Diffusion Capacitance of an Epitaxial High Barrier Schottky Diode

by

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DEDICATION

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LIST OF ABBREVIATION OF SYMBOLS

a	Ratio of electron mobility to hole mobility
A^{**}	Effective Richardson constant ($Acm^{-2}K^{-2}$)
A^{*}	Effective Richardson constant for thermionic emission theory ($Acm^{-2}K^{-2}$)
C_d	Diffusion capacitance per unit area (Fcm^{-2})
C_j	Junction capacitance per unit area (Fcm^{-2})
D_n	Diffusion coefficient for electron (cm^2s^{-1})
D_p	Diffusion coefficient for hole (cm^2s^{-1})
E	Electric field (Vcm^{-1})
E_C	Bottom of conduction band (eV)
E_{Fm}	Fermi energy level for metal (eV)
E_{Fs}	Fermi energy level for semiconductor (eV)
E_g	Band gap energy for semiconductor (eV)
E_V	Top of the valence band (eV)
ε_s	Semiconductor permittivity (Fcm^{-1})
ϕ_{Bp}	Schottky barrier height on p-type semiconductor (V)
ϕ_{Bn}	Schottky barrier height on n-type semiconductor (V)
ϕ_m	Metal work function potential (V)
ϕ_s	Semiconductor work function potential (V)
h	Planck's constant (eV-s)
J	Total current density through the device (Acm^{-2})
J_n	Total drift and diffusion electron current density in the drift region (Acm^{-2})
J_p	Total drift and diffusion hole current density in the drift region (Acm^{-2})
J_{n0}	Electron current density at the Schottky contact (Acm^{-2})
J_{p0}	Hole current density at the Schottky contact (Acm^{-2})
J_{ns}	Reverse saturation electron current density (Acm^{-2})
J_{nsD}	Reverse saturation electron current density for diffusion theory (Acm^{-2})
J_{nsT}	Reverse saturation electron current density for thermionic emission theory (Acm^{-2})
k	Boltzmann's constant (eVK^{-1})
L_d	Drift region (n-region) length (cm)
L_p	Hole diffusion length (cm)
m^*	Effective mass of electron (kg)
μ_p	Hole mobility ($cm^2V^{-1}s^{-1}$)
μ_n	Electron mobility ($cm^2V^{-1}s^{-1}$)
n_i	Intrinsic carrier concentration (cm^{-3})
n	Concentration of electron in the drift region (cm^{-3})
n^+	Heavily doped n-type substrate

n	n-type semiconductor material
N_c	Effective density of states in conduction band (cm^{-3})
N_d	Donor concentration in the n-type drift region (cm^{-3})
p	Hole concentration in the drift region (cm^{-3})
p_0	Hole concentration at the Schottky contact (cm^{-3})
p_{Ld}	Hole concentration at the n-n^+ interface (cm^{-3})
Q_p	Magnitude of total stored charge per unit area in the drift region due to hole (Ccm^{-2})
Q_s	Magnitude of charge per unit area in the depletion region (Ccm^{-2})
q	Magnitude of electronic charge (C)
$q\chi$	Electron affinity of the semiconductor measured from the bottom of the conduction band E_C (eV)
qV_n	Energy difference between E_C and the Fermi level (eV)
ρ	Charge density in the depletion region (Ccm^{-3})
S_{eff}	Effective surface recombination velocity (cms^{-1})
T	Temperature (K)
V_{bi}	Built in potential (V)
V_f	Magnitude of applied forward voltage (V)
V_r	Magnitude of applied reverse voltage (V)
V_s	Potential across the Schottky contact (V)
V_T	Thermal voltage (V)
W	Depletion layer width (cm)
x	Distance from the Schottky contact in the n-region (cm)

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ABSTRACT

A Schottky barrier diode is a majority carrier device when the barrier height is low. But, it injects minority carrier at forward bias from the Schottky contact into the semiconductor when the barrier height is high. Minority carrier charge is stored within the drift region of a high barrier Schottky diode due to this minority carrier injection at forward bias. The stored charge in the drift region gives rise to diffusion capacitance that should not be ignored for the high barrier Schottky diode. No literatures have yet been published on the diffusion capacitance of a high barrier Schottky diode. In this work, an analytical expression for diffusion capacitance of an epitaxial high barrier Schottky diode has been developed. The expression is valid for all levels of injection. The effect of different parameters on the diffusion capacitance has been studied. It has been found that the diffusion capacitance depend on the junction voltage, total current density, drift region length and effective surface recombination velocity. The diffusion capacitance depends strongly on the junction voltage, current density and drift region length.

CHAPTER 1

Introduction

1.1 INTRODUCTION

The earliest systematic study of metal–semiconductor contacts is generally attributed to Ferdinand Braun. In 1874, Braun [1] discovered that the resistance of contacts between metals and metallic sulfides (copper pyrites, galenite etc) depended on the magnitude and sign of the applied voltage and on the detailed surface conditions. The point contact rectifier in various forms found practical applications beginning in 1904. After then many literatures have been published on the rectifying metal-semiconductor contacts [2-10]. The nature of the electrical behaviour of rectifying structures is still not understood satisfactorily [7]. Metal semiconductor rectifying contacts are today used for low voltage rectification [3], in fast rectifiers and switches [7], as a bipolar mode Schottky diode [11], in bipolar memory cells [12], in logic circuits such as Integrated Schottky logic (ISL) [12] and Schottky transistor logic (STL) [13-14], in high speed devices such as microwave mixers, samplers, doublers and triplers, limiters, high frequency detectors, power monitors and fast recovery rectifiers [11,15], and as the gate electrodes of MESFETs, the drain and source contact in MOSFETs, the electrodes for high power IMPATT oscillators, the third terminal in a transferred electron device and in the photo detectors and solar cells [16].

In this chapter, we have discussed the basic theory of Schottky barrier diode briefly.

1.2 METAL SEMICONDUCTOR CONTACTS

A metal semiconductor contact may be formed simply by depositing a metal onto a semiconductor. Depending on the metal and the type of semiconductor, such contact may be

a) Rectifying i.e. may allow easy current flow in one direction and block flow of current in other direction. This type of metal-semiconductor contact is called *Schottky barrier diode (SBD)*. A metal-semiconductor contact is rectifying when a metal and an n-type semiconductor having smaller work function than the metal making contact or when a metal and a p-type semiconductor having larger work function than the metal making contact.

b) Non-rectifying i.e. may pass current easily into and out of a junction i.e. in either direction. This type of metal-semiconductor contact is called *ohmic contact*. An ohmic contact may be formed by contacting a metal with an n-type semiconductor having larger work function than the metal or by contacting a metal with a p-type semiconductor having smaller work function than the metal. Ohmic contacts are used as linearly conductive metallic connections to devices and integrated circuits.

1.3 SCHOTTKY BARRIER DIODE

Fig. 1-1 shows a Schottky barrier diode formed by contacting a metal with an n-type semiconductor having smaller work function than the metal

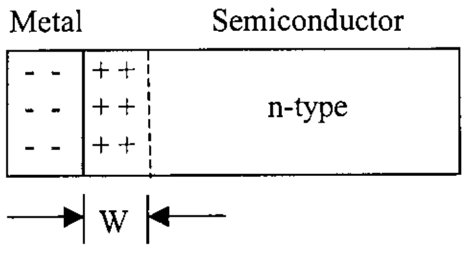

Fig. 1-1. A Schottky barrier diode

Fig.1-2 shows energy-band diagram of the metal and the semiconductor before contacting. $q\phi_m$ is the work function of the metal. The work function is the energy required to remove an electron from the Fermi level to the vacuum level outside. The work function of the semiconductor, $q\phi_s$ is equal to $q(\chi+V_n)$, where $q\chi$ is the electron affinity measured from the bottom of the conduction band E_C to the vacuum level and qV_n is the energy difference between E_C and the Fermi level. q is the charge of electron.

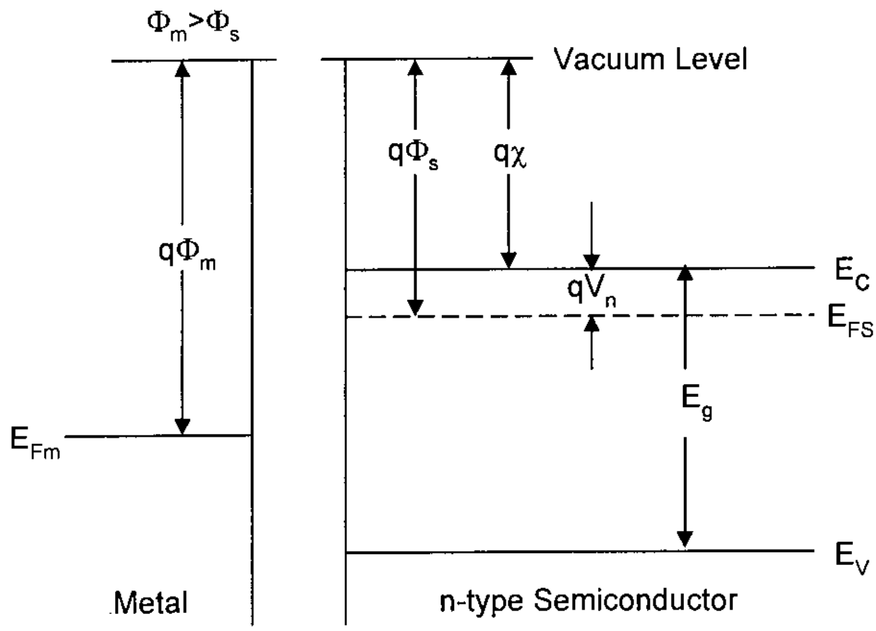

Fig. 1-2 The band diagram of the metal and n-type semiconductor before contacting.

Now when the metal is brought in contact with the semiconductor, the transfer of charge takes place from the semiconductor to the metal until the Fermi levels of the two materials align at thermal equilibrium. To align the two Fermi levels, the electrostatic potential of the semiconductor must be raised (i. e. the electron energies must be lowered) relative to that of the metal. Therefore, the Fermi level in the semiconductor is lowered relative to the Fermi level in the metal by an amount equal to the difference between the two work functions. The potential difference (ϕ_m-ϕ_s) is called the contact potential V_{bi} and it prevents further net electron diffusion from the semiconductor conduction band into the metal.

Fig. 1-3 shows the equilibrium band diagram of the SBD after forming the contact. In the n-type semiconductor a depletion region *W* is formed near the junction. The positive charge due to uncompensated donors ions within *W* matches the negative charge on the metal.

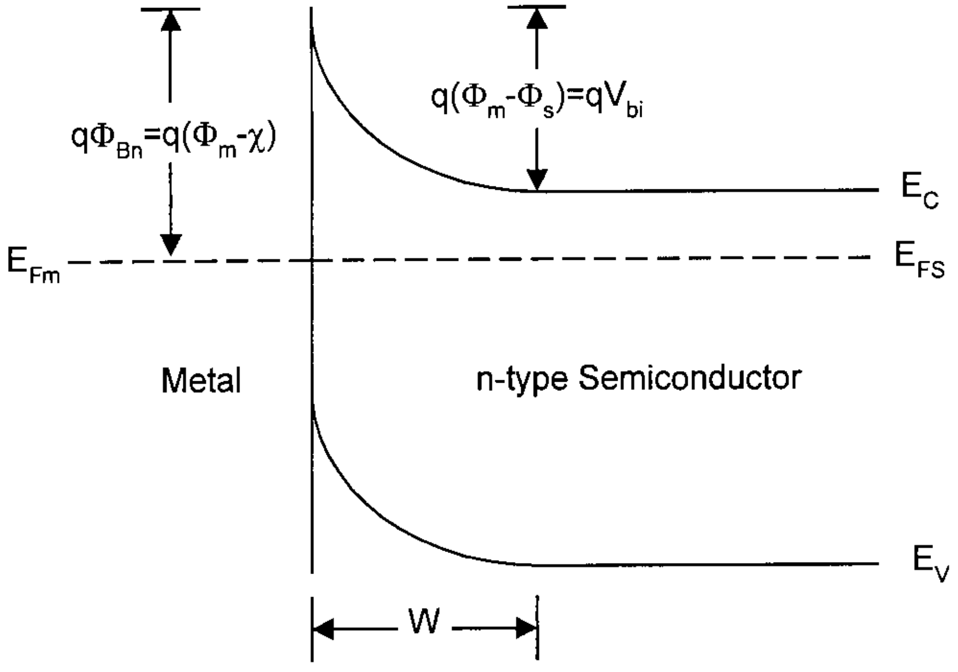

Fig. 1-3 Equilibrium band diagram of the SBD

The barrier height for electron injection from the metal into the semiconductor conduction band is simply the difference between the metal work function and the electron affinity of the semiconductor [16].

$$q\phi_{Bn} = q(\phi_m - \chi) \tag{1.1}$$

For an ideal contact between a metal and a p-type semiconductor, the barrier height $q\phi_{Bp}$ for hole is given by [16]

$$q\phi_{Bp} = E_g - q(\phi_m - \chi) \tag{1.2}$$

1.4 DEPLETION LAYER WIDTH

In the n-region, under abrupt approximation, the charge density can be written as [16]

$$\begin{aligned} \rho(x) &\cong qN_d \quad \text{for } x < W \\ &\cong 0 \quad \text{for } x > W \end{aligned} \tag{1.3}$$

and the potential gradient can be written as

$$\frac{dV(x)}{dx} \cong 0 \quad \text{for } x > W \tag{1.4}$$

where N_d is donor concentration in the n-region.

