

Nonlinear analysis of minority carrier storage time of a uniformly doped Schottky Barrier Diode

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Abstract—Minority carrier charge storage time of a uniformly doped Schottky Barrier Diode (SBD) is studied here. When barrier height is low, SBD acts as a majority carrier device. But for a high barrier SBD both majority and minority carrier currents contribute to total current. In the past, a number of research works on uniformly doped SBD have been done but in this work an analytical expression for minority carrier charge profile for a high barrier SBD is derived in a new approach. Both drift and diffusion components of majority and minority carrier currents are considered. Neglecting recombination in the epitaxial layer, a second order nonlinear differential equation is solved to obtain for all level of injections. Once minority carrier charge profile is known, stored excess minority carrier charge, storage time and injection ratio are obtained. Present work represents that minority carrier charge profile, minority carrier charge storage time and injection ratio depend on bias voltage, doping density, effective surface recombination velocity and device length.

Keywords—Schottky barrier diode, minority carrier hole profile, effective surface recombination velocity, minority carrier storage time, injection ratio.

I. Introduction

Research works on Schottky barrier diode (SBD) have been performed on different fields to utilize its potential in today's world [1]. Because of its importance in direct current and microwave applications and as intricate part of other semiconductor devices, metal-semiconductor contact has been studied extensively [2]-[4]. It is used as photo detectors [5], solar cells [6], rectifiers, gate electrode of the MESFET [7] and so on. It has also got different kinds of voltage clamping applications [8]. Many of the literatures are trying continuously in their search for other applications in various fields with SBD [9][10]. Minority carrier charge profile plays

an important role in case of SBD to determine its storage time and injection ratio. At the very beginning, only diffusion component of current is considered [11][12]. Later on, only drift component of current is considered [13]. Both drift and diffusion components of current are considered for uniformly doped SBD in some works [14][15]. Other analytical works also investigated non uniformly doped SBD [16][17].

In this work second order non linear differential equation is directly solved for the first time. By obtaining an expression for $p(x)$, minority carrier charge storage time τ_s and injection ratio γ have been studied. Both drift and diffusion current density and also finite surface recombination velocity at $n-n^+$ interface are considered in this case.

II. Mathematical Analysis

Uniform doping concentration N_d is maintained within the n region and heavily doped n^+ substrate is also present as shown in Fig.1. Under forward bias voltage, minority carrier holes are

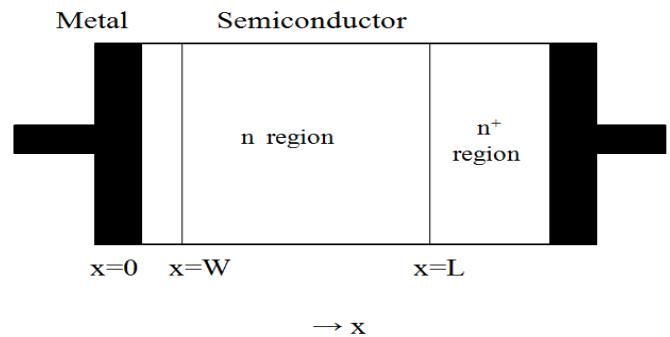


Figure 1. Structure of SBD

injected into the drift region. Blocking of holes by $n - n^+$ junction enhances accumulation of holes within drift region. The electron and hole current densities within the n region are given by,

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

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

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where, D_n and D_p are diffusion coefficients of electron and hole, μ_n and μ_p are electron and hole mobilities respectively. Neglecting recombination in the drift region, both the electron and hole current densities are considered constant throughout the drift region.

The expressions of electron and hole mobilities are given below [18],

$$\mu_n = 88 + \frac{1252}{1 + 6.98 \times 10^{-17} N_d}$$

$$\mu_p = 54.3 + \frac{407}{1 + 3.74 \times 10^{-17} N_d}$$

The quasi neutrality condition in the drift region is given by,

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

Differentiating equation (3) with respect to x ,

$$\frac{dn(x)}{dx} = \frac{dp(x)}{dx} \quad (4)$$

Using equation (1), (2), (3) and (4),

$$(N_d^2 + 3N_d p(x) + 2p(x)^2) \frac{d^2 p(x)}{dx^2} - \frac{J_n N_d}{q \mu_n V_t} \left(\frac{dp(x)}{dx} \right) + N_d \left(\frac{dp(x)}{dx} \right)^2 = 0 \quad (5)$$

