INFLUENCE OF THE ADDITIONAL ELECTRICAL FIELD ON I-V CHARACTERISTIC OF REAL SCHOTTKY DIODES

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The real Schottky diodes are usually exposed to an additional electrical field arising in near contact region of the semiconductor, because of an emission non-uniformity of the interface. It is established, that under influence of the additional electrical field, the non-ideality factor of the forward branch of their volt-ampere characteristic increases, its reverse branch is not saturated and strong raise occurs of the reverse current at low voltages, i.e. a premature breakdown of the transition takes place.

INTRODUCTION

In spite of intensive research of physical characteristics of real Schottky diodes (RSD), the analysis of influence of an additional electrical field on current transportation property has not received the due reflection in the literature. Such additional electrical field arises because of an emissive inhomogeneity of the interface and exists in the near contact region of the semiconductor almost of all kinds RSD. Research of influence of an additional electrical field on a voltage-current characteristic of RSD causes doubtless interest because of the high scientific and practical significance of RSD.

MAIN THEORETICAL THESES

A potential barrier height of RSD, having even an ideal homogeneous interface, because of limitation of the contact area, does not remain identical on all contact surface. Really, on an interface of real Schottky diodes, made on the basis of a close contact of the metal (with the work of exit Φ_M) and the semiconductor (with the work of exit Φ_S), a potential barrier arises with the height Φ_B, equal to the contact potential difference between contact surfaces of the metal and the semiconductor (i.e., $\Phi_B=\Phi_M-\Phi_S$). The contact surface of RSD is limited by free surfaces of the metal and the semiconductor. As a result a contact potential differences of values $(\Phi_M-\Phi_B)$ and $(\Phi_S-\Phi_B)$ arises [1-3] between a contact surfaces with Φ_B and free metal surfaces with Φ_M and the semiconductor surface with Φ_S. The electrical field of the potential Φ_B is main and it concentrates in all the near contact region of the semiconductor. At the same time, the additional electrical field of contact potential differences $(\Phi_M-\Phi_B)$ and $(\Phi_S-\Phi_B)$ concentrates in the peripheral contact region of the semiconductor RSD. As the work of exit of a metal and semiconductor is about 4-5eV [1,4] and a potential barrier height of RSD is of the order of 1eV [5], then the strength of an additional electrical field becomes commensurate with the strength of the main electrical field in the near contact region of the semiconductor. Therefore, a potential barrier on the peripheral contact surface and on inner contact surfaces of RSD has different heights.

However, RSD owing to a series of such causes as a polycrystalline structure of the metal, unevenness of solid-state interaction, congestion of stranger atoms and molecules etc., which in practice are always inherent to an inhomogeneous interface and their potential barrier has a different height along a contact surface [6,7,8]. Then RSD is represented as combination of the two parallel separate microcontacts with different local barrier heights. Such notion of RSD at first seems nonconvincing. Indeed, because of a inhomogeneity of the interface, the difference of potential barrier heights of microcontacts can reach up to 1eV, and the potential barrier of RSD has the same height. Therefore, the real contacts metal and semiconductor, consisting of two parallel separate microcontacts with different local barrier heights, would not have normal rectifying properties. Actually, RSD are produced without the special difficulty with satisfactory qualities and they are widely used in different electronic devices. However, some important problems of physics of RSD still remain open [5]. This contradiction is eliminated at account of the fact, that on the interface of RSD microcontacts with different local barrier heights and linear dimensions of the order of sizes of the crystalline grains of the metal, are in the direct electrical contact and interacting between themselves create an additional electrical field in the near contact region of the semiconductor. As a result, the barrier height along the contact surface smoothes and RSD is characterized by an average height of the potential barrier.

Independently of a degree of complexity of a contact area configuration and distribution of microcontacts with different local potential barrier heights along a contact surface, RSD is represented as combination of two interacting sites with different local barrier heights. The potential barrier heights of the first and second sites becomes, accordingly, lower and higher than the average potential barrier height on all contact surface of RSD. The dependence of the potential barrier height of the first site of RSD on the voltage is determined by the anomalous Schottky effect, and the second site of RSD by the normal Schottky effect.

