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MINORITY CARRIER PROFILE AND STORAGE TIME OF A NONUNIFORMLY DOPED n-Si SCHOTTKY BARRIER DIODE

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Abstract

The main objective of this paper is to find the minority carrier hole profile p(x) of an exponentially doped n-Si Schottky barrier diode (SBD in order to study storage time and injection ratio of the device. In previous analytical works, such study was done for SDBs with uniformly doped n-Si. The minority carrier density p(x) is obtained considering both the drift and diffusion components of minority- and majority-carrier currents, thermionic electron current and blocking properties of the low-high (n^-n^+) interface. The mathematical expression for p(x) is applicable for all levels of injection. Expressions for minority carrier charge storage time τ_s and minority carrier injection ratio γ are found from p(x).

Keywords: Schottky barrier diode; minority carrier profile; effective surface recombination velocity of low-high junction, minority carrier current; storage time and injection ratio.

I. INTRODUCTION

Researchers working in the field of solid-state devices have done extensive study on switching devices that have demonstrated the great potential of Schottky barrier diodes (SBDs) for fast switching speed [1]- [4]. Solutions for minority carrier profile within silicon region and minority carrier current under different levels of injection are two of the most important subjects of interest for SBDs. Previous analytical works were done for SBDs with uniformly doped Si region [5] – [9]. But doping profiles in practical devices are not uniform [10]-[11]. In this work, analysis is carried out for exponentially doped silicon region. In works on SBD with uniformly doped Si, two expressions of p(x), for (i) low level of injection ($p(x) << N_d$) and (ii) for high level of injection ($p(x) >> N_d$), were obtained separately. In the present work, p(x) and hole current density $J_p(x)$ are obtained considering both drift and diffusion currents and also the finite surface recombination velocity S_{eff} at the low-high (n^- n+) interface. The storage time τ_s and injection ratio γ are obtained from p(x) and $J_P(x)$. The mathematical expression developed for p(x) is applicable for all levels of injection.

II. MATHEMATICAL DERIVATIONS

The minority carrier holes will be injected from metal into n-Si when an n-Si Schottky barrier diode is forward biased. The minority carrier hole p(x) within the injection region can be obtained from drift and diffusion current equations. The electron and hole current densities in the quasi-neutral injection region are given by

$$J_n = qn(x)\mu_n E(x) + qD_n \frac{dn(x)}{dx} \quad (1)$$

$$J_p = qp(x)\mu_p E(x) - qD_p \frac{dp(x)}{dx} \quad (2)$$

where, $D_n(x)$ and $D_p(x)$ are the electron and hole diffusivity, $\mu_n(x)$ and $\mu_p(x)$ are electron and hole mobility respectively.

The quasi-neutral condition is

$$n(x) = p(x) + N_d(x) \quad (3)$$

where the doping density $N_d(x)$ within n- Si region of length l_d is given by

$$N_d(x) = N_o e^{-\eta x} \quad cm^{-3} \quad (4)$$

where N_o is the peak doping density at the metal-Si interface (i.e. at x = 0) and η is the logarithmic slope of the doping profile.

Differentiation of eqn. (4) gives

$$\frac{dn(x)}{dx}=\frac{dp(x)}{dx}-\eta N_d(x) \tag{5}$$

Substituting electric field E(x) obtained from eqn. (1) into eqn. (2) and using eqns. (4) and (5), a first order differential equation can be obtained as

$$(2p(x)+N_d(x))\frac{dp(x)}{dx}+\left(\frac{J_p}{qD_p}-\frac{J_n}{qD_n}-\eta N_d(x)\right)p(x)+\frac{J_p}{qD_p}N_d(x)=0 \tag{6}$$

The electron (hole) diffusion coefficient D_n (D_p) is given by Engl [12]. Doping density N_d in practical SBD does not exceed $1\text{x}10^{17}$ cm^{-3}. For $N_d \le 1\text{x}10^{17}$ cm^{-3}, D_n and D_p are constants and independent of doping density [13].

