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Unusual nonlinear current-voltage characteristics of a metal-intrinsic semiconductor-metal barrierless structure

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A nonlinear model for the electric current in a metal-intrinsic semiconductor-metal structure without potential barriers in contacts is considered using a drift diffusion approach. An analytical solution of the continuity equations and the current-voltage characteristic for various recombination rates in the contacts are obtained. It is shown that the current-voltage characteristics of such a structure exhibit not only linear behavior, corresponding to Ohm's law, but may also possess properties of current-voltage characteristics of the rectifier diode. It is also possible current-voltage characteristics with saturation in both forward and backward directions. Physical model that explains the obtained results is proposed. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4914458]

I. INTRODUCTION

Metal-semiconductor (MS) contacts have a number of advantages over *p-n* junctions and a common feature of all semiconductor electronic devices. In particular, they have better electric parameters[1,2] and, in comparison to the *p-n* junction, do not require high temperature technological processing, such as diffusion, post-ionic implantation annealing, etc.[2] The latter is especially important for those semiconductor materials that do not have a "natural protective layer," such as SiO_2, used both as a mask during chip processing and as a chip insulator. Thus, using the MS contacts instead of *p-n* junctions permits to simplify chip processing and to develop technologies that make use of semiconductor materials other than silicon and its oxides. Therefore, properties of MS contacts and their current-voltage characteristics (CVCs), in particular, remain of significant importance for application. Despite a long history of research dedicated to properties of MS contacts beginning from studies of Schottky, Mott, and Bethe[3–5] and up to the recent developments reviewed in Refs. 6–9, detailed understanding of CVCs of various types of MS contacts would be highly beneficial for novel technological developments.

There are two types of the MS contacts usually considered in the literature. One of them is the Schottky barrier-type of MS contacts used instead of *p–n* junctions[1,2] and the other is so-called ohmic contacts connecting semiconductor components to the electric circuit.[1] Properties of such contacts, and in particular their CVCs, are well understood and described in detail in numerous publications, such as Refs. 1, 2, 10, and 11. The majority of the studies deal with Schottky barrier-type of MS contacts. It is believed that a prerequisite of having a non-linear CVC with rectification effect is the presence of a potential barrier and the space charge region in a metal-semiconductor contact. In addition, CVC of such a contact with a potential barrier is investigated under the assumption that the other contact is far away and does not affect the entire structure.

A metal–*n*-type semiconductor contact possessing a small concentration of holes is among the most studied contacts in the literature. The latter assumption justifies neglect of recombination processes and makes theoretical considerations more straightforward. At the same time, in the space charge region of the *n*-type semiconductor the hole concentration is not neglected, and recombination must be taken into account. It is known that the Schottky barrier-type MS contacts may have a substantial leakage current due to a significant surface levels concentration that leads to poor rectification. This current is facilitated by recombination in the contact region, and it can be decreased using the various methods for quality improvement of the interface.[1,12] Thus, the recombination rate in the MS contact is not infinite *a priori* and is technologically controlled. The recombination problem has been thoroughly studied in Refs. 13–15, where it has been shown that the recombination rate is finite. It has also been proven that the finite recombination rate plays an important role in the case of weakly doped semiconductors, when both holes and electrons have equal importance, or in the case of *p*-type semiconductor. Taking into account this circumstance, in papers[16,17] it was shown the possibility of the charge carriers redistribution and appearing of non-equilibrium carriers in the linear approach by current in homogeneous semiconductor. Inhomogeneous distribution of non-equilibrium carriers always appears at the MS interface due to the fact that there are two types of charge carriers in the semiconductor, while there is only one type in the metal. Notably, redistribution of carriers is possible if both the semiconductor bulk and the contact recombination rates are finite.[16–18]

The major purpose of this paper is to investigate the CVC of the metal-semiconductor-metal (MSM) structure without potential barriers in the contacts in a nonlinear regime for various ratios of the recombination rates in the contacts. For simplicity, the semiconductor part of a structure is modeled as an intrinsic semiconductor.

II. MODEL AND ANALYTICAL SOLUTIONS FOR CVC

A model structure considered in this work is an intrinsic semiconductor slab of $2a$ $(-a \le x \le +a)$ in width with two identical metal contacts on each side without potential

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barriers, and as a consequence, without a space charge region. The work functions are equal on the metal and semiconductor sides of the MS contact, to ensure that in equilibrium the space charge region is absent. For simplicity, the semiconductor part of a structure is modeled as an intrinsic semiconductor since only in this case an analytic expression for CVC of the structure can be obtained. The main idea is to study CVC of the structure that is homogeneous at equilibrium due to matching the metal and the semiconductor work functions, rather than a structure where impurities are absent. While this model may be used in the case of the doped semiconductor as well, solution of a similar problem and its analysis in this case would be too complicated. As it follows from the analysis of the corresponding linear problem,[18] an inhomogeneous distribution of non-equilibrium carriers in the real space affects the resistance of a homogeneously semiconductor. Therefore, in the nonlinear approach a nonlinear CVC may appear due to a redistribution of charge carriers. Another consideration that may help solving the problem follows from the analysis of the linear problem[18] that shows that non-equilibrium carriers effects in the *n*-type semiconductor are weak compared to similar effects in the intrinsic and *p*-type semiconductors.