Under this approximations, the depletion layer width W is given by [16]

$$W = \sqrt{\frac{2\varepsilon_s}{qN_d}(V_{bi} - V_s - V_T)} \tag{1.5}$$

where ε_s is the permittivity of the semiconductor, $V_T = kT/q$ is the thermal voltage, V_s is the applied voltage across the Schottky contact and V_{bi} is the Schottky built in voltage and is given by [16]

$$V_{bi} = \phi_{Bn} - V_T \ln\frac{N_c}{N_d} \tag{1.6}$$

where N_c is the effective density of states at the edge of the conduction band.

The applied voltage across the Schottky contact, V_s can be found from the electron current density of Crowell and Sze's Thermionic Emission-Diffusion theory [17] as

$$V_s = V_T \ln\left(\frac{J_{n0}}{J_{ns}} + 1\right) \tag{1.7}$$

where J_{no} is the electron current density at the metal semiconductor junction and J_{ns} is the reverse saturation current density.

1.5 EFFECT OF FORWARD AND REVERSE BIAS ON THE SBD

The equilibrium potential difference, V_{bi} can be decreased or increased by the application of either forward or reverse bias voltage.

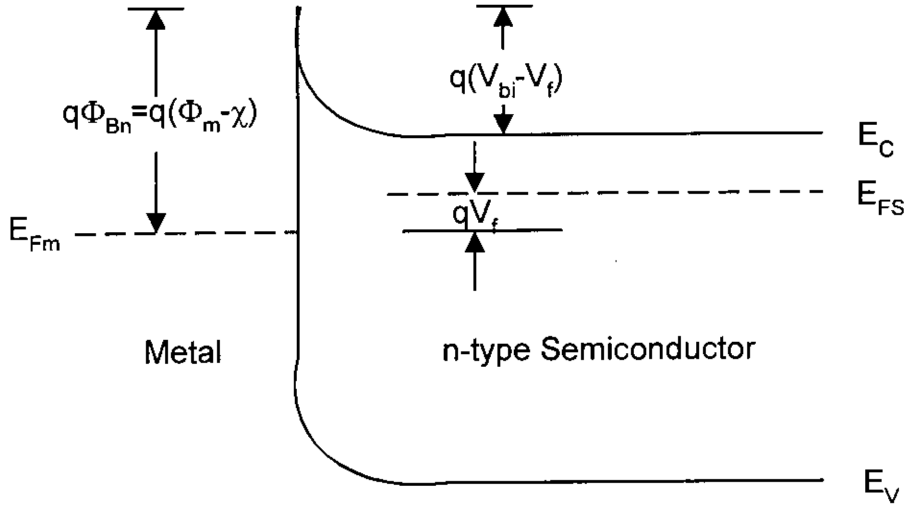

Fig. 1-4 SB junction under Forward Bias

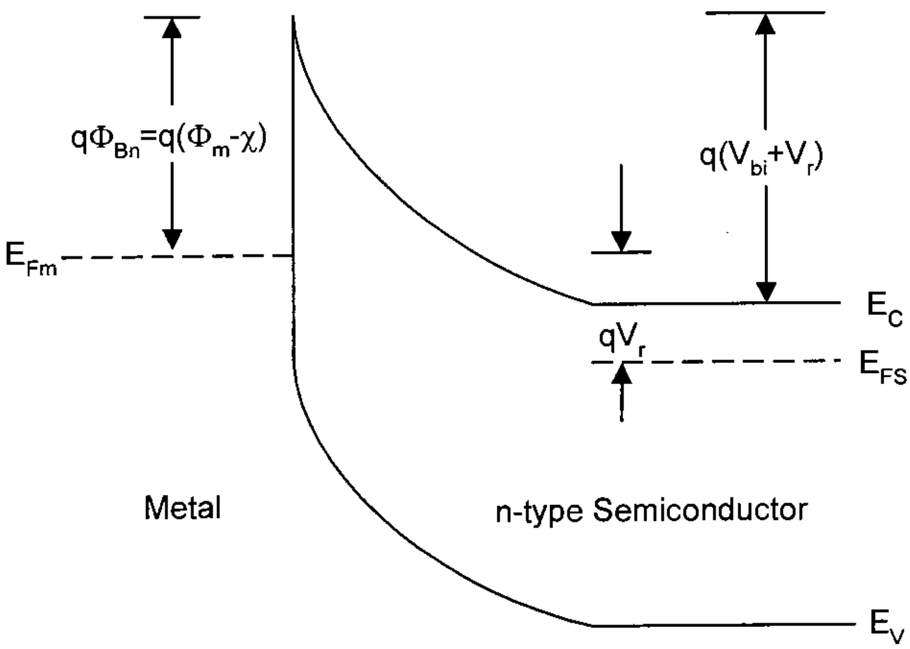

Fig. 1-5 SB junction under Reverse Bias

When a forward bias voltage $V=V_f$ is applied to the Schottky barrier, the contact potential is reduced from V_{bi} to $(V_{bi}-V_f)$. As a result, electrons in the semiconductor conduction band can diffuse across the depletion region to the metal. This gives rise to a forward current through the junction.

On the other hand, a reverse bias voltage $V=-V_r$ increases the barrier to $(V_{bi}+V_r)$, and electron flow from the semiconductor to metal becomes negligible. In either case flow of electrons from the metal to the semiconductor is retarded by the barrier $(\phi_m - \chi)$. Therefore the Schottky barrier diode is rectifying, with easy current flow in the forward direction and little current in the reverse direction. The effect of applying the forward and reverse bias on a rectifying metal semiconductor contact is shown in fig. 1-4 and fig. 1-5.

1.6 CURRENT TRANSPORT PROCESSES

The current transport in metal-semiconductor contacts is mainly due to majority carriers, in contrast to p-n junctions, where the minority carriers are responsible. Fig.1-6 shows four basic transport processes under forward bias for a Schottky barrier diode (the inverse processes occur under reverse bias) [18].

The four processes are

a) transport of electrons from the semiconductor over the potential barrier into the metal [the dominant process for Schottky diodes with moderately doped semiconductors (e.g., S_i with $N_d \leq 10^{17}$ cm^{-3}) operated at moderately temperatures (e.g., 300K)].
b) quantum-mechanical tunneling of electrons through the barrier (important for heavily doped semiconductors and responsible for most ohmic contacts).
c) recombination in the space charge region and
d) hole injection from the metal to the semiconductor

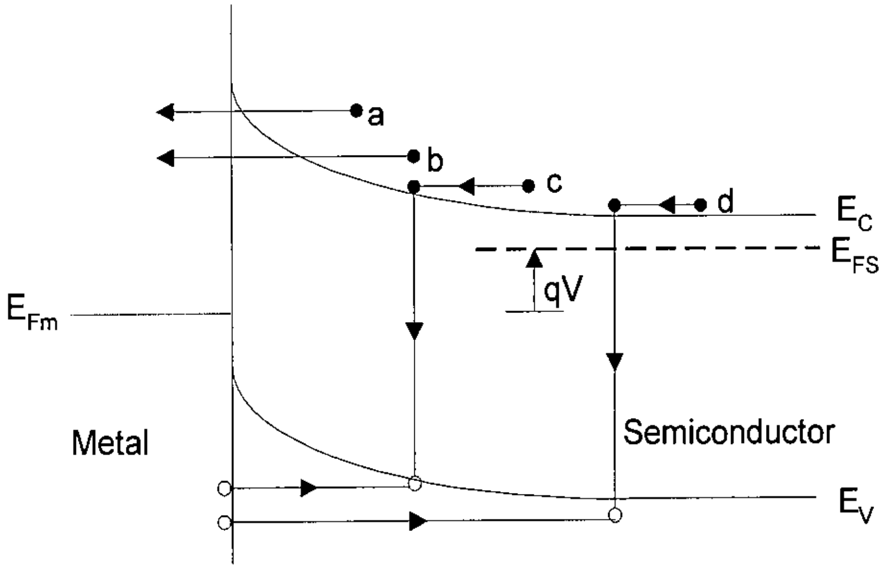

Fig. 1-6 Four basic transport processes under forward bias for a SBD

In addition, we may have edge leakage current due to high electric field at the contact periphery or interface current due to traps at the metal-semiconductor interface.

There are three different theories of transport of electrons over the potential barrier. They are as follows:

a) The Thermionic Emission Theory: This theory is given by H. A. Bethe [20] and is applicable to high mobility semiconductors. According to this theory the thermionic emission electron current density at the junction is given by

$$J_{no} = J_{nsT}\left[\exp\left(\frac{V}{V_T}\right) - 1\right] \tag{1.9}$$

where J_{nsT} is the reverse saturation current density and is given by

$$J_{nsT} = A^* T^2 \exp\left(-\frac{\phi_{Bn}}{V_T}\right) \tag{1.10}$$

where A^* is the effective Richardson constant for thermionic emission, neglecting the effects of optical phonon scattering and quantum mechanical reflection and is given by

$$A^* = \frac{4\pi q m^* k^2}{h^3} \tag{1.11}$$

where m^* is the effective mass of electron, h is the Planck's constant and k is the Boltzmann's constant.

b) The Diffusion theory: This theory is derived by W. Schottky [21] and is applicable to low mobility semiconductors. According to this theory the electron current density at the junction is given by

$$J_{no} = J_{nsD}\left[\exp\left(\frac{V}{V_T}\right) - 1\right] \tag{1.12}$$

where J_{nsD} is the reverse saturation current density and is given by

$$J_{nsD} = \left[\frac{q^2 D_n N_C}{kT}\sqrt{\frac{q(V_{bi} - V)2N_d}{\varepsilon_s}}\right]\exp\left(-\frac{\phi_{Bn}}{V_T}\right) \tag{1.13}$$

The current density expressions of the diffusion and thermionic emission theories are basically very similar. However, the "saturation current density" J_{nsD} for the diffusion theory varies more rapidly with the voltage but is less sensitive to temperature compared with the "saturation current density" J_{nsT} of the thermionic emission theory.

c) The Thermionic Emission- Diffusion theory: This generalized theory is a synthesis of the preceding two theories and proposed by C. R. Crowell and S. M. Sze [17].

According to this theory the electron current density at the junction is given by

$$J_{no} = J_{ns}\left[\exp\left(\frac{V}{V_T}\right) - 1\right] \tag{1.14}$$

where J_{ns} is the reverse saturation current density and is given by

$$J_{ns} = A^{**}T^2 \exp\left(-\frac{\phi_{Bn}}{V_T}\right) \tag{1.15}$$

where A^{**} is the effective Richardson constant and is equal to 110 $Acm^{-2}K^{-2}$ for electron and 30 $Acm^{-2}K^{-2}$ for hole [6].