Unfortunately eqn. (6) is not analytically tractable. In order to obtain an analytical tractable equation for p(x), a relation of electric field E(x) with x is proposed in this work. As electric field E(x) varies slowly in the quasi-neutral injection region, E(x) is assumed to vary in the quasi-neutral n-Si as

$$E(x)=A+Bx \tag{7}$$

where A and B are arbitrary constants. Using eqns. (1), (2), (3), (4), (6) and (7) an expression for p(x) can be obtained. Hole density p(x) is given by

$$p(x)=\left(p_o+\frac{J_p}{qD_p}\sqrt{\frac{\pi V_t}{2B}}\exp\left(\frac{A^2}{2V_tB}\right)\left(erf\left(\frac{A}{\sqrt{\pi V_tB}}\right)-erf\left(\sqrt{\frac{B}{2V_t}}x+\frac{A}{\sqrt{2V_tB}}\right)\right)\right)e^{\left(Ax+\frac{B}{2}x^2\right)} \tag{8}$$

At x = 0, p(x) = p_o and p_o is given by Wurst and Boreneman [7]

$$p_0=\frac{N_o}{2}\left(\sqrt{1+\frac{4n_{ie}^2\left(J_{no}/J_{ns}+1\right)}{N_o^2}}-1\right) \tag{9}$$

The thermionic emission diode current at x = 0 is given by [14]

$$J_{no}=J_{ns}\left(\exp\left(qV_f/nkT\right)-1\right) \tag{10}$$

where V_f is the forward biased voltage across the Schottky contact and n is the ideality factor. Constant A can be obtained from $p'(0)$, eqns. (1) and (5). The constant A can be written as

$$A=\frac{J_n+q\eta D_nN_o+J_pD_n/D_p}{q\mu_n(2p_o+N_o)}\ . \tag{11}$$

Similarly, constant B can be obtained from (8) replacing x by l_d and using $J_{pl} = qS_{eff}p_l$.

$$J_p=qS_{eff}\left(p_o+\frac{J_p}{qD_p}\sqrt{\frac{\pi V_t}{2B}}\exp\left(\frac{A^2}{2V_tB}\right)\left(erf\left(\frac{A}{\sqrt{2V_tB}}\right)-erf\left(\sqrt{\frac{B}{2V_t}}l_d+\frac{A}{\sqrt{2V_tB}}\right)\right)\right)e^{\left(Al_d+\frac{B}{2}l_d^2\right)} \tag{12}$$

Hole concentration p_l is obtained by putting x = l_d in eqn.(8). In this work, the effective surface recombination velocity S_{eff} of the low-high junction given by Godlewski et. al. [15] is used. For a given given V_f, J_{no} and p_0 can be obtained from eqns. (10) and (9). For finding A, B and p_l from eqns. (8), (11) and (12), J_p is assumed. If the assumed J_p satisfies the relation, $J_p=qS_{eff}p_l$, then values of A and B will be accepted.

The total excess minority charges stored in the quasi-neutral region can be found by integrating eqn. (8)

$$Q_s = \int_0^{l_d} \left(p(x) - \frac{n_i^2}{N_d} \right) dx \ ; \qquad (14)$$

Once J_p, A and B are obtained from eqns. (9), (10), (11) and (12), the total excess charges stored can be calculated from eqn. (14). The minority carrier charge storage time τ_s can be approximated by diving stored charge by the reverse current density J_r during the reverse recovery by Ng et. Al. [16]

$$\tau_s = \frac{Q_s}{J_r} \qquad (15)$$

Once J_n and J_p are known, the minority current injection is obtained through

$$\gamma = \frac{J_p}{J_n + J_p} \qquad (16)$$

Eqn. (12) can be simplified, if erf(x) is approximated for SDB where

$$\frac{A}{\sqrt{2V_t B}} >> 1 \ and \left(\sqrt{\frac{B}{2V_t}} l_d + \frac{A}{\sqrt{2V_t B}} \right) >> 1,$$

$$erf\left(\frac{A}{\sqrt{2V_t B}} \right) \approx 1 - \frac{e^{-\frac{A^2}{2V_t B}}}{\sqrt{\pi}} \frac{1}{A/\sqrt{2V_t B}} \qquad (17)$$

and

$$erf\left(\sqrt{\frac{B}{2V_t}} l_d + \frac{A}{\sqrt{2V_t B}} \right) \approx 1 - \frac{e^{-\left(\sqrt{\frac{B}{2V_t}} l_d + \frac{A}{\sqrt{2V_t B}} \right)^2}}{\sqrt{\pi}} \frac{1}{\sqrt{\frac{B}{2V_t}} l_d + \frac{A}{\sqrt{2V_t B}}} \qquad (18)$$

Using eqns. (17) and (18), eqn.(12) can be simplified to the form

$$B = \frac{2V_t}{l_d^2} \ell n \left(\frac{J_p / qS_{eff}}{p_o - J_p / q\mu_p A} \right) - \frac{qA}{l_d} \qquad (19)$$

III. RESULTS AND DISCUSSIONS

The equations derived in section II, are used to study the characteristics of a SBD. The minority carrier density p(x) as a function of x for a given forward biased voltage V_f for three different N_o is plotted in Fig. 1. Fig. 1 shows that p(x) decreases with increase of peak doping density N_o for a given V_f and η. Hole density p_o at x = 0 decreases with increase of N_o and this decrease in p_o causes decrease in p(x) for increasing of peak doping density N_o. PtSi Schottky barrier diode (Φ_B = 0.84 V) is used.