It is notable that hot carriers and field dependence of carrier diffusivity and mobility constitute another mechanism of the CVC nonlinearity.[19] Usually, this mechanism of nonlinearity is ignored in all conventional theories of rectifying effects. During the last decade, some papers[20,21] taking into account both mechanism of nonlinearity appeared. However, as above, redistribution of non-equilibrium carriers in the coordinate space appears in the linear approach by electric field.[16,18] At the same time, the hot carriers introduce a second-order nonlinearity in terms of the electric field.[19] As it will be seen below, the rectifying and saturation effects are observed at voltage levels close, but lower than 0.5 V. For example, for intrinsic Si with a selected thickness this corresponds to an electric field of the order of 10 V/cm. This value is two orders of magnitude lower than the electric field needed to heat the charge carriers enough to modify their mobility.[19] Of course, when the thickness of semiconductor is decreasing to 1 mkm the electric field is increasing and reaches a magnitude sufficient to heat the charge carriers. But even in this case a drift-diffusion model may remain valid. If using a pulse of duration lower than the energy relaxation time, the generation of hot carriers will be avoided.

Let us formulate a general equation and assumption for the solving of problem.

Along *y* and *z* directions, the slab is assumed to be infinite; therefore, it is possible to reduce dimensionality of the problem to one. To simplify the problem even further, the absence of bulk recombination is assumed, that is, the characteristic dimensions of the semiconductor slab are assumed much shorter than the diffusion length ($2a \ll l_D$).[22] For an intrinsic semiconductor, where non-equilibrium carriers have a long lifetime, this condition is easily met.

Under the above assumptions, the continuity equations for non-equilibrium electrons and holes reduce to[23]

$$div\boldsymbol{j}_n = 0, \quad div\boldsymbol{j}_p = 0, \tag{1}$$

respectively, where j_n and j_p are the electron and hole current densities related to the total current density in the one-dimension circuit by the expression $j = j_n + j_p = const$.

The quasi-neutrality condition is assumed to be given by relation[16,17] $a^2 \gg r_D^2$, where $r_D = \sqrt{\varepsilon_s k_B T/(q^2 n_i)}$ is the Debye radius, q is the electron charge, ε_s is the permittivity, k_B is the Boltzmann constant, T is the temperature, and n_i is the equilibrium carrier concentration in the intrinsic semiconductor. Notably, the quasi-neutrality condition is not necessary to solve this problem but the use of it provides for an opportunity to obtain an analytical solution of the problem. Under the quasi-neutrality condition, the Poisson differential equation reduces to an algebraic equality, because bulk charge becomes zero.[16,17] In the case of an intrinsic semiconductor, the quasi-neutrality condition results in equal concentrations of the electrons and holes $n = p$. Taking into account this result, the partial density currents of electrons j_n and hole j_p become integration constants of system (1) and can be written as

$$j_n = qD_n \frac{dn}{dx} - qu_n n \frac{d\varphi}{dx}, \quad j_p = -qD_p \frac{dn}{dx} - qu_p n \frac{d\varphi}{dx}, \tag{2}$$

where φ is the electrical potential, $u_{n,p}$ are the electron and hole mobilities, respectively, $D_{n,p}$ are the electron and hole diffusion coefficients, respectively.

To obtain a unique solution of Eq. (1), one has to introduce boundary conditions[13,14]

$$\begin{aligned}
&j_p(-a) = -qR^s(-a), \;\; j_p(a) = qR^s(a),\\
&\qquad j = -\sigma_n^{s,l}[\varphi(-a) - \varphi_m(-a) + (\mu_m - \mu_n + \delta\varepsilon_c)/q],\\
&\qquad j = \sigma_n^{s,r}[\varphi(a) - \varphi_m(a) + (\mu_m - \mu_n + \delta\varepsilon_c)/q],\\
&\varphi_m(0) = 0, \;\; \varphi_m(a) = V.
\end{aligned} \tag{3}$$

Here, μ_n and μ_m are the chemical potentials of electrons in the semiconductor and metal, respectively, φ_m is the electric potential in the metal, V is the voltage drop on MSM structure, σ_n^s is the electron conductivity in the contact in Ohm^{-1}cm^{-2}, R^s is the contact recombination ratio. The indices "*l*" and "*r*" indicate the left and right contacts, respectively.

The most effective recombination mechanism in the contact is enabled by the surface levels of the metal-semiconductor contact. Using the Shockley-Read model[24] and taking into account the quasi-neutrality condition for the intrinsic semiconductor, the recombination rate can be written as

$$R^s = j_r^{l,r} \frac{n^2/n_i^2 - 1}{n/n_i + n_1^{l,r}}, \tag{4}$$

where

$$j_r^{l,r} = qs^{l,r} n_i, \quad s^{l,r} = \frac{\alpha_n^{l,r}\alpha_p^{l,r} v_{th} N_t^{l,r}}{\alpha_n^{l,r} + \alpha_p^{l,r}},$$

$$n_1^{l,r} = \frac{\alpha_n^{l,r}\exp\left(\dfrac{E_t^{l,r} - E_i}{k_B T}\right) + \alpha_p^{l,r}\exp\left(-\dfrac{E_t^{l,r} - E_i}{k_B T}\right)}{\alpha_n^{l,r} + \alpha_p^{l,r}}.$$

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Here, j_r means the recombination current density, $s^{l,r}$ are the recombination velocities (in cm/s) at the left and right interfaces, respectively, N_t is the concentration of recombination center in the MS contact, $\alpha_{n,p}$ are the electron and hole capture coefficients of a recombination center, respectively, v_{th} is the thermal velocity of charge carriers, E_t is the energy level of a recombination center, and E_i is the Fermi level in the intrinsic semiconductor.