This model is widely used in different literatures [4-9] for electron current density in the drift region. In the present work, the electron current density has been described by the generalized Thermionic Emission-Diffusion theory.

1.7 HIGH BARRIER SCHOTTKY DIODE

A low barrier Schottky diode is a majority carrier device. As the barrier height for majority carriers (from the semiconductor to the Schottky contact) increases, the barrier height for the minority carriers (from the Schottky contact to the semiconductor) decreases. Therefore injection of minority carrier increases as the barrier height for the majority carrier increases. The minority carrier injection phenomenon becomes increasingly important as the barrier height for the majority carriers increases. So for a high barrier Schottky diode minority carrier have to be considered along with majority carriers. During few decades the high barrier Schottky diode have been the subject of extensive investigation [2-10]. Due to conductivity modulation of the minority carrier in the drift region, the bulk resistance is decreased. Hence forward voltage drop becomes low. That's why, a high barrier Schottky diode is used for low voltage rectification [3]. In power electronics, the SBD and p-n junction diode have been used for rectifying and freewheeling. But, they have their drawbacks: low blocking voltage and low recovery speed respectively. The minority carrier transport at the Schottky contact of a high barrier

Schottky diode can be successfully utilized for improving and optimizing these capabilities. The contact designed specifically for minority-carriers is called bipolar mode Schottky diode [11]. The high barrier Schottky diode also found extensive applications in bipolar memory cells [12], in integrated Schottky logic (ISL)[12], Schottky transistor logic (STL) [13-14], in high speed devices such as microwave mixers, samplers, doublers and triplers, limiters high frequency detectors, power monitors and fast recovery rectifiers [11,15].

1.8 EPITAXIAL SCHOTTKY BARRIER DIODE

The structure of an epitaxial Schottky barrier (SB) diode (a metal-n-n^+ Schottky barrier diode with an n-epitaxial layer and n^+ substrate) is shown in Fig. 1-7. The drift layer is made of lightly doped n-type silicon semiconductor of constant doping density N_d and is bounded by a heavily doped n^+ substrate. W and L_d are the length of the depletion and drift region respectively.

When the Schottky barrier diode is forward biased, holes will be injected into the drift region. Electrons move towards the SB contact leading to a quasi-neutral situation accompanying the hole pile up within the drift region. Blocking of the minority carrier holes by the low-high (n-n+) junction enhances the accumulation of holes within the drift region and the drift region is conductivity modulated.

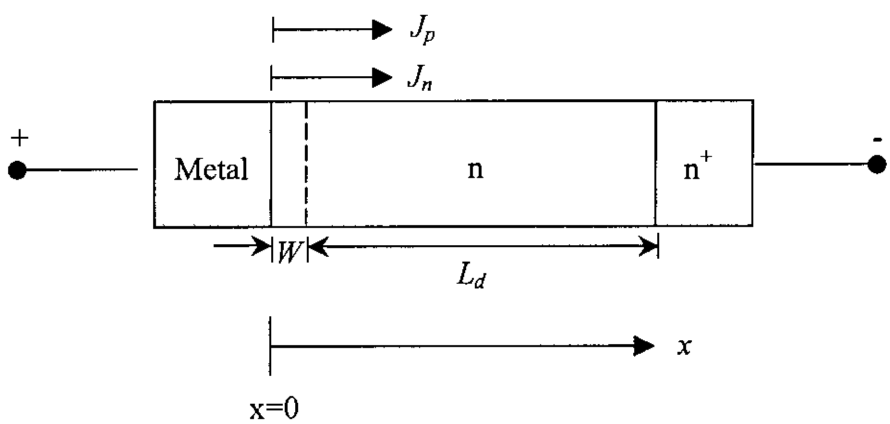

Fig.1-7 A one-dimensional Epitaxial Schottky barrier diode.

The reflecting property of the low-high (n-n+) barrier to the minority carrier flux is characterized by an effective surface recombination velocity S_{eff} [16,22]. This approach has been used by Scharfetter [2], Dutton [23], Chuang [4], Ng. et al [6], Prokoyev et al. [8], Hassan [9].

The hole current density at the low-high junction in terms of S_{eff} is given by

$$J_p(x = L_d) = qS_{eff}\, p_{L_d} \tag{1.16}$$

where p_{L_d} is the concentration of injected hole at the n-n+ junction.

1.9 CAPACITANCES OF A SCHOTTKY BARRIER DIODE

There are basically two types of intrinsic capacitances associated with a junction:

a) The junction capacitance: the junction capacitance is due to dipole in the transition region. The junction capacitance is also referred to as transition region capacitance or depletion layer capacitance.

   The junction capacitance is dominant under reverse bias conditions. The junction capacitance per unit area is defined as

$$C_j = \frac{dQ_s}{dV_s} \tag{1.17}$$

   where V_s is the voltage across the Schottky contact and Q_s is the magnitude of charge per unit area in the depletion region.

   From eqn. (1.5), Q_s is given by

$$Q_s = qN_dW = \sqrt{2q\varepsilon_s N_d (V_{bi} - V_s - V_T)} \tag{1.18}$$

b) The charge storage capacitance: the charge storage capacitance, arising from the lagging behind of voltage as current changes, is due to storage of minority carrier in the drift region. The charge storage capacitance is also referred to as diffusion capacitance. The diffusion capacitance is dominant when the junction is forward bias.

The diffusion capacitance per unit area is defined as

$$C_d = \frac{dQ_p}{dV_s} \tag{1.19}$$

where V_s is the voltage across the Schottky contact and Q_p is the magnitude of stored charge due to minority carrier (hole) per unit area in the drift region. Q_p is given by

$$Q_p = q\int p(x)dx \tag{1.20}$$

where *p(x)* is the density of hole in the drift region.

1.10 OBJECTIVE OF THE THESIS

A Schottky barrier (SB) diode is a majority carrier device when the barrier height is low. The total current is due to majority carrier only and the *J-V* characteristic is given by the exponential relationship. But, when the barrier height is high (greater than 0.7 V [3]), the minority carriers are injected from the Schottky contact into the semiconductor [2-9]. Therefore, the total current is not only due to majority carriers but also due to minority carriers. Therefore, the forward *J-V* characteristics are significantly altered from the classical exponential relationship. Several literatures have been published on the minority carrier storage and *J-V* characteristics of high barrier Schottky diode [2-9]. In 1965, D. L. Scharfetter first analyzed the minority-carrier injection and charge storage of an epitaxial Schottky barrier diode [2]. In 1984 C. T. Chuang [4] and in 1999 A. I. Prokopyev et al [8] showed that the minority carrier injection should be take into account for high barrier Schottky diode under high level injection and the current voltage characteristics of epitaxial Schottky barrier diode differ significantly from the low barrier Schottky diodes. They showed that the forward voltage drop is less for high barrier Schottky diode than for low barrier Schottky diode due to base conductivity modulation. Prokopyev et al. suggested that the injection level (i.e. the carrier density ratio) should be a more important parameter than the injection ratio to describe storage and base conductivity modulation. In 1990 W. T. Ng. et al. [6] and in 2000 M. M. Shahidul Hassan [9] investigated the characteristics of an epitaxial high barrier Schottky diode considering the recombination in the drift region.

Since minority carriers are injected for high barrier Schottky diode and cannot be neglected especially under high injection condition, diffusion capacitance must be considered for a high barrier Schottky diode under forward bias. Thus the diffusion capacitance is an unavoidable aspect for a high barrier Schottky diode under forward bias. No literatures have yet been published on the diffusion capacitance of a high barrier Schottky diode as far as we know.

The objective of this thesis is to study the diffusion capacitance of an epitaxial high barrier Schottky diode.

1.11 CONCLUSIONS

In this chapter, the basic concepts of metal-semiconductor rectifying contacts have been discussed succinctly. The injection of minority carrier of a high barrier Schottky diode at forward bias has been discussed in this chapter. The applications of high barrier epitaxial Schottky diode in modern devices have been discussed exclusively. The special emphases on high barrier Schottky diode given in current literatures have also been discussed. It can be concluded from this chapter that the diffusion capacitance of an epitaxial high barrier Schottky diode has to be considered due to significant minority carrier injection at forward bias under high-level injection.

In chapter 2, we have developed an analytical expression for diffusion capacitance for an epitaxial high barrier Schottky diode after deducing the expression for hole profile within the drift region. Based on the analytical models developed in chapter 2, the hole profile in the drift region, electric field distributions within the drift region and diffusion capacitance have been studied in chapter 3. Chapter 4 contains the concluding remarks along with suggestions for future work on this topic.

CHAPTER 2

Mathematical Derivations

2.1 INTRODUCTION

In chapter 1, we have discussed the necessary basic theory of a metal-semiconductor junction. In that chapter, we have discussed that a high barrier epitaxial Schottky diode injects minority carriers although a low barrier Schottky diode is a majority carrier device. Due to this minority carrier injection in the n-region minority carrier charge is stored in that region. The stored charges in the n-region give rise to diffusion capacitance in the forward bias and that is not negligible for Schottky barrier diode when the barrier height is high.

In this chapter, we have deduced an analytical expression for diffusion capacitance for an epitaxial high barrier Schottky diode. For studying the diffusion capacitance of an SBD, the minority carrier distribution profile within the n-region is required when the SBD is forward biased. After deriving the expression for hole profile in the n-region, we have derived an expression for minority carrier charge storage. From this expression for stored charge, we shall be able to obtain an analytical expression for diffusion capacitance. Recently, Hassan [9] and Ng. et al. [6] studied the J-V characteristics of an epitaxial high barrier Schottky diode considering the recombination in the drift region. In those literatures, the analysis has been divided into three regions of operation: low, intermediate and high level of injection. For each region they have taken simplifying assumptions because if recombination is considered, it is not possible to find a single analytical expression for hole distribution profile in the n-region and therefore diffusion capacitance due to storage of hole in the n-region. Moreover, the analysis is rigorous and expression becomes very complex. Practically, the length of the drift region is less than the length of the diffusion length for hole. For practical devices, the recombination in the drift region is insignificant and can, therefore, be neglected.

If we neglect the recombination in the drift region a single expression for hole distribution profile can be obtained and the resulting expressions becomes more compact and simple. In our analysis, we describe the n-n$^+$ junction by an effective surface recombination velocity.

2.2 ANALYSIS

The one-dimensional structure of an epitaxial Schottky barrier diode is shown in Fig. 2.1 showing the directions of hole and electron currents.

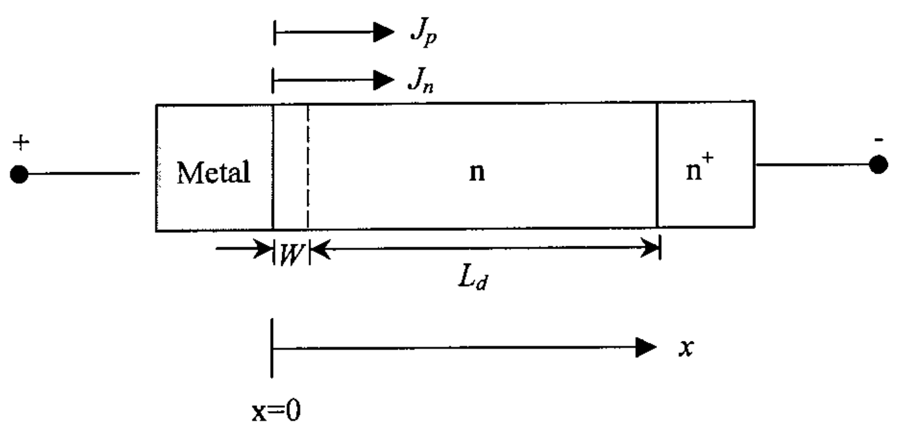

Fig. 2-1 A one-dimensional Epitaxial Schottky barrier diode.

The epitaxial layer of the Schottky barrier diode is made of lightly doped n-type silicon semiconductor of constant doping density N_d and is bounded by a heavily doped n$^+$ substrate. W and L_d are the length of the depletion and epitaxial layer respectively.