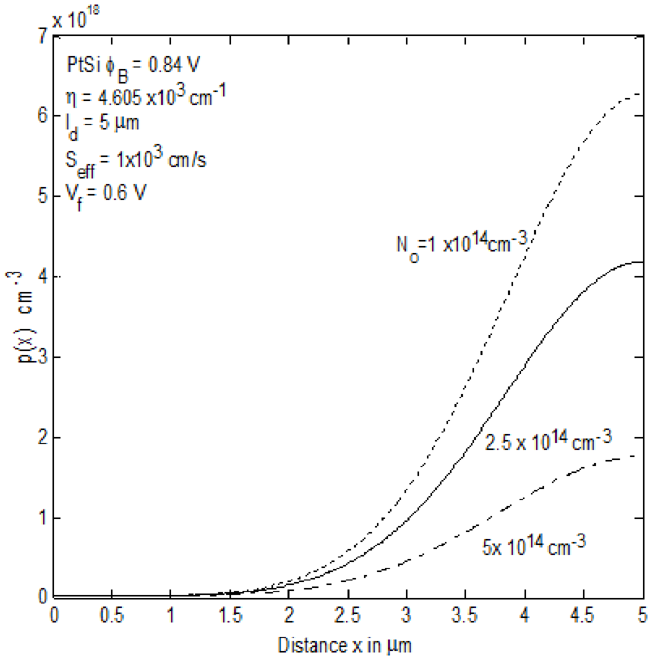

Figure 1. Distribution of minority carrier hole density p(x) within n- Si of a forward biased SB diode.

The hole current density J_p as a function of forward biased voltage V_f for three different peak doping densities is shown in Fig. 2 while Fig. 3 shows J_p for three different lengths. J_p decreases with increase of N_o for a given V_f. For a given V_f, both p_o and electric field E(x) decrease with increase of N_o resulting in decrease of J_p with increase of N_o. On the other hand, J_p increases with l_d for a given V_f and N_o. The hole density p_o depends on V_f but not on l_d. Hole density p_l at $x = l_d$ increases with l_d. Hole current density J_p at $x = l_d$ is given by $qS_{eff}p_l$ and the hole density p_l at $x = l_d$ increases with l_d. Dependence of J_p on effective surface recombination velocity S_{eff} is shown in Fig. 4. The minority current density J_p increases with S_{eff} for a given N_d and l_d.

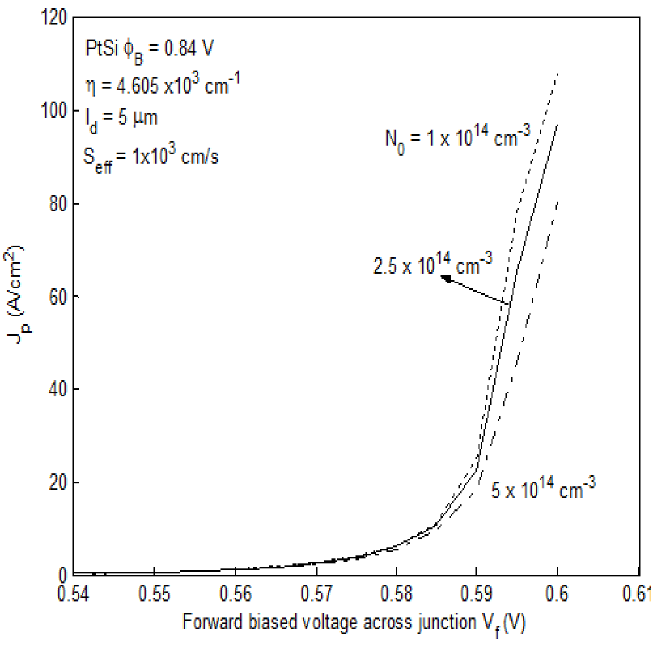

Figure 2. Dependence of hole current density J_p on peak doping density N_o.