With the condition $j = j_n + j_p = const$, the solution of the system of Eq. (2) takes the form

$$\begin{aligned} n(x) &= p(x) = n_i \frac{j-(1+b)j_p}{2j_{ni}}\left(\frac{x}{a}+C_1\right), \\ \varphi(x) &= V_T \frac{-j+(1-b)j_p}{j-(1+b)j_p}\ln\left(\frac{x}{a}+C_1\right)+C_2. \end{aligned} \tag{5}$$

Here, $V_T = k_B T/q$ is the thermal voltage, $b = D_n/D_p$ and $j_{ni} = q n_i D_n/a$.

Substituting Eq. (5) in the boundary condition (3) and taking into account Eq. (4), one can obtain a system of general equations governing CVC of the metal-intrinsic semiconductor-metal structure without potential barriers (see Appendix A for details)

$$\begin{aligned} j &= (1+b)j_p + \frac{j_{ni}}{2}\left[j_p \frac{j_r^r + j_r^l}{j_r^r j_r^l} + F^r(j_p, j_r^r) - F^l(j_p, j_r^l)\right], \\ V &= -j r_c + 2V_T \frac{j-j_p}{j-(1+b)j_p}\ln\left[\frac{-j_p/j_r^l + F^l(j_p, j_r^l)}{j_p/j_r^r + F^r(j_p, j_r^r)}\right], \end{aligned} \tag{6}$$

where $r_c = (1/\sigma_n^{s,l} + 1/\sigma_n^{s,r})$ is the contact resistance in Ohm cm^2.

Equation (6) exemplify a parametric representation of CVC, where the hole partial current j_p is a parameter. Expression (6) is applicable for all values of recombination rates in the contacts. The form of these expressions hints at the existence of non-linear behavior of CVC of the studied structure. This can also be seen clearly from the graphs of Eq. (6). At the same time, one can obtain all of the important analytical results concerning non-linearity of CVC considering various limiting cases for the recombination rates in the contacts. To simplify otherwise cumbersome analytical calculation, one can assume that energy levels of recombination centers are in the middle of the band gap $E_t = E_i$ (i.e., $n_1^{l,r} = 1$). While this assumption does not restrict generality of consideration and the obtained results, CVC in this case has a particularly simple and compact form (see Appendix A for details)

$$j = \frac{2\left[\dfrac{(1+b)j_r^r j_r^l}{j_r^r + j_r^l} + j_{ni}\right]}{\coth\left(-\dfrac{V + j r_c}{4AV_T}\right) + \dfrac{j_r^r - j_r^l}{j_r^r + j_r^l}}, \tag{7}$$

where

$$A = 1 + \frac{b j_r^r j_r^l}{j_{ni}(j_r^r + j_r^l)}. \tag{8}$$

Notably, the use of the logarithmic representation allows writing the current of Eq. (7) as an explicit function of $V(j)$, but representation of CVC in the form of Eq. (7) is very informative for further analysis.

III. DISCUSSION

Dependent upon recombination rates in the contacts at the opposite sides of the semiconductor, one can consider two cases: (a) identical recombination rates resulting in symmetry of CVC with regard to both forward and backward directions voltage and (b) different recombination rates resulting in asymmetrical CVC.

A. Identical recombination rate in the contacts

In the case of identical recombination rates in both contacts ($s_r^l = s_r^r = s_r$, $A = 1 + \frac{b j_r}{2 j_{ni}}$), Eq. (7) for CVC can be rewritten as

$$j = \left[(1+b)j_r + 2j_{ni}\right]\tanh\left(-\frac{V + j r_c}{4AV_T}\right), \tag{9}$$

which gives a symmetric CVC.

1. Infinity recombination rate in both contacts

The infinite recombination rate in both contacts is usually easy realized in practice because it does not require any special technological conditions. In this case, $s_r^l = s_r^r = s_r \to \infty$ ($j_r \to \infty$), $A \to \infty$, $\tanh\left(-\frac{V + j r_c}{4AV_T}\right) \to 0$ and Eq. (9) has an uncertainty of the type $\infty 0$. The limiting procedure is derived in Appendix B and leads to the linear CVC

$$V = -j[r_c + 2a/(\sigma_n + \sigma_p)]. \tag{10}$$

Thus, in the case of the infinite recombination rate in both contacts the linear[18] and nonlinear approaches lead to the same CVCs. Physical nature of this result becomes clear if one analyzes a distribution of carriers in the semiconductor. Using the first equation of system of equations (A6) derived in Appendix A in the case $s_r^l = s_r^r = s_r$, one can write the expression for constant C_1 featuring in those equations in the form

$$C_1 = \frac{2j_{ni}}{j-(1+b)j_p}. \tag{11}$$

Substituting Eq. (11) into Eq. (5), one obtains

$$n(x) = n_i\left(\frac{j-(1+b)j_p}{2j_{ni}}\frac{x}{a} + 1\right). \tag{12}$$

From the second equation of system of equations (A6), it follows that $j = (1+b)j_p$ if $j_r \to \infty$. Then from Eq. (12), it follows that $n(x) = const = n_i$. This means that non-equilibrium carriers are absent, if the recombination rate is infinite in both contacts. Thus, a linear CVC Eq. (10), i.e., Ohm's law, appears in the absence of non-equilibrium carriers in the semiconductor.