Let's designate the average potential barrier height of the first site of RSD through Φ_{B1}, and its increment under influence of the second site through $\Delta\Phi_{O1}$, and the average potential barrier height of the second site of RSD through Φ_{B1} and its decrease under influence of the first site through $\Delta\Phi_{O2}$.

At application of an external voltage to RSD, according to anomalous Schottky effect, the dependence of the increment of the potential barrier height of the first site $\Delta\Phi_{B1}$ on the voltage U in the first approximation is expressed by the formula:

$$\Delta\Phi_{B1}=\Delta\Phi_{O1}\pm\beta qU \qquad (1)$$

where the dimensionless factor $\beta<1$.

The dependence of a decrease of the barrier height $\Delta\Phi_{B2}$ on the voltage U for the second site of RSD, according to normal Schottky effect, is determined by the known formula:

$$\Delta\Phi_{B2} = q\left[\left(q^3 N_D/8\pi^2\varepsilon_s^3\right)\left(U_D - U - kT/q\right)\right]^{1/4}. \quad (2)$$

Here all notations are generally accepted [4]

At the application of the forward voltage to RSD with the contact area S, made of a n-type semiconductor, in a near contact region of semiconductor interfaces an external field and an additional field are parallel for the first site and are antiparallel for the second site. Barrier heights of both sites of RSD decrease on the value qU with growth of the voltage for electrons proceeding from the semiconductor to the metal. If contact areas of the first and second site of RSD are equal, accordingly, to $g_1 S$ and $g_2 S$ (where $g_1+g_2=1$), then according to the thermionic emission theory [5], the forward branch of the volt-ampere characteristic of RSD is expressed by the formula:

$$I_F = g_1 I_{F1} + g_2 I_{F2} = SAT^2\left\{g_1 exp\left[-\left(\Phi_{B1}+\Delta\Phi_{01}+\beta qU\right)/kT\right]+g_2 exp\left[-\left(\Phi_{B2}-\Delta\Phi_{B2}\right)/kT\right]\right\}\left[exp\left(qU/kT\right)-1\right]\approx$$
$$\approx S_{EF}AT^2\ exp\left(-\Phi_{BE}/kT\right)exp\left(qU/n_F kT\right)$$

(3)

where index 1 and 2 demonstrate corresponding parameters for the first and second site of RSD.

At the application of a reverse voltage to RSD, in the near contact region of the semiconductor interfaces an external field and an additional field are antiparallel for the first site and parallel for the second site. When the additional electrical field penetrates into the semiconductor on the depth l, larger than the width of a depletion layer of the semiconductor d, then redistribution of free carriers of charges occurs outside of d. Exactly this redistribution of free charges carriers causes the formation of the part $\Delta\Phi_{B1}'$ of the increment $\Delta\Phi_{B1}$ of the first site. With growth of the voltage $U=U_C$ up to the definite critical value U_{CR} (where $qU_C<\Delta\Phi_{B1}'$ and $qU_{CR}=\Delta\Phi_{B1}'$), the value Φ_{B1}' is partially compensated. At $0<U_C\le U_{CR}$ the reverse current does not flow through the first site of RSD and $\Delta\Phi_{B1}$ decreases on the value βqU, and $\Delta\Phi_{B2}$ increases. Such current transportation property was observed experimentally both at research of a contact surface of RSD with the help of a scanning electron microscope [9,10], and at research of a reverse branch of volt-ampere characteristic of RSD [11].

According to the thermionic emission theory, the reverse branch of volt-ampere characteristic of RSD at the account of a bove mentioned facts is described by the formula:

$$I_R = g_1 I_{R1}+g_2 I_{R2}=SAT^2\left\{g_1\ exp\left[-\left(\Phi_{B1}+\Delta\Phi_{01}-\beta qU\right)/kT\right]\cdot\left[exp\left(-q\left(U-U_C\right)/kT\right)-1\right]+\right.$$
$$\left.+\ g_2\ exp\left[-\left(\Phi_{B2}-\Delta\Phi_{B2}\right)/kT\right]\cdot\left[exp\left(qU/kT\right)-1\right]\right\}\approx S_{EF}AT^2\ exp\left(-\Phi_{BE}/kT\right)exp\left(qU/n_R kT\right)$$

(4)

where $U_c=0$ at the forward direction and $U_C=U\le U_{CR}$ at the reverse direction.

