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The influence of energy band bending on the photo-induced electromotive force in extrinsic semiconductors

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Abstract
A theory of the photo-induced electromotive force in extrinsic semiconductors accounting for the energy bands bending is developed. The non-equilibrium space charge layer and the boundary conditions in the real metal–semiconductor junction have been taken into account. It is shown that photo-induced electromotive force in an n-type semiconductor at any photo-excitation volume essentially depends on the surface potential for certain surface parameters.

1. Introduction

From a couple of years ago conventional theories [1, 2] of the photo-induced (PI) electromotive force (emf) have assumed local electroneutrality in the bulk of a semiconductor. The Dember emf was studied in [3] taking into account a non-equilibrium space charge layer, which arises near the illuminated sample surface. It was assumed in [3] that the illuminated sample surface is in contact with a gas (vacuum), semiconductor energy bands are flat, and the surface recombination rate is negligible. However, the PI emf is measured across the metallic contacts placed on illuminated and dark semiconductor surfaces. This results in qualitative change of the boundary conditions in the real metal–semiconductor junction. The boundary conditions in this case are formulated in [4, 5]. The energy bands bending occurs near the semiconductor surface contacting with a metal [6]. The theory of the PI emf in bipolar semiconductors accounting for the energy band bending is developed in [5, 7, 8]. It is shown that the built-in electric field [6], created by band bending, affects the PI carrier density. The PI emf essentially depends on the surface potential [6] at a small surface recombination rate because of the built-in electric field influence and the ability of the PI electrons to move from semiconductor into metal. The absorbing light and the diffusion process create a non-equilibrium carrier distribution in any type of semiconductor and therefore the PI emf occurs in extrinsic semiconductors. We can assume on the basis of results [5, 8] that the photo-induced hole density does not depend on the built-in electric field at weak photo-excitation in the n-type semiconductor. Therefore, the effective surface recombination rate (SRR) [5] must be independent of the energy band bending. This property of the effective SRR must lead to essential change of the PI emf dependence on the surface potential.

This paper is aimed at the development of the PI emf theory for extrinsic semiconductors for any value of photo-excitation.

2. Theory

Let us consider an n-type semiconductor plate $0 \leqslant x \leqslant L$ with the surface at $x = 0$ illuminated by strongly absorbed light. The thickness of the sample L essentially exceeds the diffusion length (see below). A semitransparent metallic contact is placed on the surface $x = 0$ of the sample and the grounded metallic contact is placed on the surface $x = L$. We suppose that the light wavelength corresponds to the region of fundamental absorption and that the light intensity is of arbitrary value.

The non-equilibrium densities of electrons δn and holes δp, as well as the non-equilibrium electric potential $\delta\varphi$, are obtained from solution of the continuity equations [3, 5] and the Poisson equation

$$\frac{1}{e}\frac{\mathrm{d}j_{\mathrm{n}}}{\mathrm{d}x} - \frac{\delta n}{\tau_{\mathrm{n}}} - \frac{\delta p}{\tau_{\mathrm{p}}} = 0, \tag{1}$$

$$\frac{1}{e}\frac{\mathrm{d}j_{\mathrm{p}}}{\mathrm{d}x} + \frac{\delta n}{\tau_{\mathrm{n}}} + \frac{\delta p}{\tau_{\mathrm{p}}} = 0, \tag{2}$$

$$\frac{\mathrm{d}^2\delta\varphi}{\mathrm{d}x^2} = \frac{e}{\varepsilon\varepsilon_0}(\delta n - \delta p), \tag{3}$$

where $-e$ is the electron charge, j_n, j_p are the electron and hole current densities, τ_n (τ_p) is the parameter characterizing the electron (hole) bulk recombination rate, ε is the semiconductor electrical permittivity, and ε_0 is the vacuum permittivity.