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2. Zero recombination rates in both contacts

Before considering this case, one has to make the following two points. In the first place, surface levels that are easily formed on a metal-semiconductor interface provide a high recombination rate. Therefore, zero recombination conditions in the contacts require special technological solutions (such as introduction of special, very thin buffer layers) that are likely to complicate processing. The second point is related to the fact that the band-band recombination remains possible even after exclusion of recombination by means of the surface levels. In fact, the recombination considerations must always include all possible recombination mechanisms. However, almost always one can select the most effective of such mechanisms. In contrast, when recombination is absent, one has to consider disappearance of the least effective mechanism. In the considered case, the least effective mechanism is the band-band recombination that can be neglected (see Eq. (4)) in the presence of recombination enabled by the surface levels. Thus, for calculation of the CVC in the absence of the contacts recombination through the surface levels, $s_r^l = s_r^r = s_r = 0$, one should use the expression that describes band-band recombination. Replacing the surface levels recombination model of Eq. (4) by a band-band recombination model, one obtains the following expression for CVC derived in Appendix A:

$$j = -2j_{ni}\frac{\sinh\left(\dfrac{V+jr_c}{4AV_T}\right)}{\sqrt{\cosh\left(2\dfrac{V+jr_c}{4AV_T}\right)}}. \tag{13}$$

Linearizing Eq. (13) in the case when the voltage drop is small ($V < V_T$), one obtains

$$V = -j[r_c + 2a/\sigma_n]. \tag{14}$$

This result is equivalent to that of Ref. 18 derived in the linear approximation in the case when $j_p = 0$.

In the case when the voltage drop tends to infinity, $V \to \infty$, it is easy to derive from Eq. (13) that CVC tends to saturation at the current $j = \pm\sqrt{2}j_{ni}$. Thus, if recombination in the contacts is absent the current is less then $j = \sqrt{2}j_{ni}$, but when recombination process exists the current has a greater saturation value (see Eq. (9) and Fig. 1). The minimum of saturation current is equal to j_{ni}, when the recombination rates on the contacts are different (see Eq. (16) below).

The analysis of carrier distributions in the semiconductor permits to determine the physical reason of current flow saturation. Substituting Eq. (A7) for the constant C_1 into Eq. (5), one can obtain the carrier concentration as a function of the coordinate in the form

$$n(x) = n_i\left(\frac{j}{2j_{ni}}\frac{x}{a} + \sqrt{1-\left(\frac{j}{2j_{ni}}\right)^2}\right). \tag{15}$$

From this equation, it follows that the concentration decreases compared to the equilibrium one when the electric current exists. The minimum value of the concentration equals to zero and is reached in one of the contacts when the current reaches the value $j = \sqrt{2}j_{ni}$. A decrease in the carrier concentration in one of the contacts depends on a direction of the current and causes the cutoff in the current growth with increasing voltage. In other words, there is a semiconductor region where the conductivity decreases with increasing current. This phenomenon is somewhat similar to the cutoff of the current in the field transistor with a *p*-*n* junction gate with increasing voltage between source and drain. However, in the field transistor the physics mechanism behind this phenomenon is different and is enabled by the space charge gate displacement under the action of voltage between the source and drain that reduces the cross section of the conducting channel.[2]

The limiting current-voltage characteristics of Eqs. (10) and (13) limit the set of the CVCs that corresponds to the equal recombination rates in the contacts ($s_r^l = s_r^r = s_r$) from below and from above, respectively. For an arbitrary (but not equal to zero or infinity) recombination rate, CVC plots can be built using simplified Eq. (9) or the parametric representation, Eq. (6). One of such plots for CVC of Si, which is one of the most important materials for application, is shown below in Fig. 1. For any other semiconductor materials one can also obtain such plots using Eq. (9) or (6). Thus, for GaSb the maximum current is about 2 A/cm^2, and for wide-gap semiconductor materials, such as GaAs, the maximum current may decrease by up to three orders of magnitude compared to its value for Si. The current-voltage characteristics of the intrinsic silicon with the carrier concentration $n_i = 1.5 \times 10^{10}\,\mathrm{cm}^{-3}$, the electron mobility $u_n = 1300\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$, the hole mobility $u_p = 500\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$, and the slab length $2\,a = 600$ mkm ($j_{ni} = 2.7$ mkA/cm^2) are shown in Fig. 1. The calculations demonstrate that the value $r_d = 33$ mkm (for the lifetime of carriers in the intrinsic Si of about 3 h) and the conditions $l_D \gg a \gg r_d$ are easily realized. The resistance in contact regions was neglected for simplicity, $r_c = 0$. From Fig. 1, one can see that the saturation current depends on the parameter s_r. The shape of curves 5 and 3 in

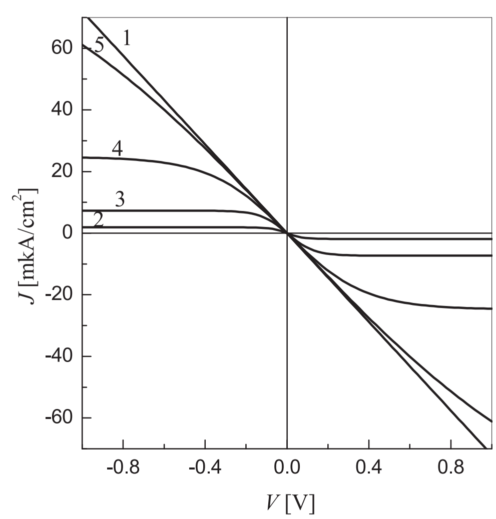

FIG. 1. Current-voltage characteristic of intrinsic silicon in the case of the identical recombination rates in both contacts: curve 1 corresponds to Eq. (10), curve 2 to Eq. (13), curves 3, 4, and 5 to Eq. (9) with $s_r = 0.1D_n/a$, $s_r = 2D_n/a$, and $s_r = 10D_n/a$, respectively.