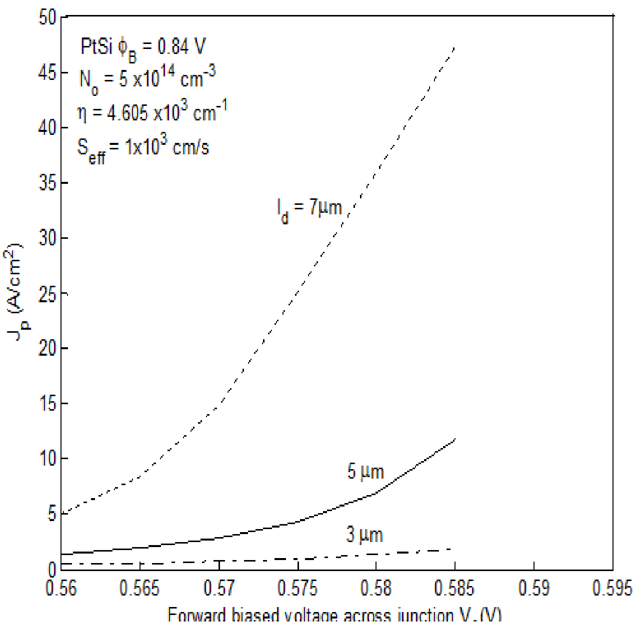

Figure 3. Dependence of hole current density J_p on length of the Si region.

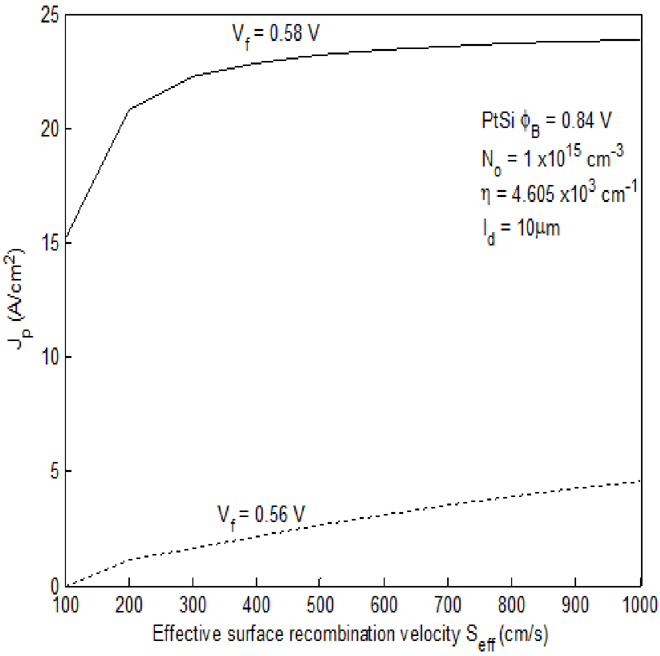

Figure 4. Dependence of J_p on effective surface recombination velocity S_{eff}.

Fig. 5 shows τ_s while Fig. 6 shows variation of γ as a function of J_n for three different values of N_o. Both τ_s and γ increase with J_n but for a given J_n both τ_s and γ decrease with increase of N_o. Both τ_s and γ depend on V_f . With increase of V_f (i.e. J_n) more holes will be injected into n-Si region and J_p will increase. On the other hand for a given V_f, J_p will decrease as shown in Fig. 2 with N_o and injection ratio γ subsequently decreases.

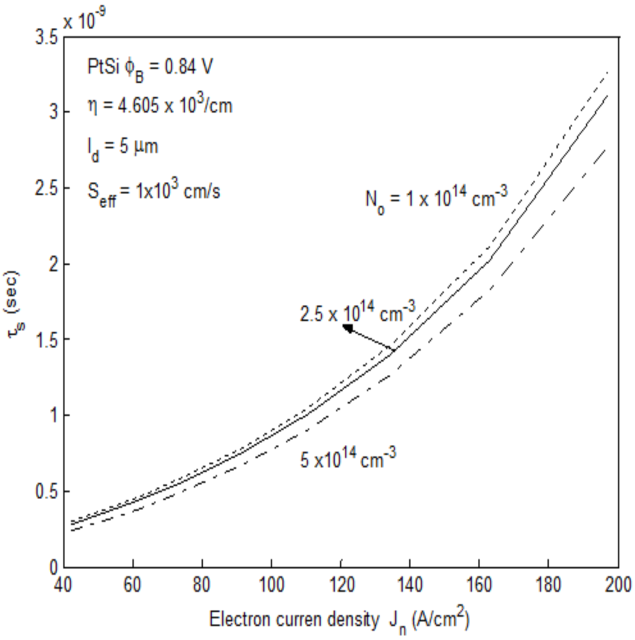

Figure 5. Variation of τ_s as a function of forward biased voltage V_f for three different values of N_o.