When the additional electrical field penetrates into the semiconductor on the depth $l<d$, then the critical voltage will be $U_{CR}=0\ (U_C=0)$ and both the forward and the reverse currents begin to flow through the first site of RSD at once with growth of the voltage (beginning from zero).

RESULTS OF CALCULATION

For a quantitative estimation of influence of the additional electrical field on volt-ampere characteristic of RSD, their forward and reverse branches were constructed according to formulas (1) - (4). Thus following reasonable values of electro-physical parameters of RSD were used:

$\Phi_{B1}+\Delta\Phi_{01}=0.60eV$; $\Phi_{B2}-\Delta\Phi_{02}=0.65eV$; $\beta=0.02$; $U_D=0.5V$; $U_{CR}=2V$; $A=120Acm^{-2}K^{-2}$; $T=300K$; $kT=0.026eV$; $N_D=5..5\cdot10^{15}cm^{-3}$; $\varepsilon s=10.6\cdot10^{-13}Kl.V^{-1}cm^{-1}$; $U_{BR}=100V$; $S=10^{-4}cm^2$; $g_2=1-g_1$; $g_1=1$; 0.5; 10^{-1}; 10^{-2}; 10^{-3}; 10^{-4}; 10^{-8}; 0; $U_F=0-0.3V$; $U_R=0-100V$.

In fig. 1 forward volt-ampere characteristics of RSD are shown at different values g_1 and g_2, calculated on the formulas (3) taking into account formulas (1) and (2). It is seen, that the current of the general contact at $g_1=1$ and $g_2=0$ consists only of the current of the first site of RSD with the effective barrier height $\Phi_{B\Im}$=0.60eV and non-ideality factor n_F=1.02, and at g_1=0 and g_2=1 consists only of the current of the second site of RSD with $\Phi_{B\Im}$=0.65eV and n_F=1.01. At decrease of g_1 from 1 up to 10^{-2}, the contribution of the current of the first site of RSD to the current of the general contact decreases. Therefore the effective barrier height of the general contact of RSD increases up to the value 0.65eV and the non-ideality factor decreases up to the value n_F=1.01.

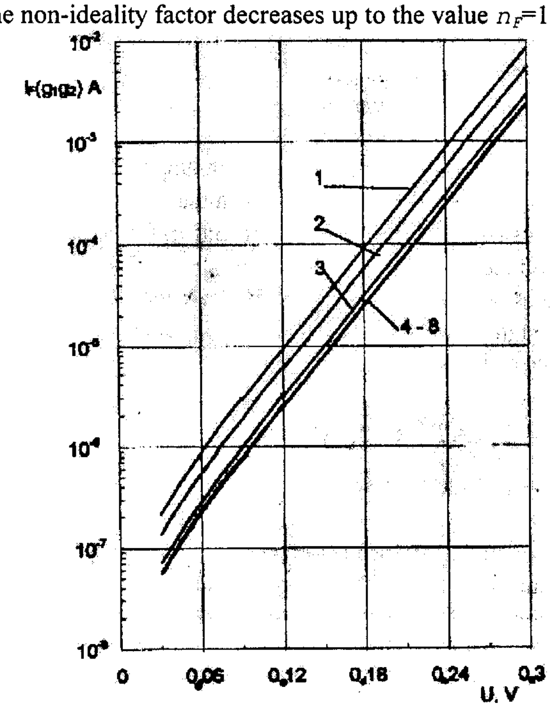

Fig.1. Forward I-V characteristics of real Schottky diodes at

$g_2=1-g_1$, where g_1 : 1) - 1; 2) – 0.5; 3) -10^{-1}; 4) -10^{-2}; 5) -10^{-3}; 6) -10^{-4}; 7) -10^{-8}; 8) - 0.