Solving this second order nonlinear differential equation,

$$\frac{q V_t \mu_n (p_L + N_d)}{J_n (2p_L + 1.5N_d)} \left[p(x) - p_W - \frac{N_d (p_L + 1.5N_d)}{2(2p_L + 1.5N_d)} \ln \left(\frac{p(x) + \frac{N_d (3p_L + 2N_d)}{2(2p_L + 1.5N_d)}}{p_W + \frac{N_d (3p_L + 2N_d)}{2(2p_L + 1.5N_d)}} \right) \right] = x - W$$

(6)

where, depletion width W is defined as [19],

$$W = \sqrt{\frac{2 \epsilon_s [\phi_{B0} - \frac{kT}{q} \ln \frac{N_c}{N_d} - \frac{kT}{q} \ln \left(\frac{J_n + 1}{J_{ns}} \right) - \frac{kT}{q}]}{q N_d}}$$

The majority carrier electron current density is defined by Crowell and Sze's Thermionic-Emission Diffusion theory [20] as,

$$J_n = J_{ns} \left(e^{\frac{qV_s}{kT}} - 1 \right)$$

where, J_{ns} = reverse saturation current density and ϕ_{B0} = barrier height.

At $x = L$, the hole current density J_p is determined by the effective surface recombination velocity S_{eff} at the $n - n^+$ junction,

$$J_p = q S_{eff} p_L$$

and p_W is the value of $p(x)$ at $x = W$ and is given by [21],

$$p_W = \frac{-N_d + \sqrt{N_d^2 + 4n_i^2 \left(\frac{J_n}{J_{ns}} + 1 \right)}}{2}$$

The excess stored minority carrier charge Q_s within drift region is given by,

$$Q_s = q \int_L^W (p(x) - \frac{n_i^2}{N_d}) dx$$

The minority carrier charge storage time τ_s can be obtained by dividing Q_s by reverse current density J_r during the reverse recovery [18],

$$\tau_s = \frac{Q_s}{J_r}$$

Hence,

$$\tau_s = \frac{q}{J_r} \left[\frac{q \mu_n \mu_p V_t (N_d p_L + p_L^2 - N_d p_W - p_W^2) + J_p \mu_n N_d (L - W)}{J_n \mu_p - J_p \mu_n} - \frac{n_i^2}{N_d} (L - W) \right] \quad (7)$$

Once J_n and J_p are known, the minority current injection ratio γ is obtained by,

$$\gamma = \frac{J_p}{J_n + J_p} \quad (8)$$

III. Result & Discussions

To study the characteristics of SBD, equations derived in section II are used. Barrier height, $\phi_{B0} = 0.85V$, effective surface recombination velocity, $S_{eff} = 1000 \text{ cms}^{-1}$ and device length, $L = 1 \mu\text{m}$ are used. Minority carrier hole profile $p(x)$ as a function of distance x with given doping density $N_d = 10^{15} \text{ cm}^{-3}$ for two bias voltages is plotted in Fig.2. In SBD, effective surface recombination velocity S_{eff} is finite at the blocking interface $n - n^+$. At this interface holes pile up. It is also seen

from this figure, hole concentration $p(x)$ increases with x . For a given distance and doping density, the hole concentration is higher for higher bias voltage. With the increase in bias voltage more holes are injected in n region. In fig. 3, hole profile is plotted for different doping concentrations with a

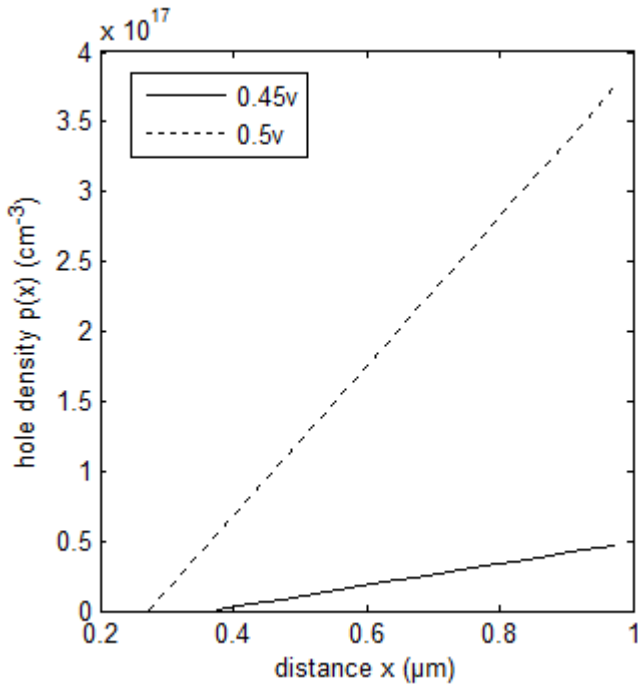


Figure 2. Hole concentration profile as a function of distance for two different bias voltages with fixed doping density