When the SBD is forward biased, holes will be injected into the drift region. Electrons move towards the SB contact leading to a quasi-neutral situation accompanying the hole pile up within the drift region. Blocking of the holes by the low-high (n-n+) junction enhances its accumulation within the drift region and the drift region is conductivity modulated. The reflecting property of the low-high (n-n+) barrier to the minority carrier flux is characterized by an effective surface recombination velocity S_{eff} [16,22].

The fundamental one-dimensional transport equations within the drift region (n-region), assuming the origin of the x-axis at the metal-semiconductor contact, are given by the following equations:

$$J_n(x) = q\mu_n n(x)E(x) + qD_n \frac{dn(x)}{dx} \tag{2.1}$$

$$J_p(x) = q\mu_p p(x)E(x) - qD_p \frac{dp(x)}{dx} \tag{2.2}$$

where, $n(x)$= the concentration of electrons in the drift region in cm^{-3}.

$p(x)$= the concentration of holes in the drift region in cm^{-3}.

$J_n(x)$= the total drift and diffusion electron current density in the n-region in A/cm^2.

$J_p(x)$= the total drift and diffusion hole current density in the n-region in A/cm^2.

$E(x)$= the electric field in the drift region in Vcm^{-1}.

μ_n= the mobility of electron in $cm^2V^{-1}s^{-1}$.

μ_p= the mobility of hole in $cm^2V^{-1}s^{-1}$.

D_n= the Diffusion coefficient of electron in cm^2s^{-1}.

D_p= the Diffusion coefficient of hole in cm^2s^{-1}.

The mobility of electron and hole depend on the doping density of the silicon [24-25]. The diffusion coefficients can be found from the Einstein relation [16] as

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} = V_T \tag{2.3}$$

where, k is the Boltzmann's constant and T is the temperature in K.

If we neglect the recombination within the drift region, the electron current density and hole current density become constant separately throughout the drift region.

$$J_n(x) = cons\tan t; \quad 0 \le x \le L_d \tag{2.4}$$

$$J_p(x) = cons\tan t; \quad 0 \le x \le L_d \tag{2.5}$$

The quasi-space charge neutrality conditions in the drift region requires that

$$p(x) + N_d = n(x); \quad W \le x \le L_d \tag{2.6}$$

Now, the width of the depletion region, W is very small as compared to the length of drift layer, L_d [6]. Therefore, the value of $p(x)$ at $x=W$ can be taken equal to the value of $p(x)$ at $x=0$. Therefore, eqn (2.6) can be written as

$$p(x) + N_d = n(x); \quad 0 \le x \le L_d \tag{2.7}$$

Differentiating eqn (2.7), one gets

$$\frac{dp(x)}{dx} = \frac{dn(x)}{dx}; \quad 0 \le x \le L_d \tag{2.8}$$

In eqn (2.7), N_d is considered constant.

2.2.1 HOLE PROFILE IN THE DRIFT REGION

Using eqn (2.3) and eqn (2.8), eqn (2.1) can be written as

$$\frac{J_n}{q\mu_n} = nE + V_T \frac{dp}{dx} \tag{2.9}$$

Similarly, using eqn (2.3), eqn (2.2) can written as

$$\frac{J_p}{q\mu_p} = pE - V_T \frac{dp}{dx} \tag{2.10}$$

After adding eqn (2.9) with eqn (2.10) and then using eqn (2.7), the electric field within the drift region is given by

$$E(x) = \frac{1}{q(2p + N_d)} \left(\frac{J_n}{\mu_n} + \frac{J_p}{\mu_p} \right) \tag{2.11}$$

Substituting the value of E from eqn (2.11) into eqn (2.2), we obtain

$$dp + \left[\frac{p - \dfrac{aN_d J_p}{(J_n - aJ_p)}}{p - \dfrac{aN_d J_p}{(J_n - aJ_p)}} \right] dp = \frac{1}{2qD_n}(J_n - aJ_p)dx \tag{2.12}$$

where, a is the ratio of electron mobility to hole mobility and is given by

$$a = \frac{\mu_n}{\mu_p} = \frac{D_n}{D_p} \tag{2.13}$$

Integrating eqn (2.12), we obtain

$$p(x) - p_0 + \left[\frac{N_d(J_n + aJ_p)}{2(J_n - aJ_p)} \right] \ln \left[\frac{p(x) - \left\{ \dfrac{aN_d J_p}{\left(J_p - aJ_p\right)} \right\}}{\left\{ p_0 - \dfrac{aN_d J_p}{(J_n - aJ_p)} \right\}} \right] = \frac{1}{2qD_n}(J_n - aJ_p)x \tag{2.14}$$

where, $p(x)$ is the hole concentration at x and p_0 is the hole concentration at x=0. The value of p_0 can be found by solving pn product and quasi-neutrality condition. The value of p_0 is given by [26]

$$p_0 = \frac{\sqrt{N_d^2 + 4n_i^2 e^{\frac{V_s}{V_T}}} - N_d}{2} \tag{2.15}$$

Eqn (2.14) is a transcendental equation and can only be solved numerically to obtain the value of $p(x)$ for different values of x if the other variables are known.

Assuming at $x = L_d$, $p(x) = p_{Ld}$, therefore eqn (2.14) at $x=L_d$ becomes

$$p_{Ld} - p_0 + \left[\frac{N_d(J_n + aJ_p)}{2(J_n - aJ_p)}\right]\ln\left[\frac{p_{Ld} - \dfrac{aN_dJ_p}{(J_n - aJ_p)}}{p_0 - \dfrac{aN_dJ_p}{(J_n - aJ_p)}}\right] = \frac{1}{2qD_n}(J_n - aJ_p)L_d \qquad (2.16)$$

2.2.2 HOLE CURRENT DENSITY

The expression for hole current density can be found by applying boundary condition at $x=L_d$. The value of the injected minority carriers at $x=L_d$ from eqn (1.16) can be written as

$$p_{Ld} = \frac{J_p(x = L_d)}{qS_{eff}} = \frac{J_p}{qS_{eff}} \qquad (2.17)$$

Combining eqn (2.16) and eqn (2.17), we get

$$\frac{J_p}{qS_{eff}} - p_0 + \left[\frac{N_d(J_n + aJ_p)}{2(J_n - aJ_p)}\right]\ln\left[\frac{\dfrac{J_p}{qS_{eff}} - \dfrac{aN_dJ_p}{(J_n - aJ_p)}}{p_0 - \dfrac{aN_dJ_p}{(J_n - aJ_p)}}\right] = \frac{1}{2qD_n}(J_n - aJ_p)L_d \qquad (2.18)$$

Also this is a transcendental equation and can only be solved numerically to obtain the value of J_p for different values of V_s if the other variables are known.

2.2.3 ELECTRON CURRENT DENSITY

The electron current at $x=0$ is given by the Crowell and Sze [17] and is expressed as

$$J_{n0} = (A^{**}T^2 e^{\frac{-q\phi_{Bn}}{kT}})(e^{\frac{qV_s}{kT}} - 1) \qquad (2.19)$$

where, A^{**} is the effective Richardson constant and equals 110 $Acm^{-2}K^{-2}$ for electron and 30 $Acm^{-2}K^{-2}$ for hole [6], V_s is the voltage across the Schottky barrier junction in volts and J_{ns} is the reverse saturation electron current density in Acm^{-2}

In absence of the recombination within the drift region, electron current density can be written as

$$J_n(x) = J_{n0} = J_{ns}(e^{\frac{V_s}{V_T}} - 1) \tag{2.20}$$

Where, J_{ns} is given by

$$J_{ns} = (A^{**}T^2 e^{\frac{-q\phi_{Bn}}{kT}}) \tag{2.21}$$

The electron current density for any V_s can be found from eqn (2.20).

2.2.4 STORED CHARGE DUE TO HOLE

The total stored charge per unit area within the drift region due to hole can be given by

$$Q_p = q\int_0^{L_d} p(x)dx \tag{2.22}$$

where, $p(x)$ can be found from eqn (2.14). But, this is a transcendental equation and therefore $p(x)$ cannot be expressed as a function of other variables. So, direct substitution of $p(x)$ is not possible. We shall derive an analytical expression for Q_p in a different way. Eqn (2.12) can be rearranged as

$$qaD_p(2p + N_d)dp = p(J_n - aJ_p)dx - aN_dJ_pdx \tag{2.23}$$

Multiplying both sides of eqn (2.23) by q and integrating the result from x=0 to x=L_d, we obtain

$$q^2aD_p\int_{p_0}^{p_{Ld}} (2p + N_d)dp = (J_n - aJ_p).(q\int_0^{L_d} pdx) - qaN_dJ_p\int_0^{L_d} dx \tag{2.24}$$

Using eqn (2.22) and upon integration to above equation the expression for total stored charge due to injected hole in the drift region becomes

$$Q_p = \frac{q^2 D_n}{(J_n - aJ_p)}\{(p_{Ld}^2 + N_d p_{Ld}) - (p_0^2 + N_d p_0)\} + \frac{qaL_d N_d J_p}{(J_n - aJ_p)} \tag{2.25}$$

Using eqn (2.15), eqn (2.25) can be written as

$$Q_p = \frac{q^2 D_n}{(J_n - aJ_p)}\{(p_{Ld}^2 + N_d p_{Ld}) - n_i^2 e^{\frac{V_s}{V_T}}\} + \frac{qaL_d N_d J_p}{(J_n - aJ_p)} \tag{2.26}$$

2.2.5 DIFFUSION CAPACITANCE

The diffusion capacitance is defined as

$$C_d = \frac{dQ_p}{dV_s} \tag{2.27}$$

where, Q_p is the total stored charge per unit area within the drift region due to hole. Putting the value of Q_p from eqn (2.26) into eqn (2.27), the diffusion capacitance per unit area becomes

$$\begin{aligned} C_d &= \left[\frac{q^2 D_n (2p_{Ld} + N_d)(J_n - aJ_p)}{(J_n - aJ_p)^2}\right]\frac{dp_{Ld}}{dV_s} \\ &+ \left[\frac{q^2 D_n n_i^2 e^{\frac{V_s}{V_T}} - qaL_d N_d J_p - q^2 D_n (p_{Ld}^2 + N_d p_{Ld})}{(J_n - aJ_p)^2}\right]\frac{dJ_n}{dV_s} \\ &+ \left[\frac{q^2 a D_n (p_{Ld}^2 + N_d p_{Ld}) - q^2 a D_n n_i^2 e^{\frac{V_s}{V_T}} + qaL_d N_d J_n}{(J_n - aJ_p)^2}\right]\frac{dJ_p}{dV_s} - \frac{q^2 D_n n_i^2 e^{\frac{V_s}{V_T}}}{V_T (J_n - aJ_p)} \end{aligned} \tag{2.28}$$

Substituting the value of J_p from eqn (1.16) into eqn (2.28), we get

$$C_d = C_1 \frac{dp_{Ld}}{dV_s} + C_2 \frac{dJ_n}{dV_s} - \frac{q^2 D_n n_i^2 e^{\frac{V_s}{V_T}}}{V_T (J_n - aJ_p)} \tag{2.29}$$

where, C_1 and C_2 are arbitrary constant and are given by the following equations

$$C_1 = \left[\frac{\left\{ \begin{array}{l} q^2 D_n (2p_{Ld} + N_d)(J_n - aJ_p) + q^3 aD_n S_{eff} (p_{Ld}^2 + N_d p_{Ld}) \\ -q^3 aD_n n_i^2 S_{eff} e^{\frac{V_s}{V_T}} + q^2 aL_d N_d S_{eff} J_n \end{array} \right\}}{(J_n - aJ_p)^2} \right] \tag{2.30}$$

$$C_2 = \frac{q^2 D_n n_i^2 e^{\frac{V_s}{V_T}} - qaL_d N_d J_p - q^2 D_n (p_{Ld}^2 + N_d p_{Ld})}{(J_n - aJ_p)^2} \tag{2.31}$$

