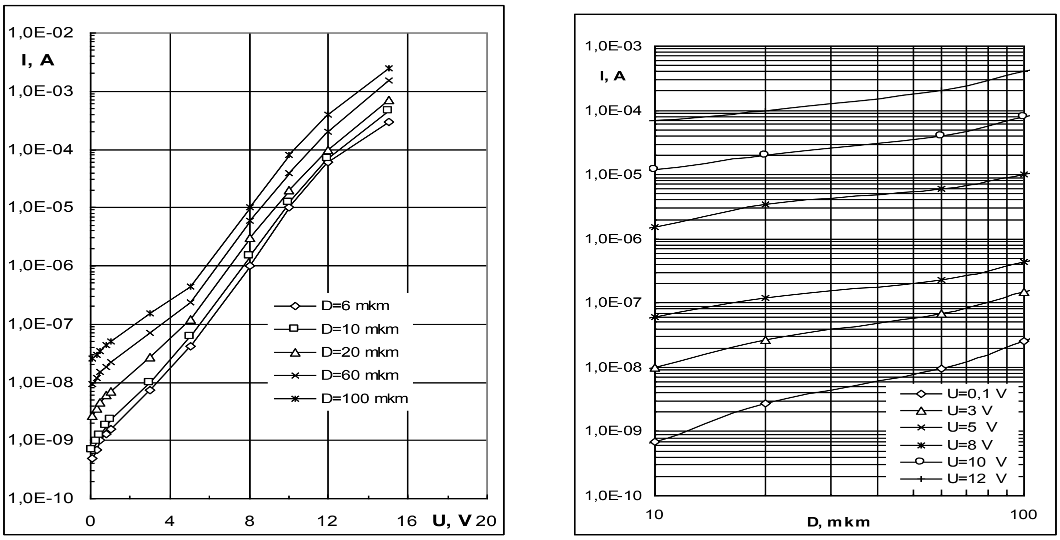
Fig. 3. The forward current–voltage characteristics of the Cu–nSi DS with different diameters (*a*) and the dependence of current on the contact diameters SD at different voltages (*b*).

Electrophysical parameters of the forward I-V characteristics DS with different diameters using Fig.3*a* and formulas (7) and (8) were calculated. To this, the values of A and T equal 120A.sm^{-2} K^{-2} and 300K, respectively. The calculated values of the effective potential barrier height (Φ_{BF}), the specific contact resistance (R_C), the ideality factor (n_f), the proportionality coefficient (β_f), the increase ($0,3 \cdot \beta_f$) of potential barrier height SD by applying voltage 0.3 V shown in Table 1. It is seen that with increasing diameter SD of 6μm to 100 μm effective potential barrier height and the contact resistance increased, but the ideality factor and proportionality coefficient remain virtually unchanged. These dependencies are caused by varying degrees of influence AEF depending on the diameter of the contact. To determine the effect of peripheral current SD have been created relationship between the current SD and diameter of contacts at different voltages, which are shown in Fig.3*b*. From the figures it is seen that these curves are represented by straight lines, the slope of the straight line has a value less of 2. This means that the observed lines I-V characteristics of SD characterized current total area of the contact surface and the peripheral current contribution to the total current SD are significant as it is confirmed and quantified the results of calculation of peripheral parameters SD (Fig.5).

Table1: The values of the electrophysical parameters the Cu-nSi Schottky Diodes at forward bias.

D (μm)	N	Φ_{BF} (eV)	n	β_f	$0.3\cdot\beta_f$ (eV)	R_C (Om.sm^2)	G_{lf} (%)	h_{LF} (μm)	$J_{LF}(0)$ (A/ μm)	Φ_{BL} (eV)
6	27778	0.589	1.10	0.90	0.027	19	80	1.5	$1.8\cdot10^{-11}$	0.589
10	10000	0.595	1.02	0.02	0.006	22	74	1.9	$2.3\cdot10^{-11}$	0.589
20	2500	0.601	1.02	0.02	0.006	27	68	2.7	$3.2\cdot10^{-11}$	0.589
60	278	0.616	1.01	0.01	0.003	48	43	2.8	$3.4\cdot10^{-11}$	0.589
100	100	0.625	1.01	0.01	0.003	67	19	1.5	$1.8\cdot10^{-11}$	0.589