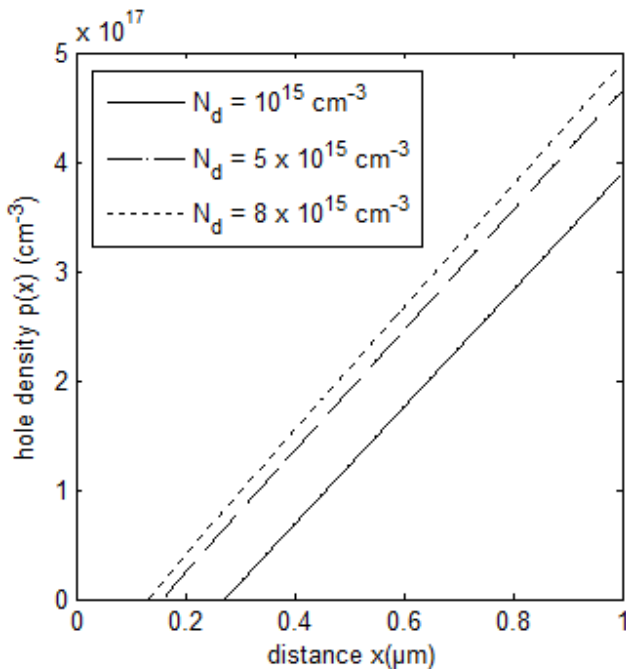


Figure 3. Hole concentration profile as a function of distance for three different doping concentration with a fixed bias voltage $V = 0.5V$

fixed bias voltage $V = 0.5V$. Hole concentration $p(x)$ increases with the increase in doping concentration N_d . With increase in N_d , depletion region length decreases. As a result, for a fixed bias voltage, $p(x)$ is higher for higher values of N_d .

In Fig.4, the electric field $E(x)$ as a function of distance x is plotted. Minority carrier hole density $p(x)$ is small or does not increase much near the metal-semiconductor junction. So, the drift component of the current is dominant and electric field becomes large. But near the $n - n^+$ interface, the rate of $p(x)$ is high. As a result, here diffusion is the major current component and small electric field persists.

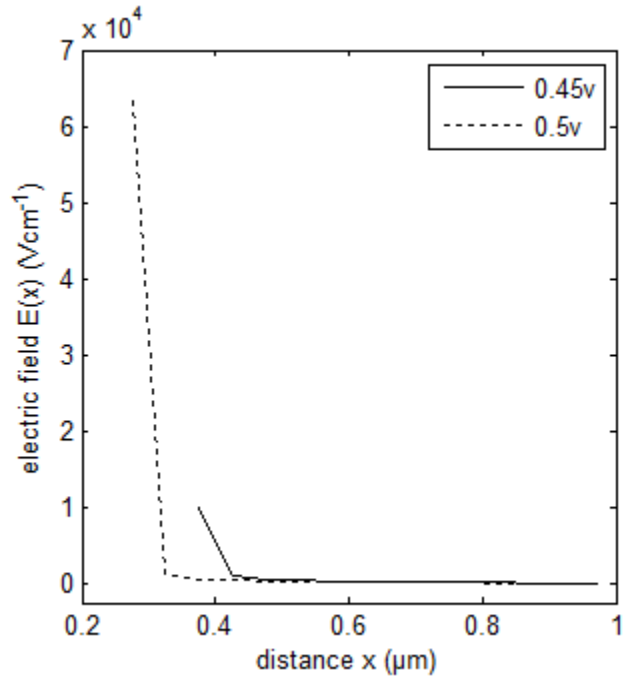


Figure 4. Electric field distribution as a function of distance for two different bias voltages with a fixed doping density $N_d = 10^{15} \text{ cm}^{-3}$

For different doping density, the effect is reflected in the electric field profile as shown in Fig.5. Near the metal-semiconductor junction $p(x)$ decreases with increasing values of N_d . So here, $E(x)$ is higher for lower N_d . But in the drift region very small electric field $E(x)$ persists for all doping densities.