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Fig. 1 indicates that the recombination rate equal to $s_r = 10D_n/a$ may be considered as infinite, and the recombination rate equal to $s_r = 0.1D_n/a$ is effectively zero. Thus, the concept of "the infinite recombination rate" in the case of the considered model of an MS contact means that the simple condition $s_r \gg D_n/a$, holds, while the concept of "the zero recombination rate" means that the condition $s_r \ll D_n/a$ holds.

Therefore, finite recombination rates in MS contacts lead to redistribution of charge carriers and appearance of non-equilibrium carriers in semiconductor. At the same time, nonlinearity of CVCs in the model system considered here is caused by charge carrier depletion region that develops near one of the contacts defined by the current direction. Notably, the depletion region concerns both types of carriers, and the space charge region is absent due to the quasi-neutrality assumption.

B. Different recombination rate in the contacts

Consider asymmetrical boundary conditions for simple setups. Assuming that the relation between the recombination rates in the right and left contacts is $s_r^l \gg s_r^r$, CVC of Eq. (7) takes the form

$$j = \frac{2\left[(1+b)j_r^r + j_{ni}\right]}{\coth\left(-\dfrac{V + jr_c}{4AV_T}\right) - 1}. \tag{16}$$

Here, $A = 1 + bj_r^r/j_{ni}$. For the case of $s_r^l \ll s_r^r$, one must choose the positive sign before 1 in the denominator of Eq. (16) and replace j_r^r with j_r^l.

The analysis of carrier distributions in the semiconductor permits to understand the behavior of CVC. Obtaining the constant C_1 from Eq. (A6) of Appendix A and substituting it in Eq. (5), one can derive the concentration in the form

$$n(x) = n_i\left[1 + \frac{j}{2\left[(1+b)j_r^r + j_{ni}\right]}\left(\frac{x}{a} + 1\right)\right]. \tag{17}$$

It immediately follows from this equation that in contact where recombination is strong the concentration depends on the current only weakly and tends to its equilibrium value. In the other contact, the carrier concentration depends on a direction of the current. It decreases to zero for $j > 0$, when the absolute value of the current is equal to $j_s = (1+b)j_r^r + j_{ni}$, and increases with an increase in the current for $j < 0$ (Fig. 2(a)). This behavior of the carrier concentration is a prerequisite for the current saturation in one direction and its rapid growth in the other (so-called super Ohmic behavior). Assuming $s_r^r = 0$ for simplicity, one finds that $A = 1$ and CVC formula takes the form

$$j = \frac{2j_{ni}}{\coth\left(-\dfrac{V + jr_c}{4V_T}\right) + 1}. \tag{18}$$

The current-voltage characteristics of Eqs. (16) and (18) are asymmetrical, increasing by absolute value to infinity at $V > 0$ and saturating at $V < 0$. However, asymmetry of the CVC, defined by Eq. (16) is not as strong as that of the CVC defined by Eq. (18) (see Fig. 3, curves 1 and 2, respectively). Asymmetry of these curves depends on the value of the constant A that is equal to 1 when the recombination in one or on both contacts is absent, and is always greater than 1 if recombination takes place in both contacts. The constant A plays the role of the ideality factor usually used in the diode current-voltage characteristics. It is known from experiment that the ideality factor of a diode depends on the recombination rate and current.[2,25] The structure considered in this paper is simpler than a diode, yet the equations and the boundary conditions describing this structure are identical to those of a diode. Thus, one can assume that the obtained expression for A is an analytical representation of dependence of the ideality factor on the recombination rate and current.

The current-voltage characteristics for any s_r^r/s_r^l calculated using Eq. (7) are presented in Fig. 3 (curves 3 and 4). Asymmetry of these CVCs (the rectifying effect) is determined by the ratio of the recombination rates of the contacts s_r^r/s_r^l. Ratios of recombination rates s_r^l and s_r^r to the value of D_n/a determine the saturation current for the "direct branch" of CVCs.

The concentration profile in this case can be written as

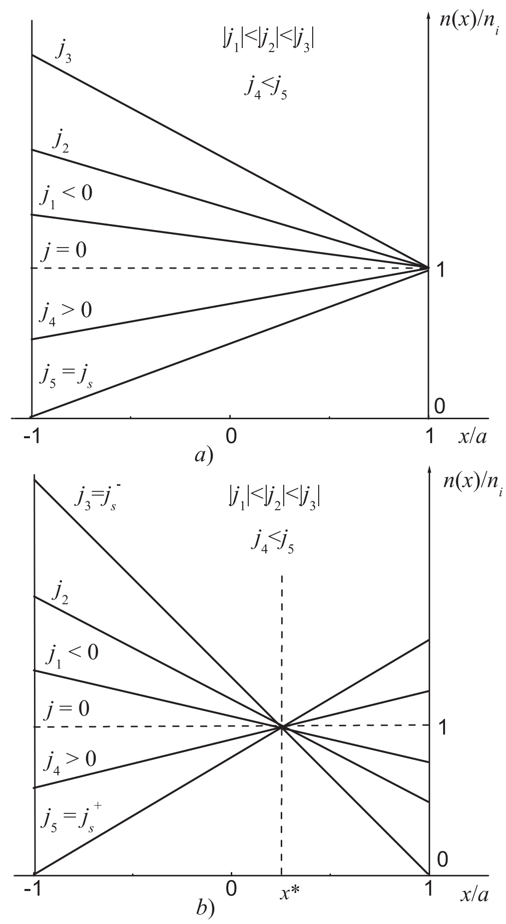

FIG. 2. Profiles of the carrier concentration in the semiconductor for different recombination rates in the contacts $s_r^l \neq s_r^r$: (a) Eq. (17) and (b) Eq. (19).