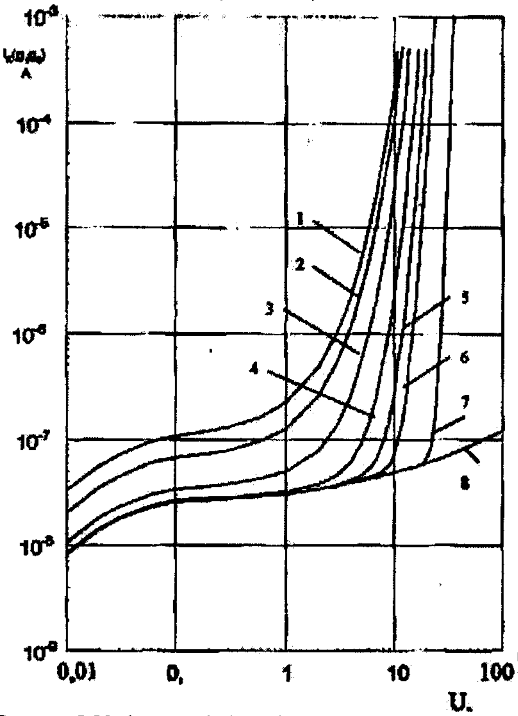

Fig.2. Reverse I-V characteristics of real Schottky diodes at U_C=0 and $g_2=1-g_1$, where g_1: 1) - 1; 2) – 0.5; 3) -10^{-1}; 4) -10^{-2}; 5) -10^{-3}; 6) -10^{-4}; 7) -10^{-8}; 8) - 0.

At further decrease of g_1, i.e. at $0\le g_1<10^{-2}$, the contribution of the current of the first site to the current of the general contact of RSD is not essential. It is necessary to mark, that at β=0.1 the factor n_F increases and becomes equals 1.11.

In fig.2 reverse branches of the volt-ampere characteristic of RSD are constructed on the formula (4) at U_C=0 and different values g_1 and g_2. At g_1 =1 and g_2 = 0 the current of the general contact consists only of the current of the first site of RSD with the effective barrier height Φ_{BE}=0.60eV and area $S_{EF}=S$. The dependence of the reverse current on the voltage at $U\ge0.1$V has the exponential nature and is determined by the formula:

$$I_R=S_{EF}AT^2\exp(-\Phi_{BE}/kT)\exp(qU/n_RkT) \quad (5)$$

Here the dimensionless factor n_R becomes equal to $n_R=n_F/(n_F-1)=51$. At the voltage U=10V the barrier height of RSD decreases on βqU=0.2eV and the reverse current raises on four order of magnitude. At g_1 =0 and g_2 = 1 the current of the general contact consists only of the current of the second site of RSD with the effective barrier height Φ_{BE}=0.65eV and its dependence on the voltage expresses by the formula:

$$I_R = S_{EF}AT^2\exp\left(-\Phi_{BE}/kT\right)\exp\left\{q\left[\left(q^3N_D/8\pi^2\varepsilon_s^3\right)\left(U_D+U-kT/q\right)\right]^{1/4}/kT\right\} \quad (6)$$

It is seen from the figure that at g_2 =1 the current I_R increases nonconsiderably with growth of the voltage.

At $g_1<1$, $g_2>0$ reverse branches of the volt-ampere characteristic of RSD express by the sum $I_R=g_1I_{R1}+g_2I_{R2}$. At $g_1\ge0.01$ volt-ampere characteristics of the general contact are completely determined by the current of the first site of RSD. With decrease of g_1, i.e. at $g_1<0.01$, the weak growth of the back current of the general contact takes place at initial values of the voltage. Even at $g_1=10^{-8}$ it is watched only up to U=25V.

In fig.3 the reverse branches of the volt-ampere characteristics of RSD are constructed on the formula (4) at $U_C\neq0$ and different values g_1 and g_2. At g_1 =1 and g_2= 0 with increase of the voltage $U=U_C$ up to the value $U=U_{CR}$=2V, the reverse current does not flow through RSD. At U>2V the current starts to flow through contact which increases exponentially with the voltage growth according to the formula:

$$I_R = S_{EF}AT^2\exp\left[-\left(\Phi_{BE}-\beta qU\right)/kT\right]\cdot \cdot\left[\exp\left(q\left(U-U_C\right)/kT\right)-1\right] \quad (7)$$

At g_1=0 and g_2=1, the volt-ampere characteristic expresses by the formula (6). At $g_1<1$ and $g_2>0$ currents of the general contact consist of the sum of currents of two sites of RSD.