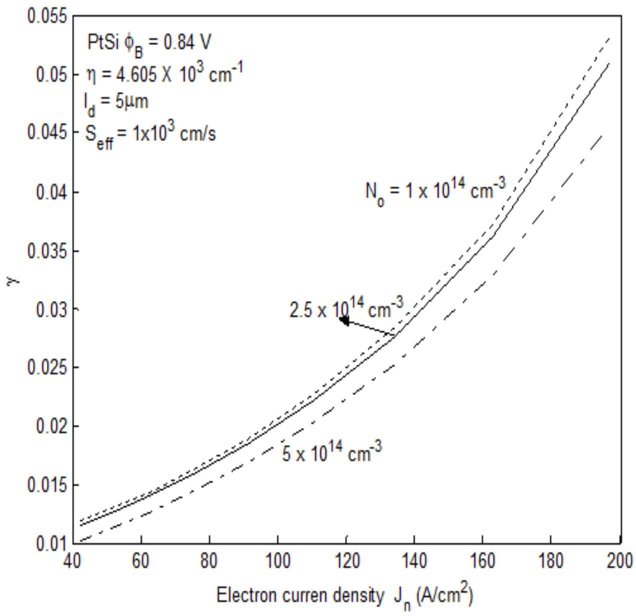

Figure 6. Variation of γ as a function of J_n for three different values of N_o.

Fig. 7 and Fig. 8 illustrate the variation of τ_s and γ with J_n for three different values of η respectively. The aiding electric field E increases with η and this field increases drift component of J_p resulting in increasing of Q_s and J_p. For $\eta \rightarrow 0$, N_d approaches N_o. For uniformly doped Si, $N_d = N_o$ and $\eta = 0$. For a given V_f and N_o, both τ_s and γ will take the lowest values when $\eta = 0$. Uniformly doped Si of a SBD shows better performance as a switch.

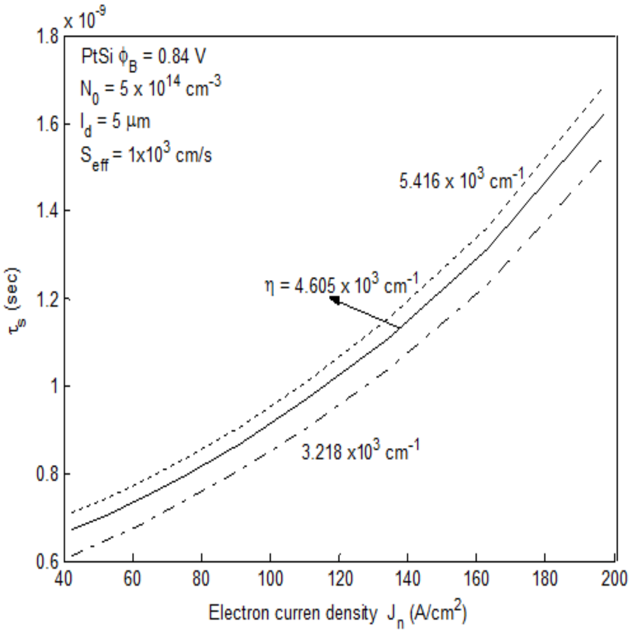

Figure 7. Storage time τ_s as a function of J_n for three different values of η.

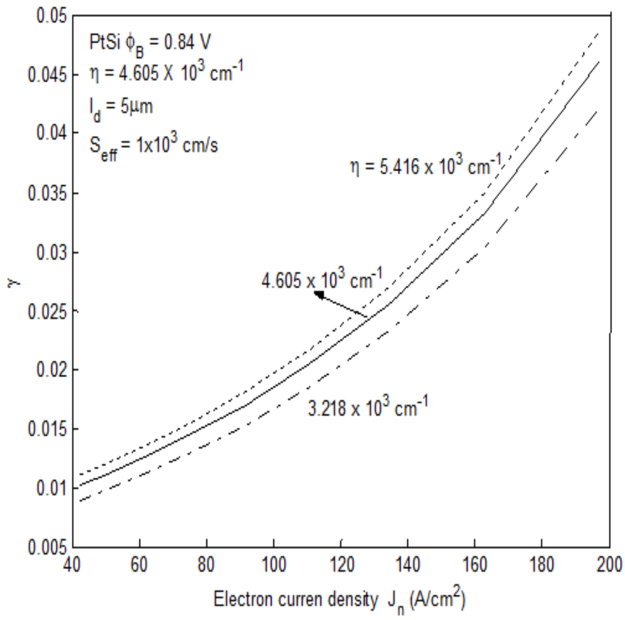

Figure 8. Injection ratio γ as a function of J_n for three different values of η.