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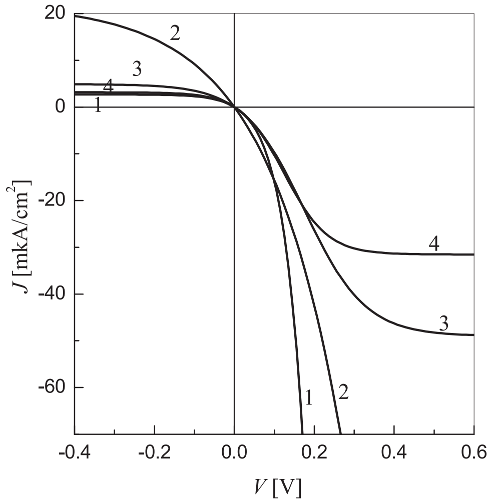

FIG. 3. Current-voltage characteristics of the intrinsic silicon for the different recombination rates in both contacts: curve 1 corresponds to Eq. (16), curve 2 to Eq. (18), curves 3 and 4 to Eq. (7) with the ratio of recombination rates on the contacts $s_r^r/s_r^l = 10$ and $s_r^r = 2D_n/a$ and $s_r^r = 0.2D_n/a$, respectively.

$$n(x)=n_i\left[1+\frac{j(j_r^l+j_r^r)}{2\left[(j_r^l+j_r^r)j_{ni}+(1+b)j_r^l j_r^r\right]}\left(\frac{x}{a}+\frac{j_r^l-j_r^r}{j_r^l+j_r^r}\right)\right]. \quad (19)$$

The concentration of Eq. (19) may become zero for any contact depending on the current direction in the case of the finite recombination rate in that contact. The larger is the recombination rate in the contact compared to the value of D_n/a, the larger must be the current in that contact to ensure that the concentration of Eq. (19) reaches its zero value. The equilibrium concentration plane is located close to the contact with the higher recombination rate, and its x-coordinate is $x^* = a(j_r^r - j_r^l)/(j_r^r + j_r^l)$ (Fig. 2(b)). In the case of the equal recombination rates in the contacts, the value of this coordinate is zero $x^* = 0$, and the saturation current becomes the same for both voltage polarities corresponding to a symmetric CVC in Fig. 1.

As mentioned in a comment preceding Eq. (13) of Sec. III A 2, Eq. (18) is valid when the band-band recombination is neglected. Considering that the condition $s_r^r = 0$ does not guarantee the absence of the recombination in a contact (because the band-band recombination may exists), the condition $s_{bb} = 0$ (where $s_{bb} = \alpha n_i$ and α are the capture coefficients in the intrinsic semiconductor[2]) must hold to validate Eq. (18).

An analytical expression for CVC becomes somewhat more complicated in the case when $s_r^r = 0$, $s_{bb} \neq 0$, taking the form (Appendix C)

$$j=\frac{2\left[2(1+b)j_r^{bb}+j_{ni}\right]}{\coth\left(-\dfrac{V+jr_c}{4AV_T}\right)-1}+\frac{4(1+b)j_r^{bb}}{\left[\coth\left(-\dfrac{V+jr_c}{4AV_T}\right)-1\right]^2}. \quad (20)$$

Expression (20) reduces to Eq. (18) in the case when $j_r^{bb} = 0$. The saturation current in the expressions (16) and (20) is likely to depend on the smallest of the recombination rates.

In conclusion, we note that it is possible to validate experimentally the predictions by using a metal-semiconductor-metal structure with intrinsic or p-type semiconductors. Metal contacts must provide a weak recombination rate and have nearly the same work function than the semiconductor.

IV. CONCLUSION

In this study, a general expression (6) for the current-voltage characteristics of the metal-intrinsic semiconductor-metal structures was obtained. Analysis of this expression demonstrates that in the model metal-semiconductor-metal structure investigated here the presence of a potential barrier is not necessary for occurrence of asymmetric CVCs and the rectifying effect. In order to obtain a nonlinear CVC, it is sufficient that recombination is weak at least in one contact. Analysis of the non-equilibrium carrier distribution showed that the major physical reason behind non-linearity of the current-voltage characteristics of the studied model structure is strong carrier depletion or enrichment (depending on the current direction) in the contact, where recombination is weak. Notably and despite simplicity of the studied structure, it may act both as common resistor, and as a diode or bipolar transistor with the disabled base. The obtained results point out toward a possibility to use the metal-semiconductor structures without space charge as a new type of semiconductor devices.

Qualitatively, the form of CVC derived in this paper should also hold for the case of MSM structures using an extrinsic semiconductor without space charge, since the initial equations and boundary conditions for that case are the same as those for MSM structures using an intrinsic semiconductor without space charge. However, in the case of the extrinsic semiconductor-base MSM structures, the corresponding analytical expression can only be present in the parametric form and thus can only be analyzed numerically. In addition, the obtained results indicate that the recombination effects described in this paper may also occur in the presence of potential barriers in the metal-semiconductor contacts. Thus, such effects should be considered when the current-voltage characteristic of MSM structure with non-zero potential barriers is investigated.