With the variation of bias voltage V , minority carrier charge storage time τ_s variation is shown in Fig.6. As V increases, more holes are injected in the n region. $p(x)$ also increases with increase in N_d . So for increasing junction voltage with varying doping densities, τ_s increases more.

In Fig.7, injection ratio γ as a function of junction voltage for three different doping densities is shown. J_p increases with increasing doping and J_n increases with the increase in bias

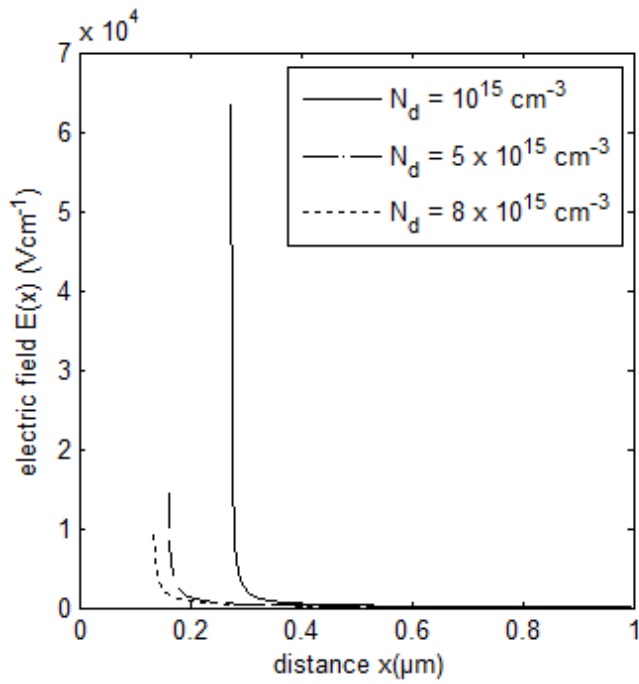


Figure 5. Electric field profile as a function of distance for three different doping concentration with a fixed bias voltage $V = 0.5V$

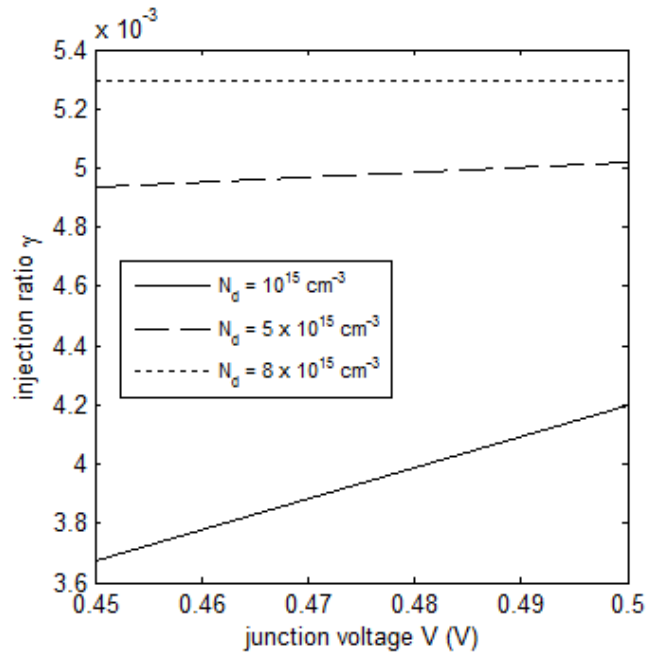


Figure 7. Injection ratio as a function of junction voltage for three different doping densities

voltage. But γ is dependent on the relative change of the ratio of J_p to total current density $J_p + J_n$. As a result, injection ratio γ increases. In Fig.8, with the variation of

effective surface recombination velocity S_{eff} , minority carrier charge storage time τ_s is plotted. Variation of p_L is very slow with respect to S_{eff} . So τ_s also varies very slowly with S_{eff} . Injection ratio γ as a function of effective surface