Differentiating eqn (2.16) with respect to V_s, the value of $\frac{dp_{Ld}}{dV_s}$ can be found as

$$\frac{dp_{Ld}}{dV_s} = \left[\frac{(1 - C_5)}{(1 + C_3 + C_6 + C_9)} \right] \frac{dp_0}{dV_s} + \left[\frac{(C_8 + C_7 - C_4)}{(1 + C_3 + C_6 + C_9)} \right] \frac{dJ_n}{dV_s} \tag{2.32}$$

Where, C_3, C_4, C_5, C_6, C_7, C_8 and C_9 are arbitrary constant and are given by the following equations

$$C_3 = \left[\left\{ \frac{N_d}{2} \frac{(J_n + aJ_p)}{(J_n - aJ_p)} \right\} \frac{\left\{ \begin{array}{l} (p_0 J_n^2 - 2ap_0 J_p J_n - aN_d J_p J_n + a^2 p_0 J_p^2 + a^2 N_d J_p^2 \\ -qap_0 N_d S_{eff} J_n + qap_{Ld} N_d S_{eff} J_n) \end{array} \right\}}{(p_{Ld} J_n - ap_{Ld} J_p - aN_d J_p)(p_0 J_n - ap_0 J_p - aN_d J_p)} \right] \tag{2.33}$$

$$C_4 = \frac{N_d}{2} \frac{(J_n + aJ_p)}{(J_n - aJ_p)} \frac{(ap_0 N_d J_p - ap_{Ld} N_d J_p)}{(p_{Ld} J_n - ap_{Ld} J_p - aN_d J_p)(p_0 J_n - ap_0 J_p - aN_d J_p)} \tag{2.34}$$

$$C_5 = \frac{N_d}{2}\frac{(J_n + aJ_p)}{(J_n - aJ_p)}\frac{(2ap_{Ld}J_pJ_n - p_{Ld}J_n^2 + aN_dJ_pJ_n - a^2p_{Ld}J_p^2 - a^2N_dJ_p^2)}{(p_{Ld}J_n - ap_{Ld}J_p - aN_dJ_p)(p_0J_n - ap_0J_p - aN_dJ_p)} \quad (2.35)$$

$$C_6 = \frac{qaS_{eff}N_dJ_n}{(J_n - aJ_p)^2}\ln\frac{p_{Ld}J_n - ap_{Ld}J_p - aN_dJ_p}{p_0J_n - ap_0J_p - aN_dJ_p} \quad (2.36)$$

$$C_7 = \frac{aN_dJ_p}{(J_n - aJ_p)^2}\ln\frac{p_{Ld}J_n - ap_{Ld}J_p - aN_dJ_p}{p_0J_n - ap_0J_p - aN_dJ_p} \quad (2.37)$$

$$C_8 = \frac{L_d}{2qD_n} \quad (2.38)$$

$$C_9 = \frac{aL_dS_{eff}}{2D_n} \quad (2.39)$$

Now substituting $\frac{dp_{Ld}}{dV_s}$ from eqn (2.32) into eqn (2.29), the diffusion capacitance can be expressed as

$$C_d = \left[\frac{C_1(1 - C_5)}{(1 + C_3 + C_6 + C_9)}\right]\frac{dp_0}{dV_s} + \left[\frac{C_1(C_8 + C_7 - C_4)}{(1 + C_3 + C_6 + C_9)} + C_2\right]\frac{dJ_n}{dV_s} - \frac{q^2D_nn_i^2e^{\frac{V_s}{V_T}}}{V_T(J_n - aJ_p)} \quad (2.40)$$

Putting the value of p_0 and J_n from eqn (2.15) and eqn (2.20) into eqn (2.40), the expression for diffusion capacitance finally becomes

$$C_d = \left[A\left\{\frac{n_i^2}{(2p_0 + N_d)}\right\} + BJ_{ns} - \frac{q^2D_nn_i^2}{(J_n - aJ_p)}\right]e^{\frac{V_s}{V_T}} \quad (2.41)$$

where, A and B are arbitrary constant and are given by the following equations

$$A = \frac{C_1(1 - C_5)}{V_T(1 + C_3 + C_6 + C_9)} \tag{2.42}$$

$$B = \frac{1}{V_T}\left[\frac{C_1(C_8 + C_7 - C_4)}{(1 + C_3 + C_6 + C_9)} + C_2\right] \tag{2.43}$$

2.3 CONCLUSIONS

In this chapter, we have derived an analytical expression for diffusion capacitance of an epitaxial high barrier Schottky diode. At first, the hole profile in the drift region is derived assuming no recombination within the drift region and considering recombination at the low-high junction. Knowing the hole concentration in the drift region, an analytical expression for total stored charge in the drift region is deduced by simply integrating the hole concentration with respect to distance. The diffusion capacitance is determined by differentiating the total stored charge in the drift region with respect to the junction voltage.

The results based on analytical solutions of this chapter are given in the next chapter.

CHAPTER 3

Results and Discussions

3.1 INTRODUCTION

In this thesis, we are studying the diffusion capacitance of an epitaxial high barrier Schottky diode. The necessary basic theory has been discussed in chapter 1 briefly. For finding mathematical expression for diffusion capacitance, the hole density profile, electric field, hole current density within the drift region are required. The equations are derived in chapter 2 and using these equations, expression for diffusion capacitance is obtained. Using these analytical equations, computer programs have been written and results are computed varying different parameters.

In this chapter, we have plotted the hole density profile and electric field as a function of distance from the Schottky contact. The effect of different parameter such as length of drift region, effective surface recombination velocity and junction voltage on the hole concentration distribution and electric field distribution are studied. Diffusion capacitance has been plotted as a function of junction voltage. The diffusion capacitance of the epitaxial high barrier Schottky diode has also been plotted with total current density to show the dependency of diffusion capacitance with current. Comparison has been made varying the length of drift region among the curves. The diffusion capacitance has been plotted with respect to drift region length. The effects of effective surface recombination velocity and junction voltage on the plots have been studied. All studies are performed for barrier height of 0.85 Volts (Pt-Si diode). The parameters required for the computational work are taken from table 3.1.

3.2 MINORITY CARRIER PROFILE IN THE DRIFT REGION

The hole concentration profile derived in chapter 2 eqn (2.14), is a transcendental equation and can only be solved numerically to obtain the value of *p(x)* for different values of *x* if other variables (J_n, p_0, μ_n, μ_p, D_n, D_p, a, J_p) are known.

TABLE 3.1 Parameters used in the calculation

Parameters	Value used	Units
n_i	$1.5*10^{10}$	cm^{-3}
A^{**}	110	$Acm^{-2}K^{-2}$
ϕ_{Bn}	0.85	V
L_d	10-30	μm
N_d	$5*10^{13}$-$5*10^{14}$	cm^{-3}
S_{eff}	500-2000	cms^{-1}

For a given value of V_s, p_0 and J_n can be computed using eqn (2.15) and eqn (2.20) respectively. The dependence of mobilities on the doping concentrations are considered in this work and are given by [24-25].

$$\mu_n = 88 + \left(\frac{1252}{1 + 0.698 \times 10^{-17} N_d} \right) \tag{3.1}$$

$$\mu_p = 54.3 + \left(\frac{407}{1 + 0.374 \times 10^{-17} N_d} \right) \tag{3.2}$$

Using eqn (3.1) and eqn (3.2), the electron and hole diffusion coefficients and mobility ratio can be determined from eqn (2.3) and eqn (2.13). Using these calculated values of J_n, p_0, μ_n, μ_p, D_n, D_p and a, the values of J_p can be calculated from eqn (2.18). *p(x)* are calculated from eqn (2.14) and are plotted in fig. 3.1, 3.2 and 3.3 respectively.

Fig. 3.1 shows the hole density distribution within the drift region for three different values of L_d while fig. 3.2 and fig. 3.3 illustrate the distribution with S_{eff} and V_s as parameter respectively. It is seen from fig. 3.1 that for a particular value of L_d the hole concentration increases with x. As x increases, there is more hole accumulation as predicted by eqn (2.14). Therefore, the hole accumulation at x=20 μm will be greater than at x=10 μm and similar for other values of x and the slope of the curve with higher L_d will be higher. Since the recombination in the drift region is neglected, the hole concentration varies almost linearly with the distance x. This result is similar to the one observed by Ng et al [6].

The effect of S_{eff} on the $p(x)$-x characteristics is shown in fig 3.2. The hole density $p(x)$ at x=0 is constant, but at $x=L_d$ it depends on S_{eff} and p_{Ld} becomes higher for lower S_{eff}. When the low-high (n-n$^+$) interface is less transparent to holes, more holes are piled up and as a result p_{Ld} increases with decrease of S_{eff}.

Distribution of hole concentration within the drift region of the epitaxial high barrier Schottky diode is shown in fig 3.3. The curve shows that the concentration of holes in the drift region increases with junction voltage V_s. The hole concentration at x=0 depends on the junction voltage and increases with it as predicted by eqn (2.15). The hole concentration increases with distance as can be seen from fig. 3.1. Therefore, the hole concentration with higher junction voltage will also be higher and the slope of the p (x) curve with higher V_s will be higher.

3.3 ELECTRIC FIELD DISTRIBUTION

The electric field distribution within the drift region for various L_d is shown in fig. 3.4 while the distribution with S_{eff} as parameter is shown in fig. 3.5. After calculating J_n, μ_n, μ_p, J_p and $p(x)$ in previous section, the electric field is calculated using eqn (2.11).

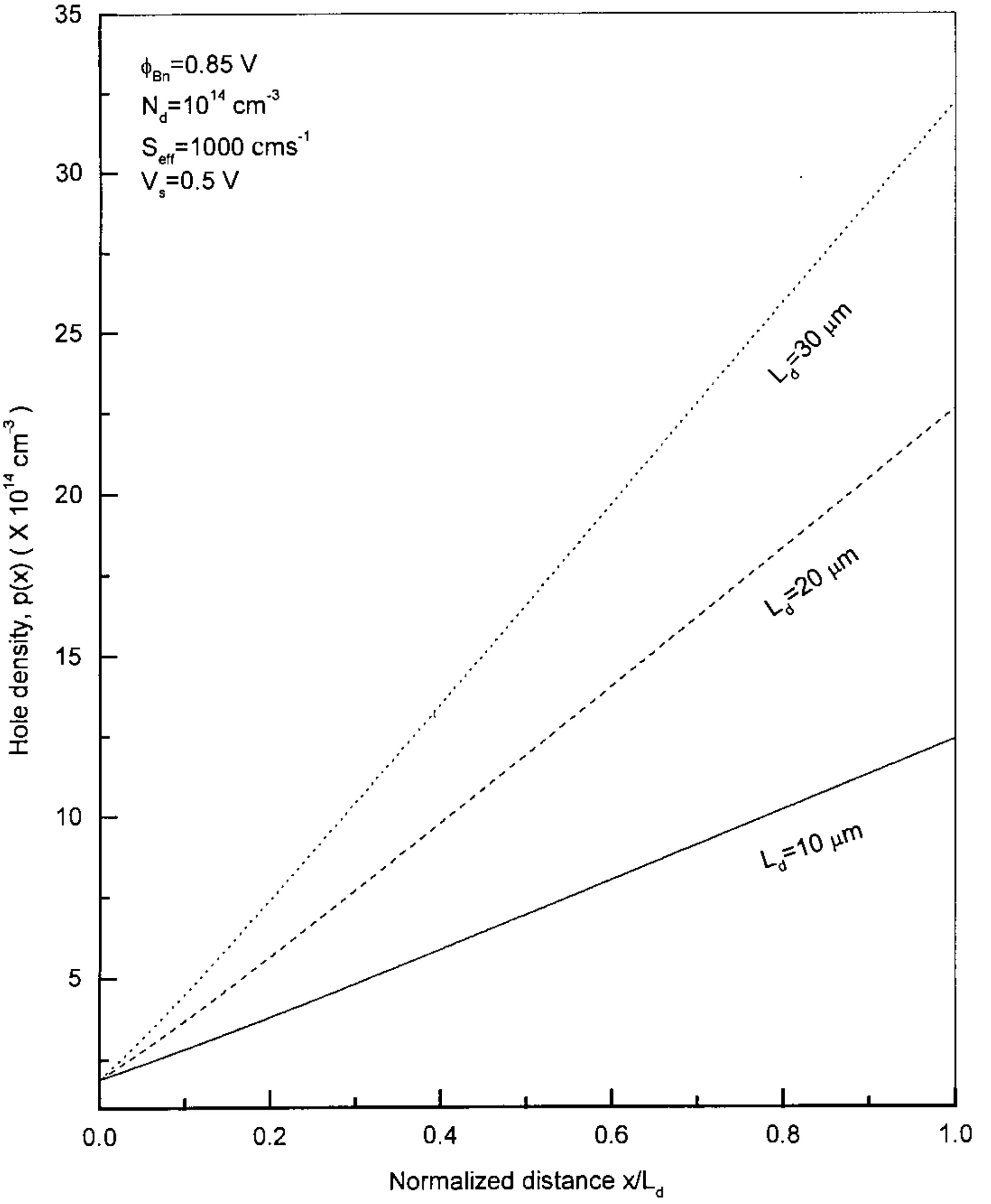

Fig. 3.1: The hole density distribution within the drift region for different drift region lengths.