The effects of surface recombination velocity S_{eff} on τ_s and γ are shown in Fig. 9 and Fig. 10 respectively. Plots show that the storage time τ_s decreases with increase of S_{eff}. In the other hand, γ increases with S_{eff} for a given N_o, η and l_d. Hole current density J_p increases with $S_{eff,}$ thereby, causing increase of γ .

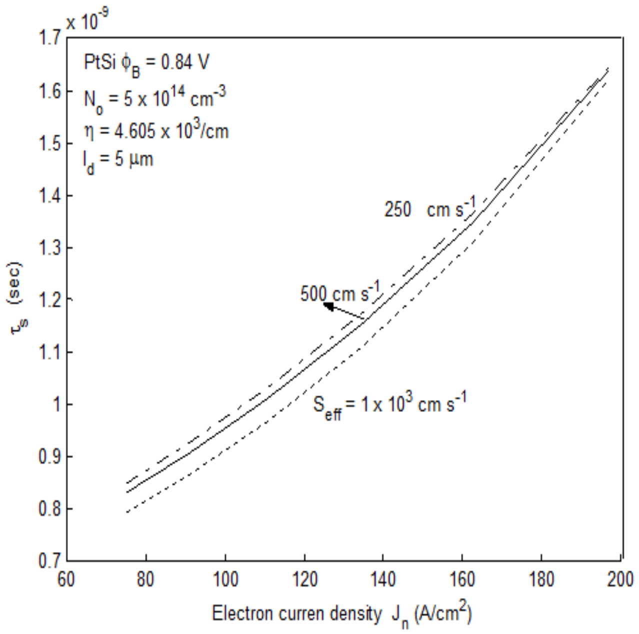

Figure 9. Dependence of τ_s on effective surface recombination velocity S_{eff}.

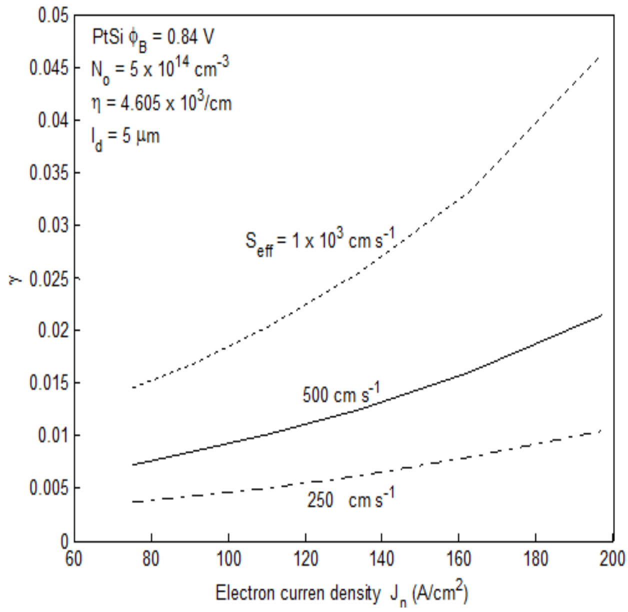

Figure 10. Dependence of γ on effective surface recombination velocity S_{eff}.

IV. CONCLUSION

An equation for p(x) is obtained for exponentially doped Si region. The equation is applicable for all levels of injection. Unlike previous models separate equations for low, intermediate and high levels of injection are not required for studying characteristics of SDB. The equation for p(x) is reduced to a simple form if erf(x) is replaced by appropriate expression given in Eq. (17). Study shows that the storage time τ_s and storage charge Q_s depend upon minority carrier current J_p and effective surface recombination velocity S_{eff}. It is concluded that J_p must not be neglected in obtaining J and Q_s. The study also shows that Schottky diodes with thin Si region and higher peak doping concentration give smaller storage time τ_s and injection ratio γ . Larger logarithmic slope of the doping profile η increases τ_s andγ.

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