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APPENDIX A: CVC FOR GENERAL CASE

The boundary conditions of Eq. (1) include the chemical potential, $\mu_n(x)$. An analytical expression for the chemical potential can be obtained using the well-known relation[2] $n = N_c \exp[(\mu_n - \varepsilon_c)/k_B T]$, where ε_c is the minimum energy of the conduction band and, N_c is the density of states in the conduction band

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$$\mu_n(x) = \frac{\varepsilon_g/2 + \varepsilon_c}{q} + V_T\left[C_2 + \frac{3}{4}\ln\left(\frac{m_p}{m_n}\right) - \ln\left(\frac{j-(1+b)j_p}{2j_{ni}}\right) + \ln\left(\frac{x}{a} + C_1\right)\right]. \quad \text{(A1)}$$

Substituting Eqs. (5), (A1) and the expression for recombination (4) into the boundary conditions (3), and excluding a constant C_2, one obtains the following system of equations the variables j_p, j, and C_1:

$$\begin{aligned}
j_p &= -j_r^l \frac{\left[\frac{j-(1+b)j_p}{2j_{ni}}(C_1-1)\right]^2 - 1}{\frac{j-(1+b)j_p}{2j_{ni}}(C_1-1) + n_1^l},\\
j_p &= j_r^r \frac{\left[\frac{j-(1+b)j_p}{2j_{ni}}(C_1+1)\right]^2 - 1}{\frac{j-(1+b)j_p}{2j_{ni}}(C_1+1) + n_1^r},\\
jr_c &= -V + V_T\frac{2(j-j_p)}{j-(1+b)j_p}\ln\left(\frac{C_1-1}{C_1+1}\right).
\end{aligned} \quad \text{(A2)}$$

From the first and second equations of system (A2), one finds that

$$\begin{aligned}
\frac{j-(1+b)j_p}{j_{ni}}(C_1-1) &= \left[-\frac{j_p}{j_r^l} + F^l(j_p, j_r^l)\right],\\
\frac{j-(1+b)j_p}{j_{ni}}(C_1+1) &= \left[\frac{j_p}{j_r^r} + F^r(j_p, j_r^r)\right],
\end{aligned} \quad \text{(A3)}$$

where

$$\begin{aligned}
F^r(j_p, j_r^r) &= \sqrt{\left(\frac{j_p}{j_r^r}\right)^2 + 4\left(1 + \frac{j_p n_1^r}{j_r^r}\right)},\\
F^l(j_p, j_r^l) &= \sqrt{\left(\frac{j_p}{j_r^l}\right)^2 + 4\left(1 - \frac{j_p n_1^l}{j_r^l}\right)}.
\end{aligned}$$

Equation (6) for CVC can be obtained by solving Eq. (A3) for $(C_1 \pm 1)$ and substituting the solutions in the third equation of system (A2) to exclude the constant C_1. Notably, the expressions on the left hand side of Eq. (A3) signify concentrations that cannot be negative, so the sign "+" must be selected at the square roots.

For simplicity, the energy levels of the recombination centers are assumed to be located in the middle of the band gap $E_t = E_i$ thus signifying that $n_1^{l,r} = 1$. Rewriting the third equation of system (A2) with respect to the constant C_1, one can rewrite this system in the form

$$\begin{aligned}
-j_p &= j_r^l\left[\frac{j-(1+b)j_p}{2j_{ni}}(C_1-1) - 1\right],\\
j_p &= j_r^r\left[\frac{j-(1+b)j_p}{2j_{ni}}(C_1+1) - 1\right],\\
C_1 &= \coth\left(-\frac{V+jr_c}{4AV_T}\right),
\end{aligned} \quad \text{(A4)}$$

where

$$A = (j - j_p)/[j - (1+b)j_p]. \quad \text{(A5)}$$

Summing and substituting the first two equations of system (A4), one can replace these equations with the corresponding sum and difference

$$\begin{aligned}
\frac{j-(1+b)j_p}{2j_{ni}}C_1 &= 1 + \frac{j_p}{2}\left(\frac{1}{j_r^r} - \frac{1}{j_r^l}\right)\\
\frac{j-(1+b)j_p}{2j_{ni}} &= \frac{j_p}{2}\left(\frac{1}{j_r^r} + \frac{1}{j_r^l}\right).
\end{aligned} \quad \text{(A6)}$$

Solving the second equation of the system (A6) for j_p and substituting the result into Eq. (A5), one can obtain Eq. (8) for A. Substituting C_1 from Eq. (A4) and j_p into the first equation of system (A6), one can derive CVC of Eq. (7).

In the case of zero recombination, $s_r^l = s_r^r = s_r = 0$ ($j_r = 0$), the hole current is absent ($j_p = 0$), and instead of the first and second equations in the boundary conditions of Eq. (3), one has only one equation. In an intrinsic semiconductor for the band-band recombination model, ($R = \alpha(n^2 - n_i^2)$), this equation has the form

$$n^2(-1) + n^2(+1) = 2n_i^2. \quad \text{(A7)}$$

Substituting in this equation the expression for $n(x)$ from Eq. (5), one can derive the following equation for C_1:

$$C_1^2 + 1 = \left(\frac{2j_{ni}}{j}\right)^2. \quad \text{(A8)}$$

In this case, $A = 1$ and substituting C_1 from the third equation of system (A4) into (A8), one can obtain CVC of Eq. (13).