In our considered case the expressions for the x-component of partial currents take the form [6]

$$\begin{aligned} j_n &= -e\mu_n n\frac{d\varphi}{dx} + \mu_n kT\frac{dn}{dx} \\ j_p &= -e\mu_p p\frac{d\varphi}{dx} - \mu_p kT\frac{dp}{dx}, \end{aligned} \qquad (4)$$

where μ_n (μ_p) is the electron (hole) mobility, $n(x)$, $p(x)$ are the densities of electrons and holes accordingly, φ is the electric potential, k is the Boltzmann constant, and T is the temperature of the semiconductor.

The boundary conditions (BCs) on the real metal–semiconductor junction (MSJ) are obtained in [4, 5]:

$$j_p(0) = e(-v\delta p(0) + G), \qquad (5)$$

$$\delta n(0) = 0, \qquad (6)$$

$$\delta\varphi_M = \delta\varphi(0), \qquad (7)$$

where v is the surface recombination rate (SRR), $\delta\varphi_M$ is the variation of electric potential of metallic contact, and G is the surface electron–hole pair (EHP) generation rate.

The BCs (5), (6) can be explained as follows: the non-equilibrium electrons can cross the metal–semiconductor junction (MSJ; the electron surface conductivity [5] is large enough) and therefore do not accumulate on the surface $x = 0$. The non-equilibrium holes do not cross the MSJ (there are no holes in the metal) and recombine on the surface $x = 0$. In the model considered the MSJ thickness is significantly less than the Debye length. Therefore, the parameter v characterizes the SRR in the real MSJ. Note that in the quasi-neutrality approximation the BCs have been formulated at a virtual surface, which is disposed at a distance of several Debye lengths from the real MSJ.

In most semiconductors the diffusion length λ significantly exceeds the Debye length r_D. Under this condition the solution of equations (1)–(4) could be obtained as a sum of two modes: the diffusion–recombination (DR) mode and the screening (S) mode [4, 7]. The DR mode and the S mode are denoted by subscripts R and S accordingly:

$$\begin{gathered} \delta n = \delta n_R + \delta n_S, \qquad \delta p = \delta p_R + \delta p_S, \\ \delta\varphi = \delta\varphi_R + \delta\varphi_S. \end{gathered} \qquad (8)$$

The characteristic S mode decay length is the Debye length r_D and the characteristic DR mode decay length is the diffusion length λ. We can neglect the bulk recombination deriving the S mode owing to the inequality $r_D \ll \lambda$. Moreover, we can consider the densities $n_{eq} + \delta n_R(0)$ and $p_{eq} + \delta n_R(0)$ as the equilibrium electron and hole densities for the S mode. Here n_{eq} (p_{eq}) is the real equilibrium density of electrons (holes) and $\delta n_R(0)$ is the DR mode electron density at the surface $x = 0$. The continuity equations (1), (2) for the S mode (as in the case of flat energy bands [3]) take the form

$$j_{nS} = 0, \qquad j_{pS} = 0. \qquad (9)$$

Solving equations (4), (9) we obtain for n-type semiconductor

$$\delta n_S = [n_{eq} + \delta n_R(0)]\,[\exp(e\delta\varphi_S/kT) - 1], \qquad (10)$$

$$\delta p_S = \delta n_R(0)\,[\exp(-e\delta\varphi_S/kT) - 1]. \qquad (11)$$

It follows from equations (10), (11), and (6) that

$$\delta n_R(0) = -\delta n_S(0) = n_{eq}(0)[\exp(-e\delta\varphi_S(0)/kT) - 1], \qquad (12)$$

$$\delta p_S(0) = n_{eq}(0)[\exp(-e\delta\varphi_S(0)/kT) - 1]^2, \qquad (13)$$

$$\delta\varphi_S(0) = -kTe^{-1}\ln\,[1 + \delta n_R(0)/n_{eq}(0)]. \qquad (14)$$

The DR mode is obtained from the solution of equations (1)–(4) taking into account that λ is the characteristic DR mode decay length and the inequality $\lambda \gg r_D$ is valid. Therefore, deducing the DR mode we can assume that $n_{eq} = n_0$ and $\varphi_{eq} = 0$. Note that the diffusion coefficient and the lifetime of the EHP do not depend on the non-equilibrium carrier density δn_R for weak or strong photo-excitation only.