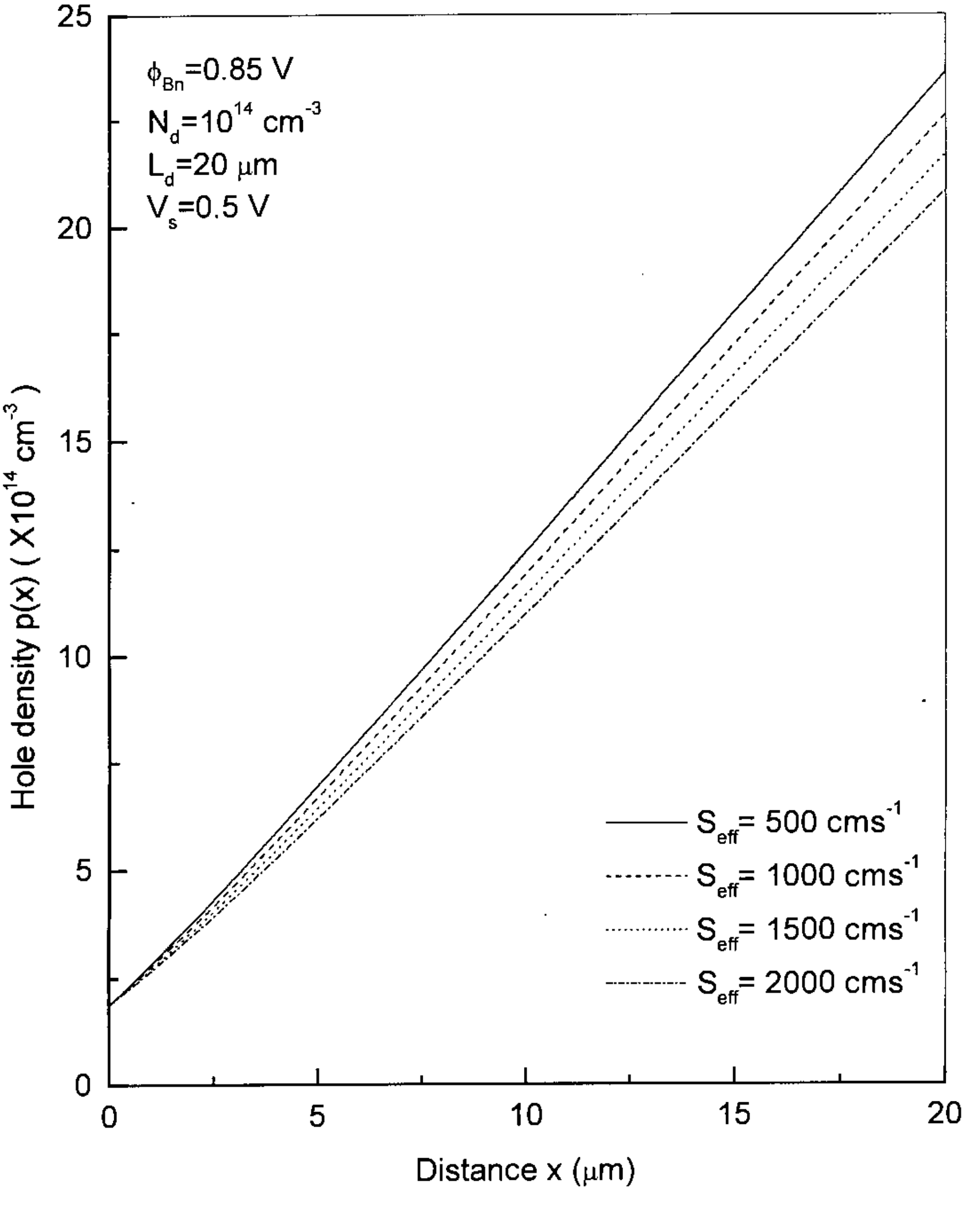

Fig 3.2: Hole density as a function of distance for various values of effective surface recombination velocity.

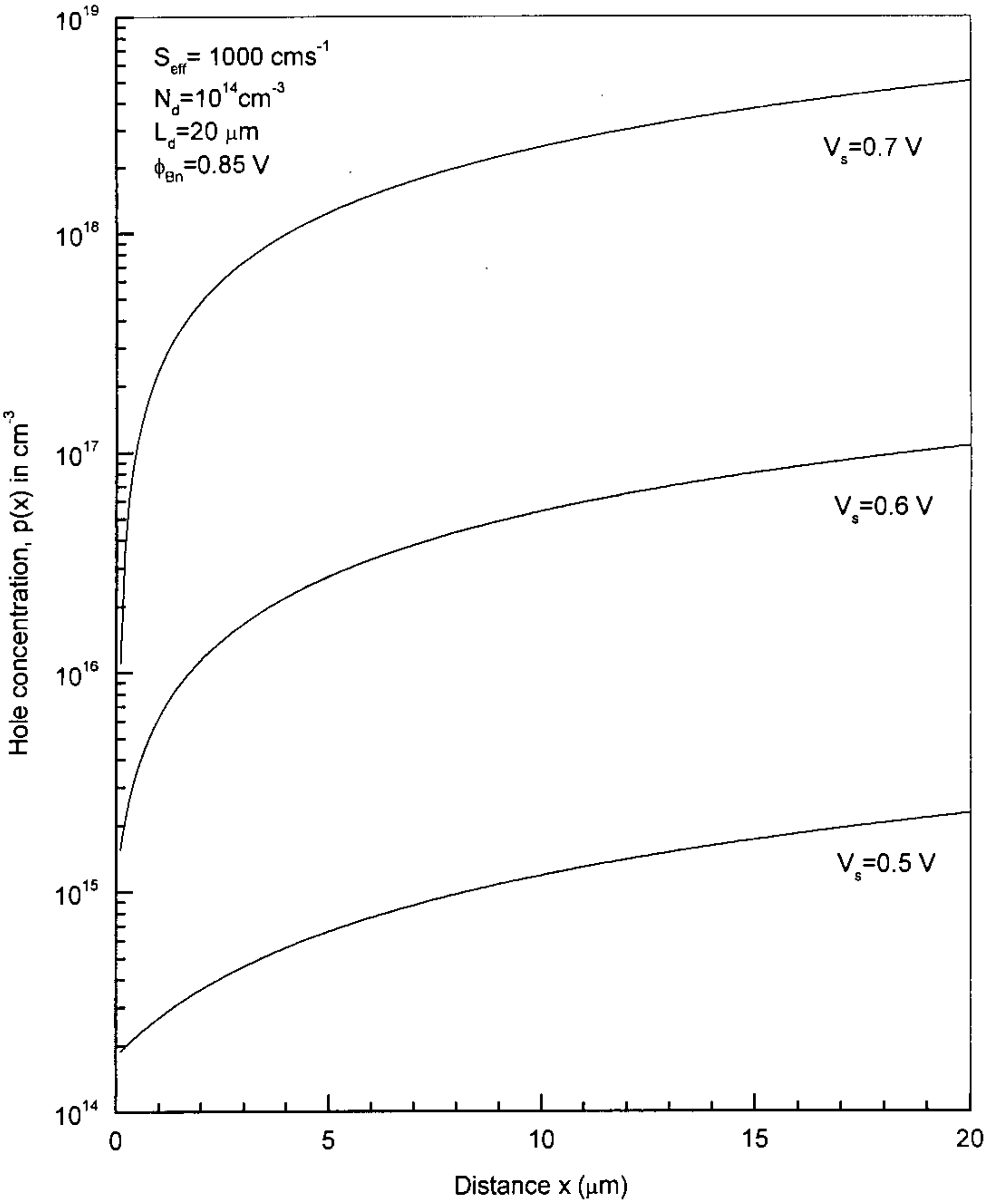

Fig. 3.3: Hole density profile versus distance for various junction voltages.

Fig. 3.4 shows the dependence of the electric field on the distance x for three different values of L_d. The curves show high electric field at the Schottky junction and it decreases with increase of x. The electric field drops rapidly in the drift region where resistance is very low due to the effect of conductivity modulation of stored charge. Fig. 3.1 shows that for a given V_s, N_d and S_{eff}, the hole density increases with x and eqn (2.11) predicts that the electric field decreases with increase of $p(x)$. Therefore the electric field will decrease with increase of x. The plots also show that the electric field at x=0 is higher for higher L_d. The value of J_p is higher for larger L_d because for a given V_s, N_d and S_{eff} the value of p_{Ld} is higher for greater L_d as can be seen from fig. 3.1. Physically, as L_d increases the stored charge within the drift region increases and hence current density J_p will increase due to more recombination of the hole at the n-n$^+$ interface. From eqn (2.2) it is seen that if J_p increases electric field must also increase to keep the equation in balance as other variables are constant for given V_s, N_d and S_{eff}. Though at x=0, $p(x)$ is fixed for a given V_s, N_d and S_{eff}, J_p is greater for larger L_d and therefore the electric field at x=0 will be higher for larger L_d as predicted by eqn (2.11).

The dependence of the electric field on the distance x for different effective surface recombination velocity S_{eff} is shown in fig. 3.5. Fig. 3.2 shows that as S_{eff} increases, $p(x)$ decreases due to more recombination at the n-n$^+$ interface and therefore $E(x)$ will increase with increase of S_{eff}.

3.4 DIFFUSION CAPACITANCE

The variation of diffusion capacitance of an epitaxial high barrier Schottky diode with respect to junction voltage for two different drift region lengths is shown in fig. 3.6. The diffusion capacitance is low when the junction voltage is low. But it increases exponentially with V_s. Fig. 3.3 shows that as junction voltage increases the minority carriers within the drift region also increase. Therefore, the diffusion capacitance of a high barrier Schottky diode will increase with the increase of junction voltage.