Were calculated average linear density J_{LF} (0) of the current flowing through the periphery SD at U = 0 by the formula (1), the area (S_L) and width (h_L) of the peripheral contact surface (where, $h_L = S_L / L$, when L >> d) by formula (2), the potential barrier height Φ_{BL}, contribution G_L of peripheral current to the total current DS (i.e., the ratio of peripheral current I_{OL} to the total current I_O of contact) for SD with different diameters, which are presented in Table 1. It can be seen that the J_{LF} (0) has similar values of the order of 10^{-11} A / μm for the DS with different diameters. This means that the potential barrier height around the periphery of the contact remains almost the same for SD with different diameters. The potential barrier height around the periphery of the contact SD has a height at about 40 meV less than the rest of the contact surface. Above presented results of experimental studies SD shows that currents of a forward bias in the Cu-nSi DS with the limitation of the contact surface with free surfaces of the contacting materials is defined similarly as in the idealized DS with effective barrier height Φ_{BF} . In the peripheral contact area S_L with a width h_L of SD barrier height Φ_{BL} becomes lower barrier height Φ_{BF} on the rest of its contact surface. and the contribution of the peripheral current to the total current SD increased with decreasing its contact diameters. *Reverse bias.* Typical reverse İ-V characteristics Cu-nSi SD with different diameters are shown in Fig.4*a*. It is seen that the SD are depicted two specific portions: a first initial portion includes a voltage range from 0 to about 1V, and the second portion includes a voltage range about 1V to the breakdown voltage. Current first section of the I-V characteristics for all SD with different diameters slowly increases with increasing voltage U.



a) b)

Fig. 4. The reverse current–voltage characteristics of the Cu–nSi DS with different diameters (*a*) and the dependence of current on the contact diameters SD at different

According to the thermionic emission theory, the first initial portion of the İ-V characteristics SD when $/qU/>>kT$ described by the following formula [3]:

$$\mathrm{I}_R = SAT^2 \exp\left(-\frac{\Phi_{BA}-\beta_r qU}{kT}\right)\left[\exp\left(-\frac{qU}{kT}\right)-1\right] \approx$$
$$\approx SAT^2 \exp\left(-\frac{\Phi_{BA}}{kT}\right)\exp\left(\frac{\beta_r qU}{kT}\right) = I_{OR}\exp\left(\frac{qU}{n_r kT}\right) \quad (5)$$

were,

$$\mathrm{I}_{OR} = SAT^2 \exp\left(-\frac{\Phi_{BA}}{kT}\right) \quad \text{and} \quad n_r = \frac{1}{\beta_r} \quad \text{or} \quad \beta_r = \frac{1}{n_r} \quad (6)$$

Electro physical parameters of the reverse I-V characteristics SD with different diameters using the formula (9) and (10) were calculated. The calculated values of the basic parameters (Φ_{BR}, β_r, n_r) SD are shown in Table 2. There are shown a decrease (1.0 • β_r) effective potential barrier height SD by applying a reverse voltage U = 1,0 V. From Table 2 it is clear that the effective potential barrier height SD with different diameters are virtually equal to the barrier height, determined from a forward I-V characteristics SD. Dimensionless coefficients (n_r) increased and the proportionality coefficient (β_r) decreased with increasing diameter of SD. The obtained depending in reverse bias also caused varying degrees of influence of the AEF, depending on the diameter of the contact, as in the forward bias.

Table 2: The values of the electrophysical parameters the Cu-nSi Schottky Diodes at reverse bias.

D (µm)	N	Φ_{BR} (eV)	n_r (1)	β_r	$1.0\cdot\beta_r$ (eV)	Φ_{BL} (eV)	n_L	β_L	$10\cdot\beta_L$ (eV)	h_L (µm)
6	27778	0.585	33	0.030	0.030	0.620	34	0.029	0.29	1.5
10	10000	0.603	32	0.031	0.031	0.620	36	0.027	0.27	2.1
20	2500	0.604	40	0.025	0.025	0.620	37	0.027	0.27	2.1
60	278	0.628	48	0.021	0.021	0.620	36	0.028	0.28	1.2
100	100	0.629	59	0.017	0.017	0.620	37	0.027	0.27	1.80