We derive the DR mode value from equations (1), (2), and (4):

$$\delta n_R = \delta n_R(0)\exp(-x/\lambda) \cong \delta p_R, \qquad (15)$$

$$\delta\varphi_R = \frac{kT}{e}\frac{(\mu_n - \mu_p)}{(\mu_n + \mu_p)}\ln\left(1 + \frac{(\mu_n + \mu_p)}{n_0\mu_n}\delta n_R\right). \qquad (16)$$

Here $\lambda = \sqrt{D\tau}$ is the diffusion length, $\tau = \tau_n\tau_p/(\tau_n + \tau_p)$ is the lifetime of the EHP in the bulk of the sample, the diffusion coefficient is equal to $D = kT\mu_p/e$ for weak photo-excitation [9] and is equal to $D = 2kT\mu\mu_p/(\mu_n + \mu_p)e$ for strong photo-excitation [9], n_0 is the electron equilibrium density in the bulk of the sample.

It follows from equations (10), (11), and (5) that

$$\delta n_R(0) = \frac{n_{eq}(0)}{2S}\left[-(1 + S) + \sqrt{(1 + S)^2 + \frac{4G\lambda S}{Dn_{eq}(0)}}\right], \qquad (17)$$

where $S = v\tau/\lambda$ is the normalized SRR, $n_{eq}(0) = n_0\exp(e\varphi^S/kT)$ is the real equilibrium electron density at the surface $x = 0$ [6], and φ^S is the surface potential (SP).

The measured PI emf φ_{PI} is equal to the variation of the electric potential of the illuminated metallic contact (the dark metallic contact is grounded). We obtain from equations (7), (14), and (16)

$$\begin{aligned} \varphi_{PI} = \frac{kT}{e}\Bigg\{&\frac{(1 - \beta)}{(1 + \beta)}\ln\left[1 + \frac{\delta n_R(0)}{n_0(1 + \beta)^{-1}}\right] \\ &- \ln\left[1 + \frac{\delta n_R(0)}{n_{eq}(0)}\right]\Bigg\}, \end{aligned} \qquad (18)$$

where $\beta = \mu_p/\mu_n$, and the value $\delta n_R(0)$ is defined by equation (17).

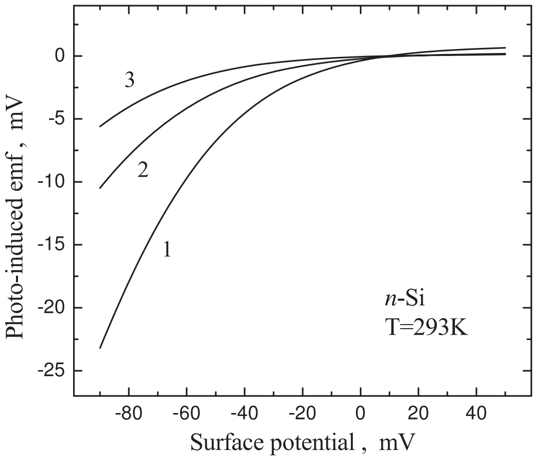

Figure 1. The PI emf dependence on the SP $\varphi^{\rm S}$ at weak photo-excitation for some SRR values: 1—$v = 20$ cm s^{-1}, 2—$v = 400$ cm s^{-1}, 3—$v = 1200$ cm s^{-1}.