APPENDIX B: CVC FOR INFINITY RECOMBINATION RATE IN BOTH CONTACTS

The limiting transition to CVC of Eq. (10) can be derived directly from Eq. (9), but it is simpler to do it indirectly in several steps. Substituting C_1 from the 3rd equation of system (A4) into the first equation of system (A6), one can rewrite this equation in the form

$$1 = \frac{-2j_{ni}}{\cosh\left(-2\frac{V+jr_c}{4AV_T}\frac{j-(1+b)j_p}{2j_{ni}}\right)} \times \frac{\sinh\left(-2\frac{V+jr_c}{4AV_T}\frac{j-(1+b)j_p}{2j_{ni}}\right)}{j-(1+b)j_p}, \quad \text{(B1)}$$

where in the argument of the hyperbolic functions the expression for A from Eq. (8) or Eq. (A5) was used.

In the case of infinite recombination rate $j_r \to \infty$, from the second equation of system (A6) it follows that $j \to (1+b)j_p$, and consequently, $j - (1+b)j_p \to 0$, and $\cosh\left(-2\frac{V+jr_c}{4AV_T}\frac{j-(1+b)j_p}{2j_{ni}}\right) \to 1$. Then at the right side of Eq. (B1) takes the form $\sinh(Bx)/x$ when $x \to 0$ (here $x = j-(1+b)j_p, B = \frac{V+jr_c}{4AV_T(j-j_p)}$). Thus, as a result of the limiting transition $j_r \to \infty$, Eq. (B1), and therefore Eq. (9), reduces to the form

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$$1 = -2j_{ni}\frac{V + jr_c}{4AV_T}\frac{1}{j - j_p} \Rightarrow (j - j_p)\frac{2V_T}{j_{ni}} = -V - jr_c. \quad \text{(B2)}$$

The expression $j_p = j/(1 + b)$ follows from the second equation of system (A6). Substituting this expression into Eq. (B2) and using Einstein's relation to substitute the diffusion coefficients with the mobilities, one obtains CVC of Eq. (10).

APPENDIX C: CVC FOR A WEAK RECOMBINATION RATE ON THE ONE CONTACT

Consider a case when recombination via the surface energy levels in the left contact is strong and recombination in the right contact is a weak $s_r^l \gg s_r^r$. Strong recombination via the surface levels in the left contact means that band-band recombination in this contact can be neglected, $s_r^l \gg s_{bb}$. At the same time, it is necessary to take into account band-band recombination in the right contact, since the limiting transition, $s_r^r = 0$, is of interest here. Thus, system (A4) takes the form

$$\begin{aligned} &j_r^l\left[\frac{j-(1+b)j_p}{2j_{ni}}(C_1 - 1) - 1\right] = -j_p, \\ &j_r^r\left[\frac{j-(1+b)j_p}{2j_{ni}}(C_1 + 1) - 1\right] \\ &\quad + \left[\left(\frac{j-(1+b)j_p}{2j_{ni}}\right)^2 (C_1+1)^2 - 1\right] j_r^{bb} = j_p, \\ &C_1 = \coth\left(-\frac{V + jr_c}{4AV_T}\right), \end{aligned} \quad \text{(C1)}$$

where $j_r^{bb} = qs_{bb}n_i$ characterize band-band recombination.

Solving the first and the second equations in Eq. (C1) for j_p and C_1, respectively, after lengthy calculations one obtains

$$\begin{aligned} &C_1 = \left(1 - \frac{j_p}{j_r^l}\right)\frac{2j_{ni}}{j-(1+b)j_p} + 1, \\ &\frac{j-(1+b)j_p}{2j_{ni}} \\ &\quad = \frac{1}{2\left(1 + \frac{2j_{ni}}{(1+b)j_r^l}\right)} \\ &\quad \times \left[-F + \sqrt{F^2 + \left(1 + \frac{2j_{ni}}{(1+b)j_r^l}\right)\left(1 - \frac{j_r^r}{j_r^l}\right)\frac{j}{(1+b)j_r^{bb}}}\right], \end{aligned} \quad \text{(C2)}$$

where

$$F = 1 - \frac{j}{(1+b)j_r^l} + \frac{j_r^r}{2j_r^{bb}} + \left(1 - \frac{j_r^r}{j_r^l}\right)\frac{j_{ni}}{2(1+b)j_r^{bb}}.$$

The sign "+" in front of the square root reflects a requirement that when the voltage is turned off and the total current vanishes $j = 0$, j_p also vanishes.

Subsequently, setting $j_r^l \to \infty$ and j_r^r, from Eq. (C2) one finds that

$$\begin{aligned} &\frac{j-(1+b)j_p}{2j_{ni}} = \frac{1}{C_1 - 1}, \\ &\frac{j-(1+b)j_p}{2j_{ni}} = \frac{1}{2}\left[-1 - \frac{j_{ni}}{2(1+b)j_r^{bb}}\right. \\ &\qquad \left. + \sqrt{\left[1 + \frac{j_{ni}}{2(1+b)j_r^{bb}}\right]^2 + \frac{j}{(1+b)j_r^{bb}}}\right]. \end{aligned} \quad \text{(C3)}$$

Combining the expressions (C3) and using C_1, from the third equation of Eq. (C1), one obtains CVC Eq. (20).

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