Results of the study dependence between the current I_R and the contact diameter SD at various voltages presented on Fig.4*b* shown that they represented by straight lines. The slope of this straight line at voltages up to 3 has a value approximately equal less of 2. By increasing the voltage the slope is reduced and becomes 1. This means that the total current of SD consists only of the currents flowing through the peripheral region of the contact surface. Was defined contribution G_L peripheral current to the total current SD with different diameters at different voltages, which is shown in Fig.5. It can be seen that with increase voltage the contribution peripheral current to the total current SD increases and at U> 8V the total current SD with different diameters consists only of the current flowing along the periphery of the contact. The reverse I-V characteristics SD with different diameters on a semi-logarithmic scale are presented in Fig.6b. The figure shows that the dependence at voltages greater than 6V represented by straight lines, similar to the forward I-V characteristics SD. Such nature of current along the periphery of SD means that it is determined by thermionic emission mechanism, and hence defined the formula [19]:

$$I_L = S_L AT^2 \exp\left(-\frac{\Phi_{BL} - \beta_L qU}{kT}\right) = S_L AT^2 \exp\left(-\frac{\Phi_{BL}}{kT}\right)\exp\left(\frac{\beta_L qU}{kT}\right) = I_{LO}\exp\left(\frac{qU}{n_L kT}\right) \quad (7)$$

Here, Φ_{BL} - the potential barrier height on the peripheral contact surface with the area S_L and width h_L, n_L – the dimensionless coefficient, β_L – the proportionality coefficient, U -the applied voltage. Were determined electrophysical and geometric parameters of the peripheral region SD which are presented in Table 2. To this, were extrapolated straight lines to the axis of ordinate on the Fig.5 and was determined saturation current I_{OL} peripheral region SD with different diameters D. Using the formula (2) and (3) were calculated the peripheral contact area S_L and width h_L, through which the current I_L, and the barrier height for peripheral SD, the dimensionless coefficient n_L and the proportionality coefficient β_L for SD with different diameters. The barrier height is determined by I-V characteristics, which used I_{LO} and S_L. The dimensionless coefficient and the proportionality coefficient were determined by formula similar to the definition of the relevant parameters of the forward I-V characteristics DS.

The Table 2 also shows the reduction of the barrier height ($10 \cdot \beta_L$) by applying a reverse voltage to 10V.

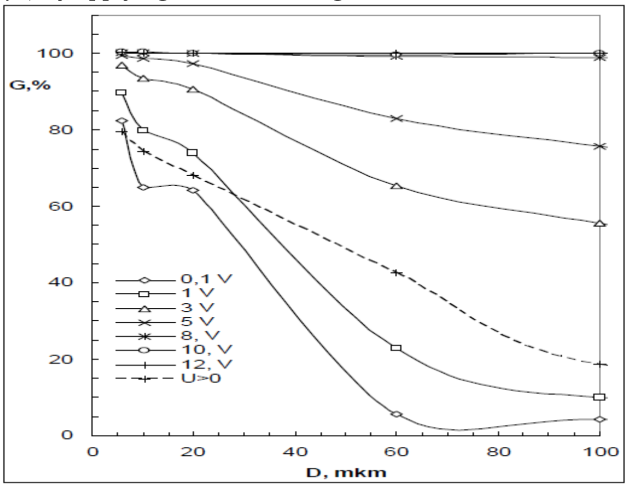


Fig. 5. Dependence the contribution of peripheral current in the total current on the diameters Cu-nSi SD at different voltages.

Thus, it became clear that the current flow in the reverse bias Cu-nSi SD with limitation contact surface is significantly different from the current flow in the idealized SD. The reverse current (I_R) SD is the sum of the currents flowing through the peripheral surface of a certain width (I_L) and the rest inner part of contact surface. As can be seen from Table 2, the electrophysical parameters of the internal and peripheral parts of the contact surface SD differ markedly. At the same time great interest the essential difference between the barrier height dependence on the applied voltage the internal and peripheral parts of the contact surface SD.

IV. CONCLUSION

In Cu-nSi SD with different diameters AEF arising due to the limitation of the contact surface with free surfaces of the contacting materials significantly influence on the electrophysical properties of Cu-nSi SD. In SD at the active participation of AEF formed a effective potential barrier height. Forward and initial reverse I-V characteristics SD are determined by the current flowing through as periphery of contact surface as its rest surface and is well described by the thermionic emission theory, as in the idealized homogeneous SD. In a forward and primary reverse bias with increasing diameter SD of 6μm to 100 μm effective potential barrier height and the contact resistance increased, but the ideality factor and proportionality coefficient remain virtually unchanged. STM images SD and their I-V characteristics show that, the contribution of peripheral current to total current of SD increases with increasing reverse voltage. The second section of the reverse I-V characteristics SD, which consists only of peripheral current is represented by a straight line in a semi-logarithmic scale. The potential barrier height, a dimensionless coefficient, the contact resistance, the area and the width of the periphery of the contact surface different from that for of the first initial portion I-V characteristics SD. The dependence of electrophysical parameters and characteristics of SD from the diameters of contacts are caused by varying degrees of influence AEF arising in the near-contact region of semiconductor.

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