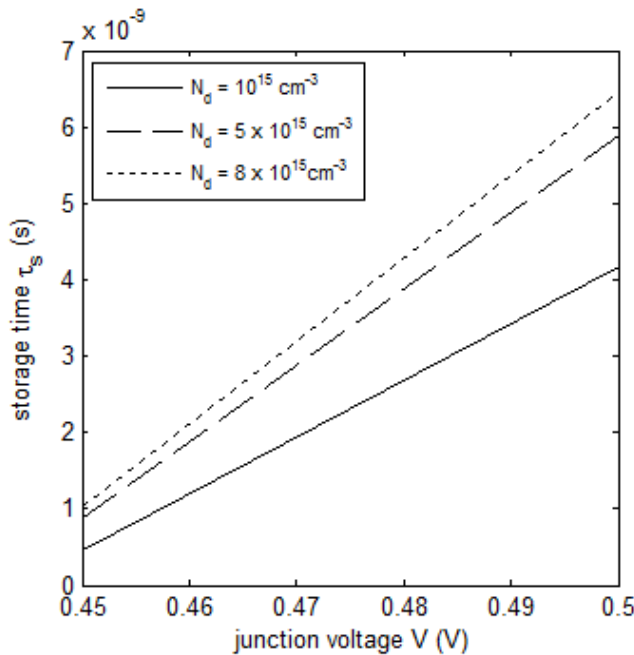


Figure 6. Storage time as a function of junction voltage for three different doping densities

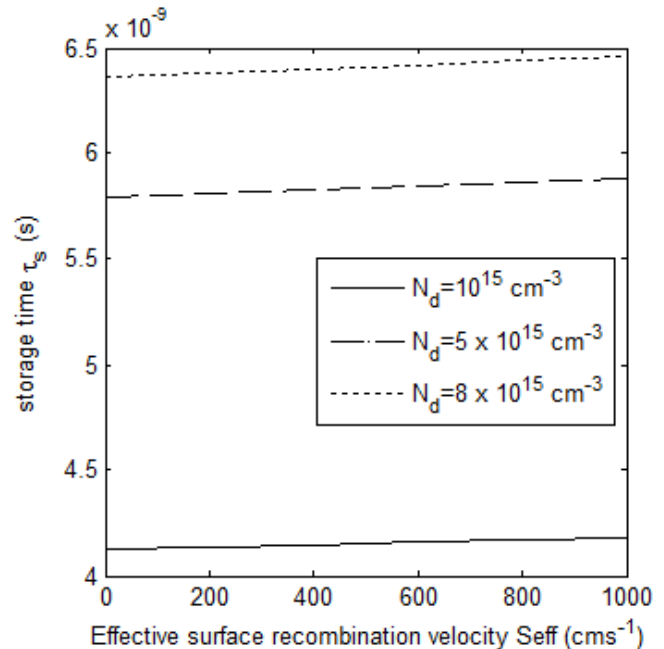


Figure 8. Storage time as a function of effective surface recombination velocity for three different doping densities

recombination velocity S_{eff} for three different doping densities N_d is shown in Fig.9. Minority carrier hole profile $p(x)$

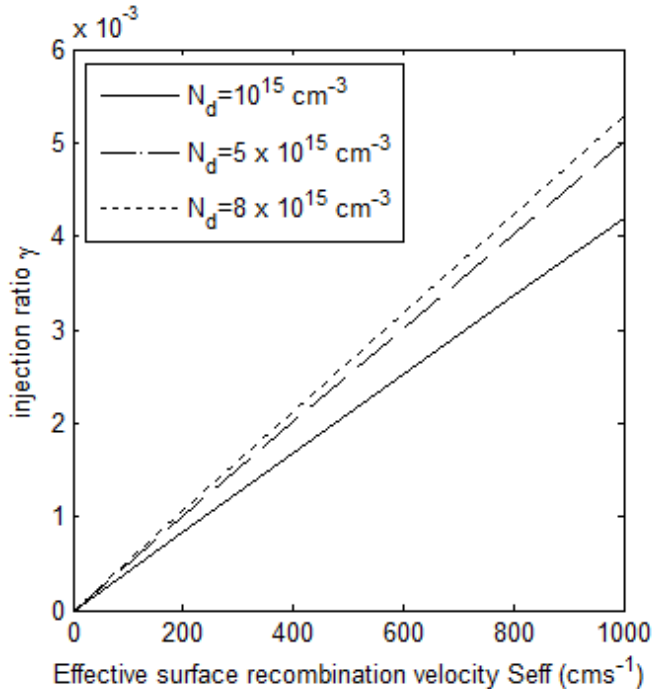


Figure 9. Injection ratio as a function of effective surface recombination velocity for three different doping densities

increases with doping density and J_p is $p(x)$ dependent. Also J_p increases with S_{eff} . So, injection ratio γ increases. In Fig.10, with the variation of J_n , minority carrier charge storage time τ_s