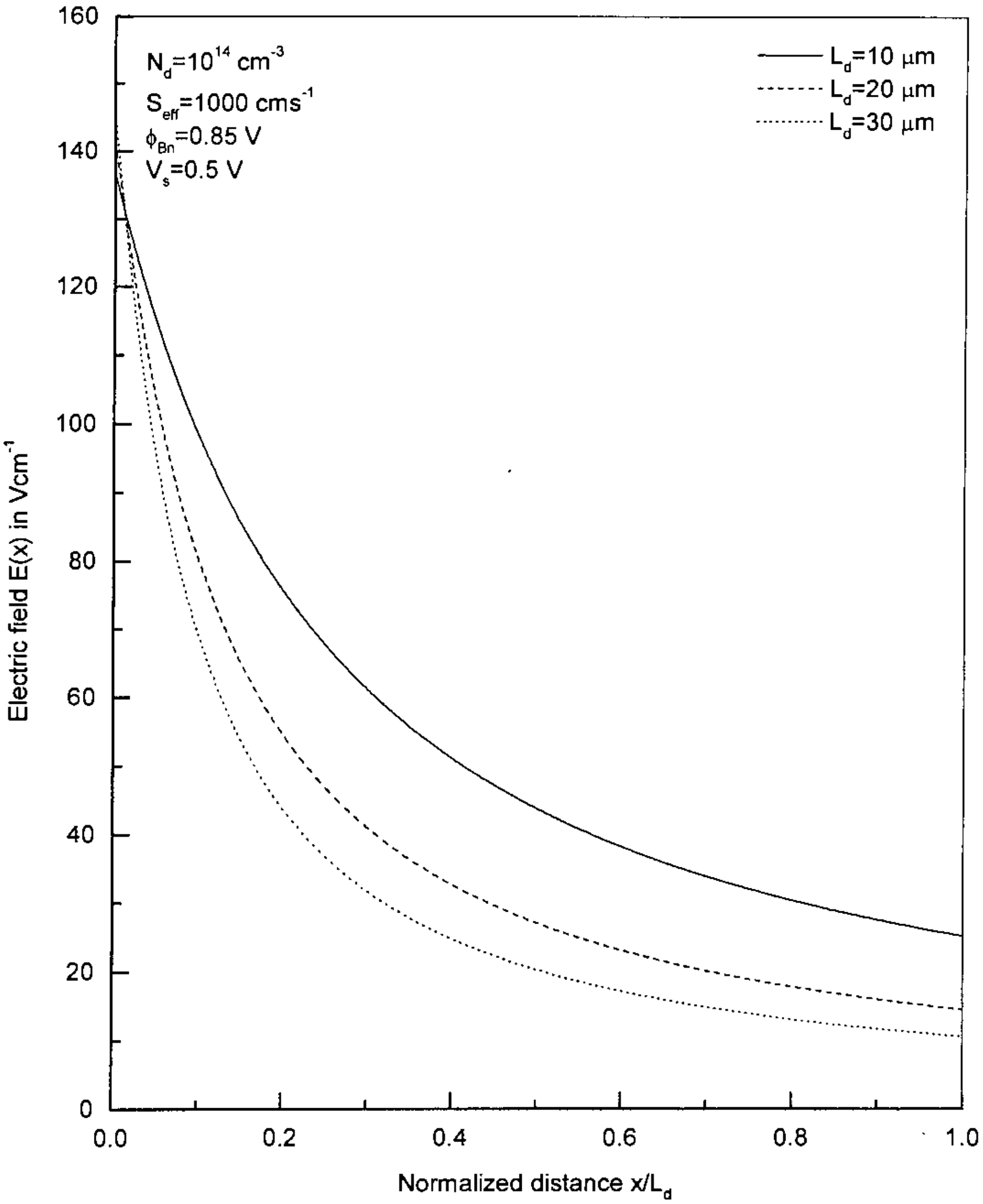

Fig. 3.4: Dependence of electric field in the drift region on the normalized distance for various drift region length.

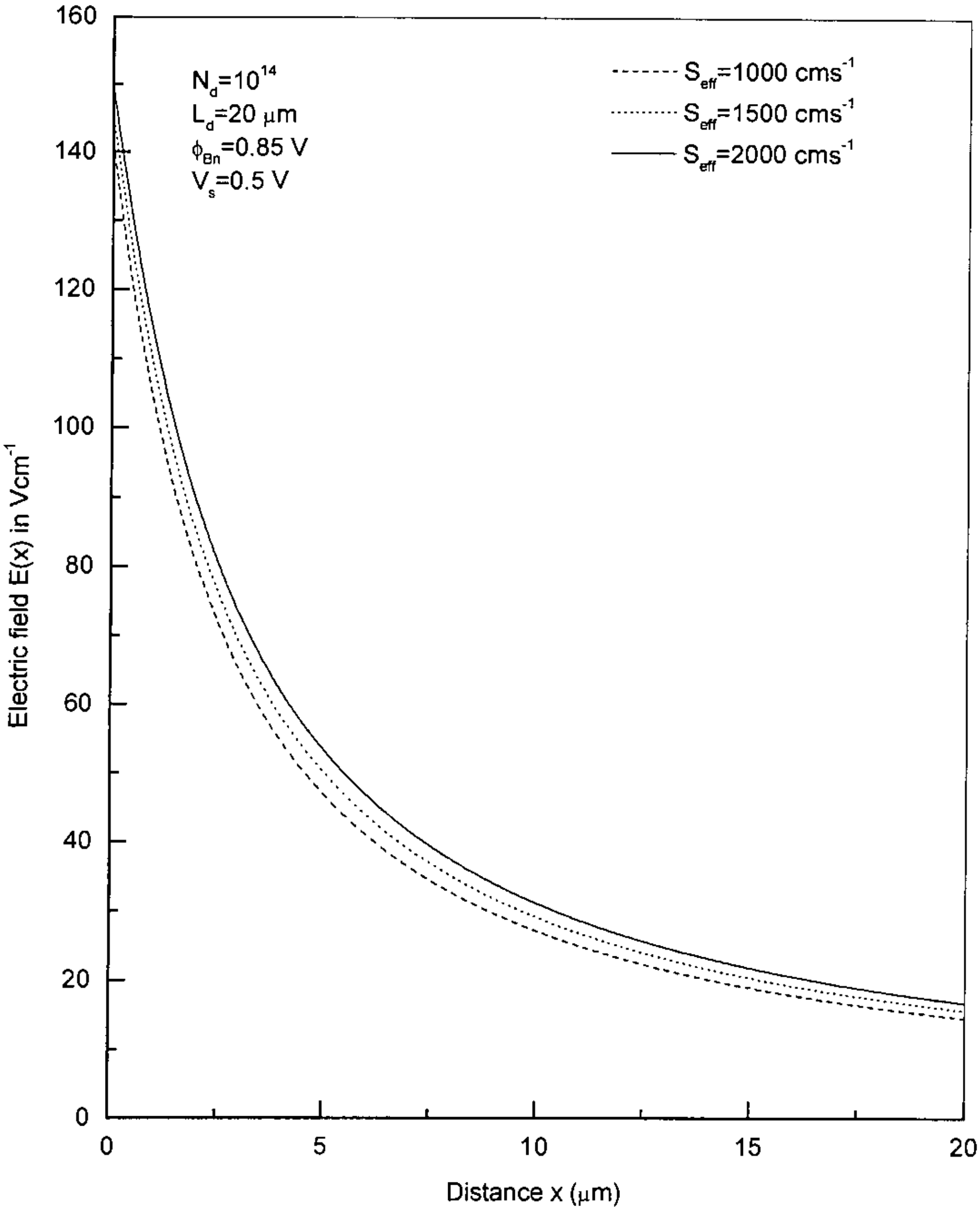

Fig. 3.5: The effect of effective surface recombination velocity on the electric field.

At high junction voltage the diffusion capacitance is significant and should not be ignored. This is due to the facts that at high junction voltage, a significant amount of minority carriers are injected within the drift region. The stored charge within the drift region due to this injected hole is considerable. Hence the diffusion capacitance of a high barrier Schottky diode under high level injection should be taken into consideration due to the substantial stored charge within the drift region. It is also seen from the plot that the diffusion capacitance increases as the length of drift region increases. The value of p_{Ld} increases with L_d as can be seen from the fig. 3.1 and hence the stored charge due to hole in the drift region increases as predicted by eqn (2.26). Therefore, the diffusion capacitance for higher L_d is higher.

Fig. 3.7 shows the variation of diffusion capacitance as a function of total current density for two different L_d. The curve shows that the diffusion capacitance of the epitaxial high barrier Schottky diode is low for low current density but significantly high for high current density. As the junction voltage increases the injected minority carrier within the drift region increases that in turn increases the diffusion capacitance of the device. The hole current density increases with the increase of minority carrier. Eqn (2.20) shows that the electron current density increases exponentially with V_s. Therefore, total current density increases with increase of V_s. Hence diffusion capacitance will increase with the increase of total current. It is seen from the curve that there is a switch over point when the curve goes from the low injection to high injection level. This is due to change of resistance of the drift region due to conductivity modulation [6]. As the stored charge will be greater for larger L_d, so the diffusion capacitance for larger L_d will also be higher.

Fig. 3.8(a), (b) and (c) show the dependence of the diffusion capacitance on the drift region length for four different effective surface recombination velocities. The plots show a low diffusion capacitance when the drift region length is low but diffusion capacitance increases exponentially with the increase of drift region length. Fig. 3.1 shows that for a given value of V_s, N_d and S_{eff}, p_{Ld} increases with L_d and eqn. (2.26) predicts that the stored charge within the drift region increases as p_{Ld} and L_d increases.

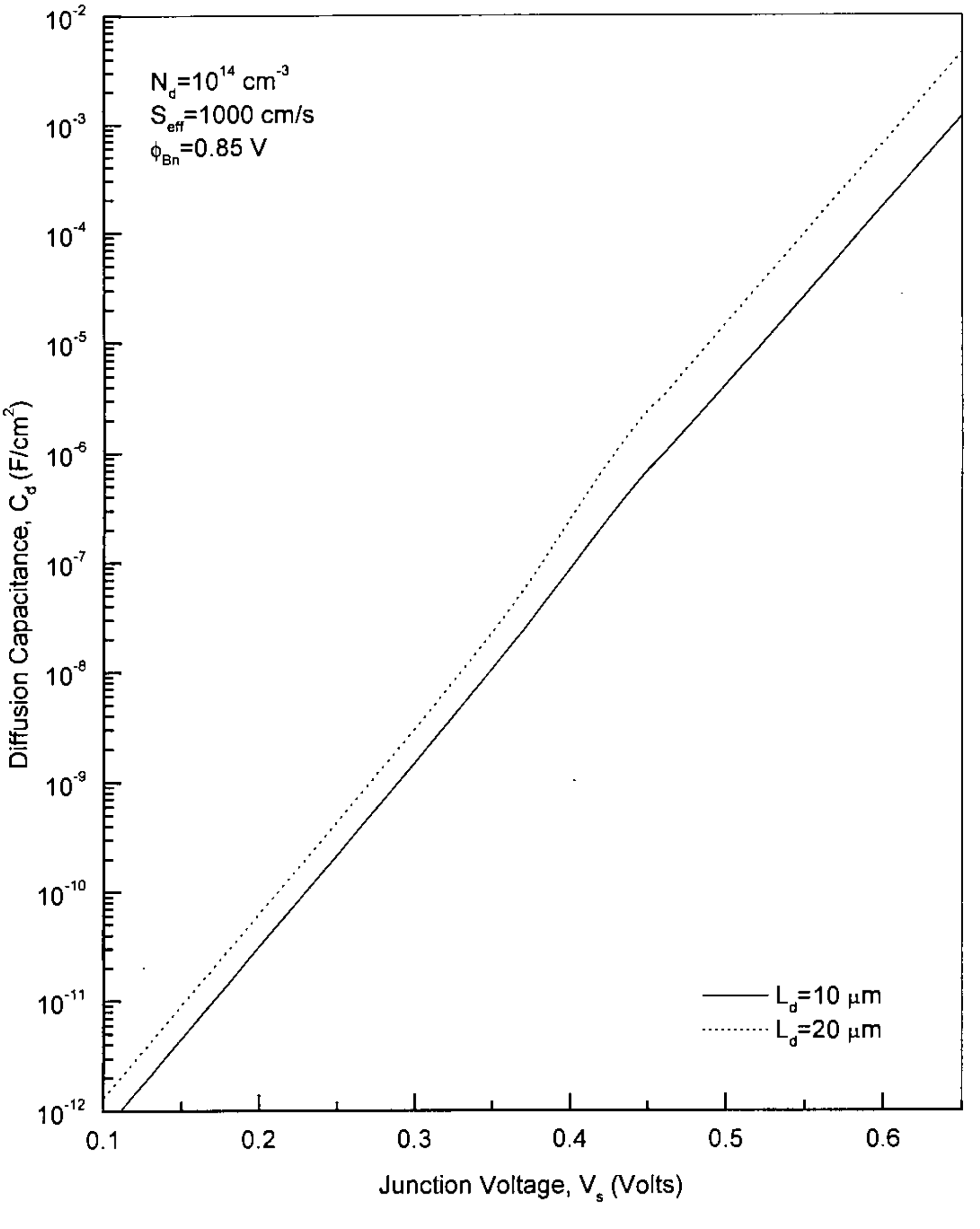

Fig. 3.6: Variation of diffusion capacitance as a function of junction voltage for various drift region lengths.