As it is seen from fig. 2 and fig. 3, the sharp growth of the reverse current of RSD reminds the process of the electric breakdown of the transition, whose theoretical value is 100V. A breakdown voltage of RSD is usually determined as the voltage, at which the reverse current starts strongly to increase. Whereas it is seen from fig. 2, that at $g_1=10^{-2}$ the increase of the reverse current becomes noticeable at I_R=0.001 A and the reverse voltage has the value U=6V much smaller, than the breakdown voltage 100V. Notwithstanding that, at $g_1<10^{-2}$ the current of the first site of RSD has not an effect in the current of the general contact in the forward direction, it becomes essential in backwards.

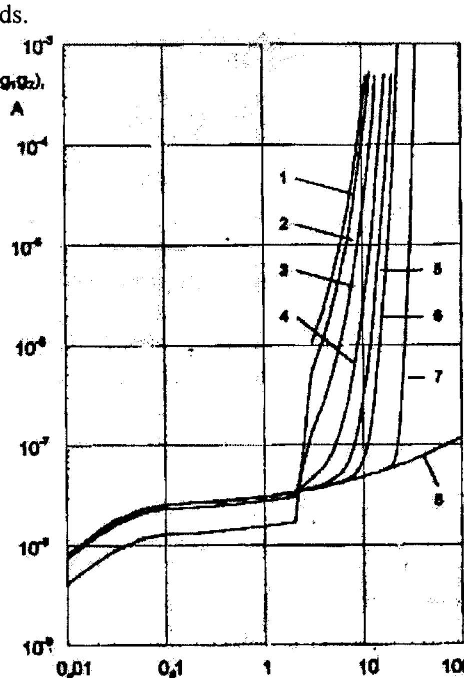

Fig.3. Reverse I-V characteristics of real Schottky diodes at $U_C\neq0$ and $g_2=1-g_1$, where g_1: 1) - 1; 2) – 0.5; 3) -10^{-1};

4) -10^{-2}; 5) -10^{-3}; 6) -10^{-4}; 7) -10^{-8}; 8) - 0.

Thus at $g_1=10^{-5}$ the early breakdown is watched at U=12V, and at $g_1=10^{-8}$ the voltage of the premature is only U=25V. Only at g_1=0 and g_2=1 a breakdown of the RSD takes place at the voltage U=100V.

CONCLUTIONS

In summary it is possible to say, that under influence of the additional electrical field the non-ideality factor of the forward branch of their volt-ampere characteristics of RSD increases, its reverse branch is not saturated and at low voltages the strong growth of the reverse current occurs, i.e. there is a premature breakdown of RSD.

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REAL ŞOTTKİ DİODLARININ VAX-na ƏLAVƏ ELEKTRİK SAHƏSİNİN TƏSİRİ

Real Şottki diodları, adətən, yarımkeçiricinin kontaktaltı hissəsində kontakt səthinin emissiya qeyri-bircinsliyi hesabına yaranan əlavə elektrik sahəsinin təsirinə məruz qalır. Aşkar edilmişdir ki, əlavə elektrik sahəsinin təsiri ilə VAX-ın qeyri-ideallıq əmsalı artır, əks istiqamətdə cərəyanın doyma halı baş vermir və gərginliyin kiçik qiymətlərində əks cərəyan sürətlə artır, yəni keçiddə vaxtından əvvəl elektrik deşilməsi baş verir.

Р.К. Мамедов

ВЛИЯНИЕ ДОПОЛНИТЕЛЬНОГО ЭЛЕКТРИЧЕСКОГО ПОЛЯ НА ВАХ РЕАЛЬНЫХ ДИОДОВ ШОТТКИ

Реальные диоды Шоттки обычно подвергаются воздействию дополнительного электрического поля, возникающего в приконтактной области полупроводника из-за эмиссионной неоднородности границы раздела. Установлено, что под влиянием дополнительного электрического поля коэффициент неидеальности прямой ветви их ВАХ увеличивается, ее обратная ветвь не насыщается и при низких напряжениях происходит сильное возрастание обратного тока, т.е. происходит преждевременный пробой перехода.

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