3. Discussion of results

In the case of weak photo-excitation ($\delta n_{\rm R}(0) \ll n_0$) we obtain from equations (17), (18)

$$\delta n_{\rm R}(0) = \frac{G\lambda}{D(1+S)}, \tag{19}$$

$$\varphi_{\rm PI} = \frac{G\lambda kT}{eDn_0(1+S)}\left[(1-\beta) - \exp\left(-\frac{e\varphi^{\rm S}}{kT}\right)\right]. \tag{20}$$

It follows from equation (19) that the DR mode does not depend on the SP (which is as it should be in the linear approximation). It follows from equation (20) that the PI emf is a monotone increasing function of the SP ($\varphi^{\rm S}$) in n-type semiconductor instead of the case for the bipolar semiconductor [5, 7]. This can be explained by the absence of the S mode holes at weak photo-excitation in n-type semiconductor (see equation (14)). The PI emf dependence on the SP in n-Si ($\lambda = 0.05$ cm, $T = 293$ K, $n_0 = 10^{15}$ cm^{-3}, $G = 10^{16}$ cm^{-2} s^{-1}, $\mu_{\rm n} = 1450$ cm^2 V^{-1} s^{-1}, $\mu_{\rm p} = 450$ cm^2 V^{-1} s^{-1}) in the case of weak photo-excitation for some SRR values is shown in figure 1. It is seen from figure 1 that the PI emf essentially depends on the SP for small SRR value (curve 1, $S = 0.088$), as for comparatively large SRR value (curve 3, $S = 5.26$). The absolute value of the PI emf $|\varphi_{\rm PI}(\varphi^{\rm S} = -90\ {\rm mV})|$ is 38.4 times more than the classical Dember emf (the term in parenthesis in equation (20)) at large SRR value ($S = 5.26$). The value $|\varphi_{\rm PI}(\varphi^{\rm S} = -90\ {\rm mV})|$ is 28.4 times more than the classical Dember emf at small SRR value ($S = 0.088$).

It follows from equation (17) that in the case of strong photo-excitation ($\delta n_{\rm R}(0) \gg n_0$) the DR mode depends on the SP (which is as it should be in the non-linear theory). The classical Dember emf in this case is equal to

$$\varphi_{D0} = \frac{kT}{e}\frac{(1-\beta)}{(1+\beta)}\ln\left[1 + \frac{(1+\beta)}{(1+S)}\frac{G\lambda}{Dn_0}\right]. \tag{21}$$

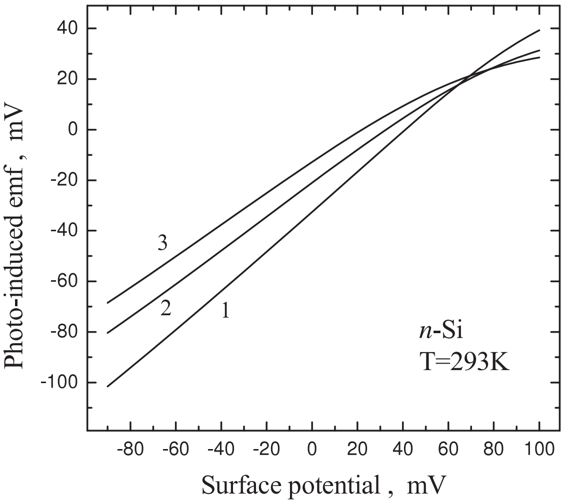

Figure 2. The PI emf dependence on the SP $\varphi^{\rm S}$ at strong photo-excitation for some SRR values: 1—$v = 20$ cm s^{-1}, 2—$v = 400$ cm s^{-1}, 3—$v = 1200$ cm s^{-1}.

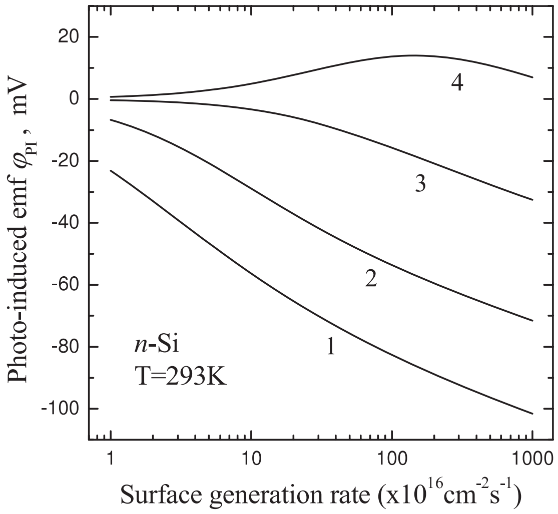

Figure 3. The PI emf dependence on the surface EHP generation rate G for some SP values: 1—$\varphi^{\rm S} = -90$ mV, 2—$\varphi^{\rm S} = -50$ mV, 3—$\varphi^{\rm S} = 0$, 4—$\varphi^{\rm S} = 50$ mV.