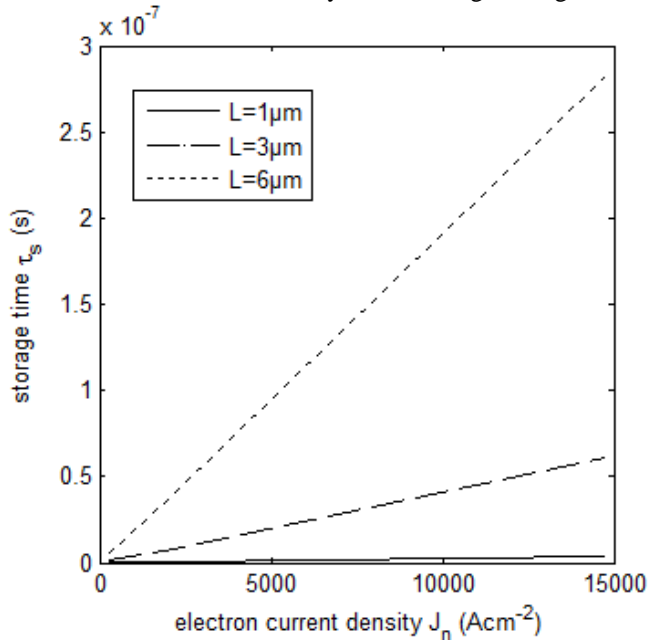


Figure 10. Storage time as a function of electron current density for three different device lengths

is plotted for three different device lengths L . With the increase of L , minority carrier charge $p(x)$ increases resulting stored excess minority carrier charge Q_s to increase. As a result, τ_s increases.

Injection ratio γ as a function of electron current density J_n for three different device lengths L is shown in Fig.11. With the increase of device length L , minority carrier $p(x)$ increases resulting J_p to increase. But J_n is constant. As a result, injection

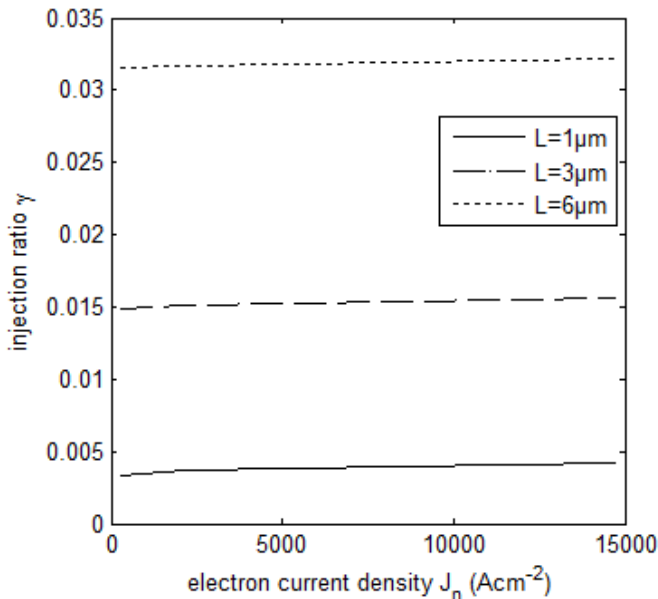


Figure 11. Injection ratio as a function of electron current density for three different device lengths

ratio γ increases as shown. For a particular length, the rate of increase of J_p is very slow. So variation of γ is nearly constant.

IV. Conclusion

Uniformly doped Schottky barrier diode (SBD) with characteristic properties is studied here. The objective of this work is to establish an expression for minority carrier charge storage time. For this purpose, the main challenge is to determine an expression for minority carrier charge (hole) distribution $p(x)$ with respect to device length. Second order nonlinear differential equation is solved for this purpose. Important characteristic plots of $p(x)$, electric field $E(x)$, minority carrier charge storage time τ_s and injection ratio γ are studied. Effects of different doping concentrations and bias voltages on minority carrier charge profile, electric field, storage time, injection ratio are studied. It is observed that with increase of N_d , minority carrier charge storage time τ_s and injection ratio γ increase. The variation of τ_s is nearly independent with S_{eff} but γ increases with S_{eff} . With increase of device length L , minority carrier charge increases, results in

increase of Q_s , τ_s and γ . So to achieve good performance, both length and doping of the SBD should be lower.

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