The PI emf dependence on the SP in n-Si ($G = 10^{19}$ cm^{-2} s^{-1} and the other parameters are the same as in figure 1) in the case of strong photo-excitation for some SRR values is shown in figure 2. It is seen from figure 2 that the PI emf is a monotone increasing function of the SP. The value $|\varphi_{\rm PI}(\varphi^{\rm S} = -90\ {\rm mV})|$ is 2.07 times more than the classical Dember emf at large SRR value ($S = 5.26$) and the value $|\varphi_{\rm PI}(\varphi^{\rm S} = -90\ {\rm mV})|$ is 1.83 times more than the classical Dember emf at small SRR value ($S = 0.088$). As is seen from figure 2 the PI emf dependence on the SP is practically linear in the range $-90\ {\rm mV} < \varphi^{\rm S} < 20$ mV. It is seen from comparison of figure 2 with figure 1 that the PI emf depends on the SRR (in the SP range $-90\ {\rm mV} < \varphi^{\rm S} < 0$ mV) at strong photo-excitation more weakly than at weak photo-excitation.

The PI emf dependence on the surface EHP generation rate G in n-Si ($v = 20$ cm s^{-1}) for some SP values is shown in figure 3. The diffusion length and the lifetime of the EHP constancy are assumed, calculating with the data of figure 3. It is seen from figure 3 that the PI emf essentially depends on the G value in the SP range -50 mV $< \varphi^{\mathrm{S}} < 0$ mV. The PI emf is negative and its dependence from the G value is a monotone decreasing function at the SP values $\varphi^{\mathrm{S}} \leqslant 0$. The PI emf is positive and the relationship $\varphi_{\mathrm{PI}}(G)$ has a maximum at the SP value $\varphi^{\mathrm{S}} = 50$ mV.

Note that the SP value is limited by the condition $\varphi^{\mathrm{S}} \gg 0.5\, kTe^{-1} \ln(p_0/n_0)$ because the semiconductor is n-type on the surface $x = 0$ (p_0 is the hole equilibrium density in the bulk of the sample).

In that way it is easy to prove that the PI emf absolute value for the p-type semiconductor is significantly less than that for the n-type semiconductor.

4. Conclusions

The theory of the photo-induced emf in extrinsic semiconductors accounting for the boundary conditions in a real metal–semiconductor junction as well as the energy band bending near the semiconductor surface has been developed. It is shown that the photo-induced emf in the n-type semiconductor essentially depends on the surface potential for small as for large surface recombination rate at arbitrary photoexcitation value.

References

[1] Kronik L and Shapira Y 1999 *Surf. Sci. Rep.* **37** 1

[2] Chazalviel J N 1999 *Coulomb Screening by Mobile Charges* (Boston, MA: Birkhäuser)

[3] Krčmar M and Saslow W M 2002 *Phys. Rev.* B **65** 233313

[4] Konin A 2006 *Lithuan. J. Phys.* **46** 233

[5] Konin A 2007 *J. Phys.: Condens. Matter* **19** 016214

[6] Bonch-Bruevich V L and Kalashnikov S G 1977 *Physics of Semiconductors* (Moscow: Nauka) (in Russian)

[7] Konin A 2005 *Lithuan. J. Phys.* **45** 373

[8] Konin A 2007 *Semiconductors* **41** 1185

[9] Peka G P 1984 *Physical Effects on Semiconductor Surface* (Kiev: Visha Shkola) (in Russian)