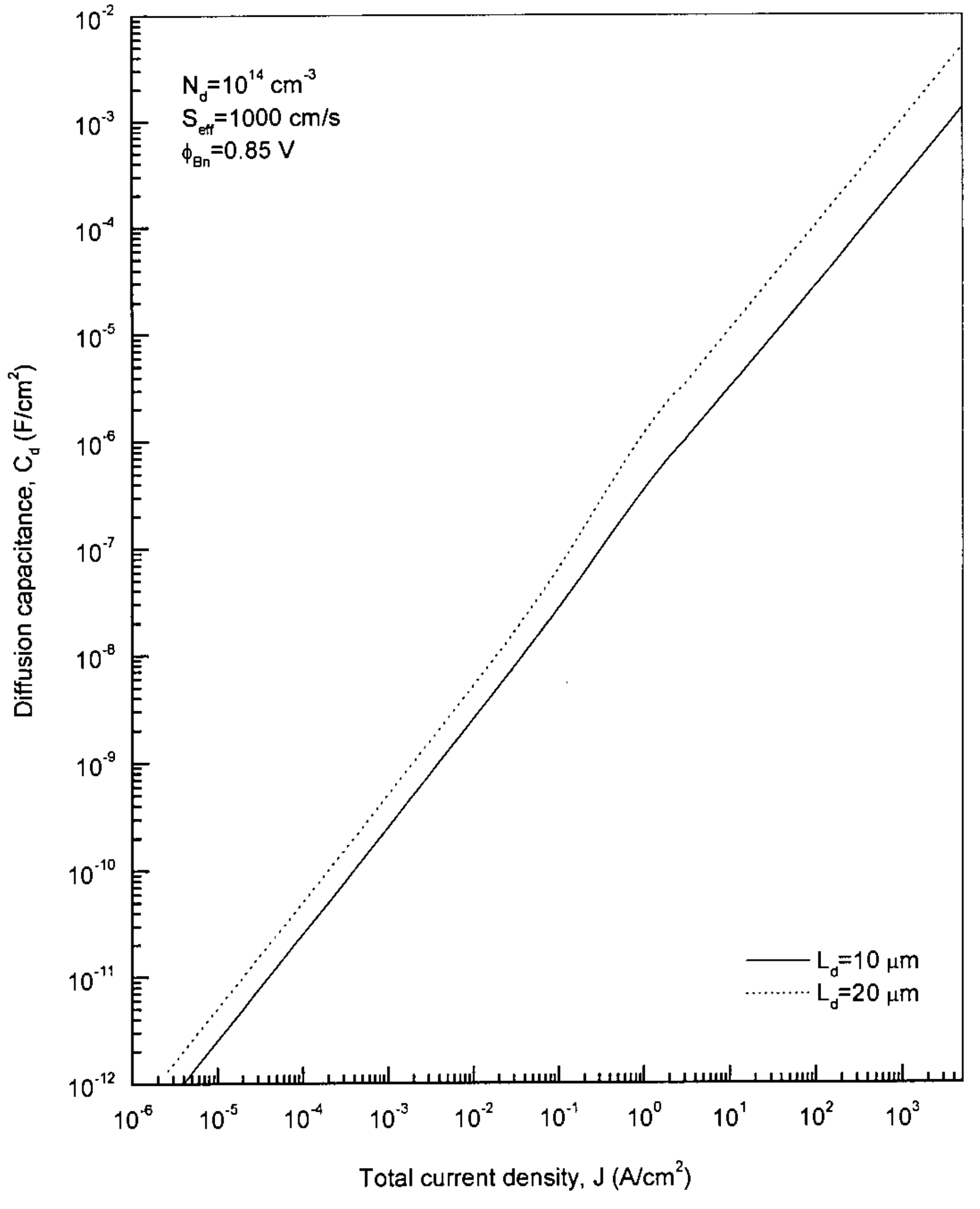

Fig 3.7: Variation of diffusion capacitance as a function of total current density for various drift region lengths.

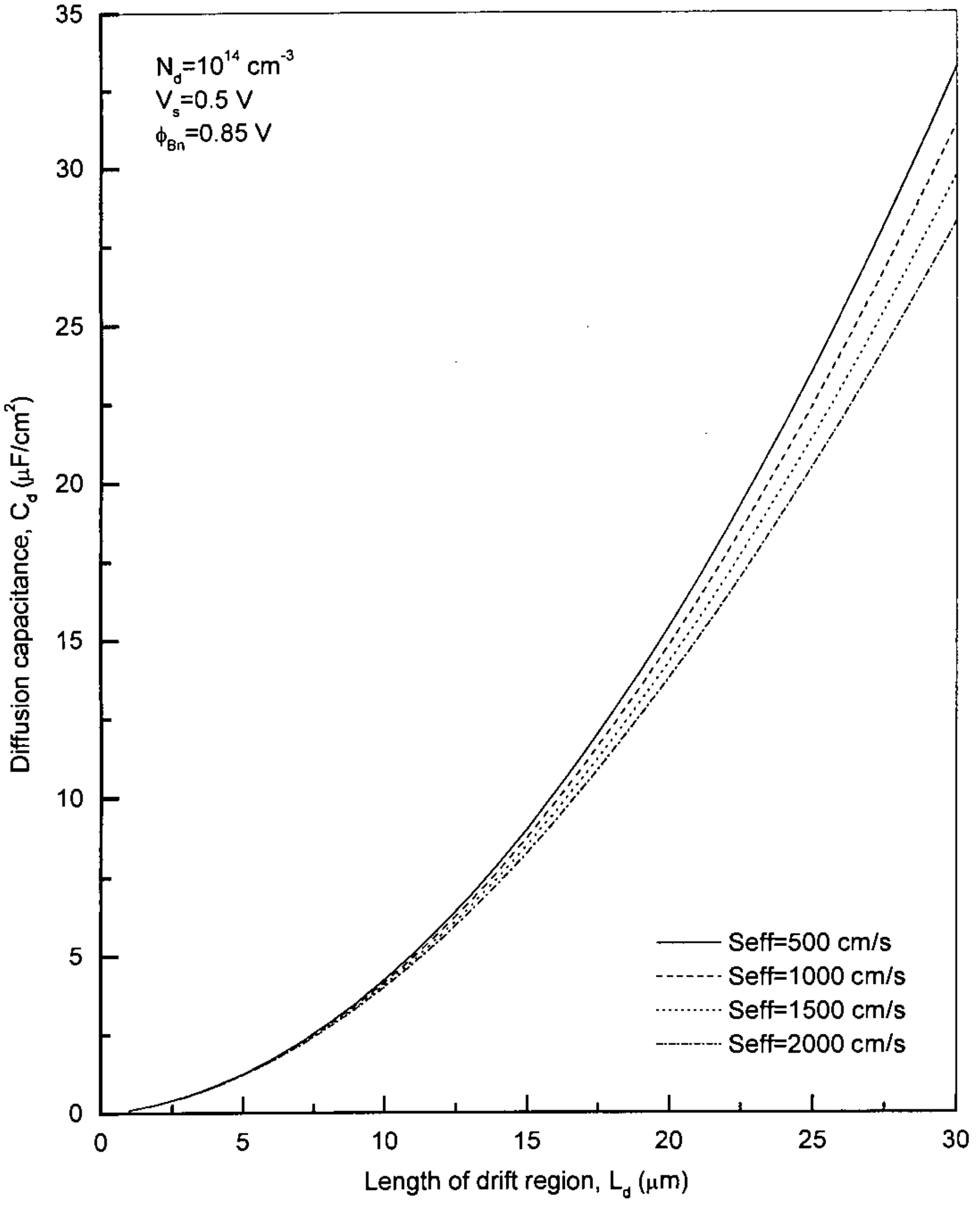

Fig 3.8 (a): Variation of diffusion capacitance as a function of drift region length for various effective surface recombination velocities.

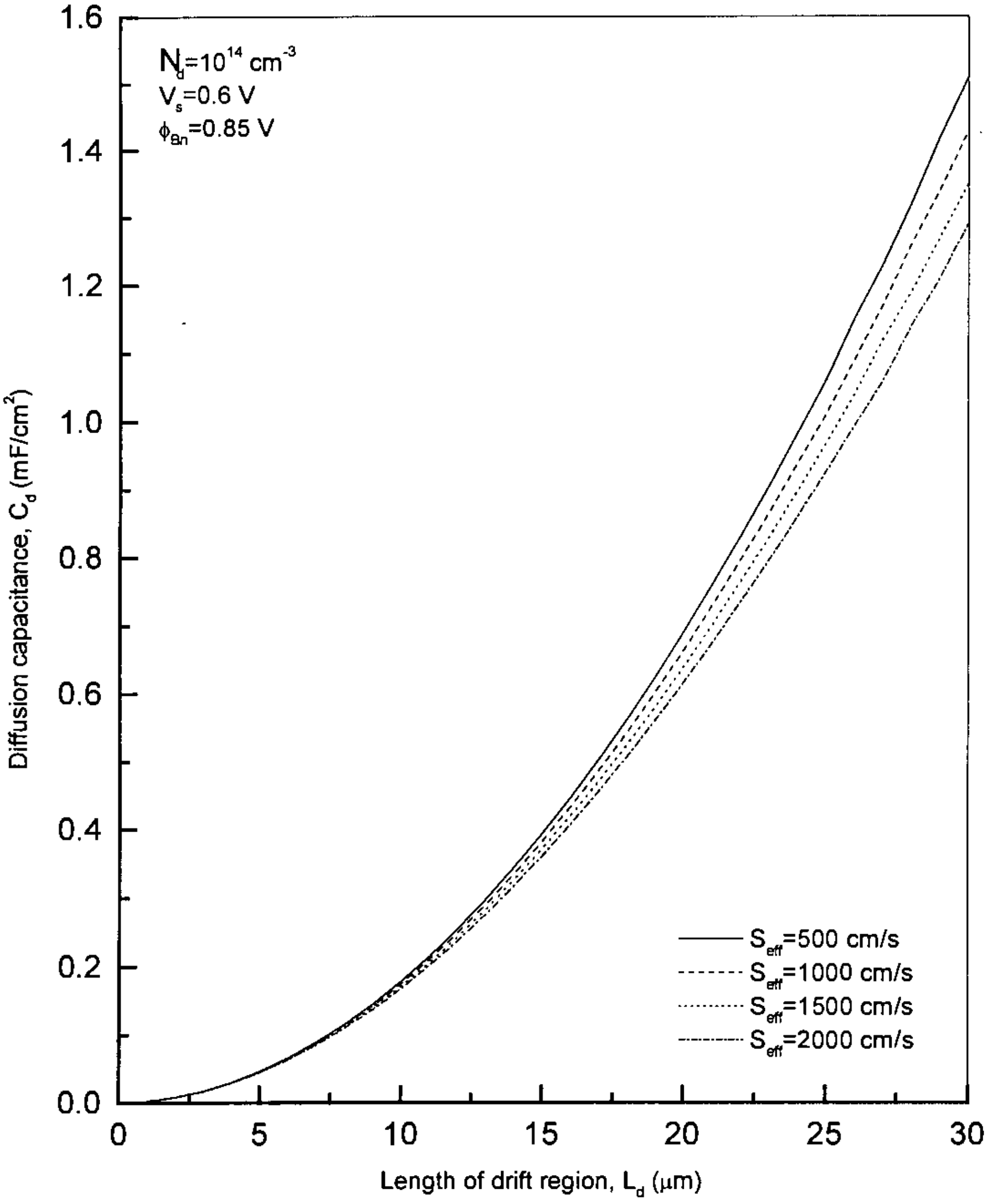

Fig 3.8 (b): Variation of diffusion capacitance as a function of drift region length for various effective surface recombination velocities.

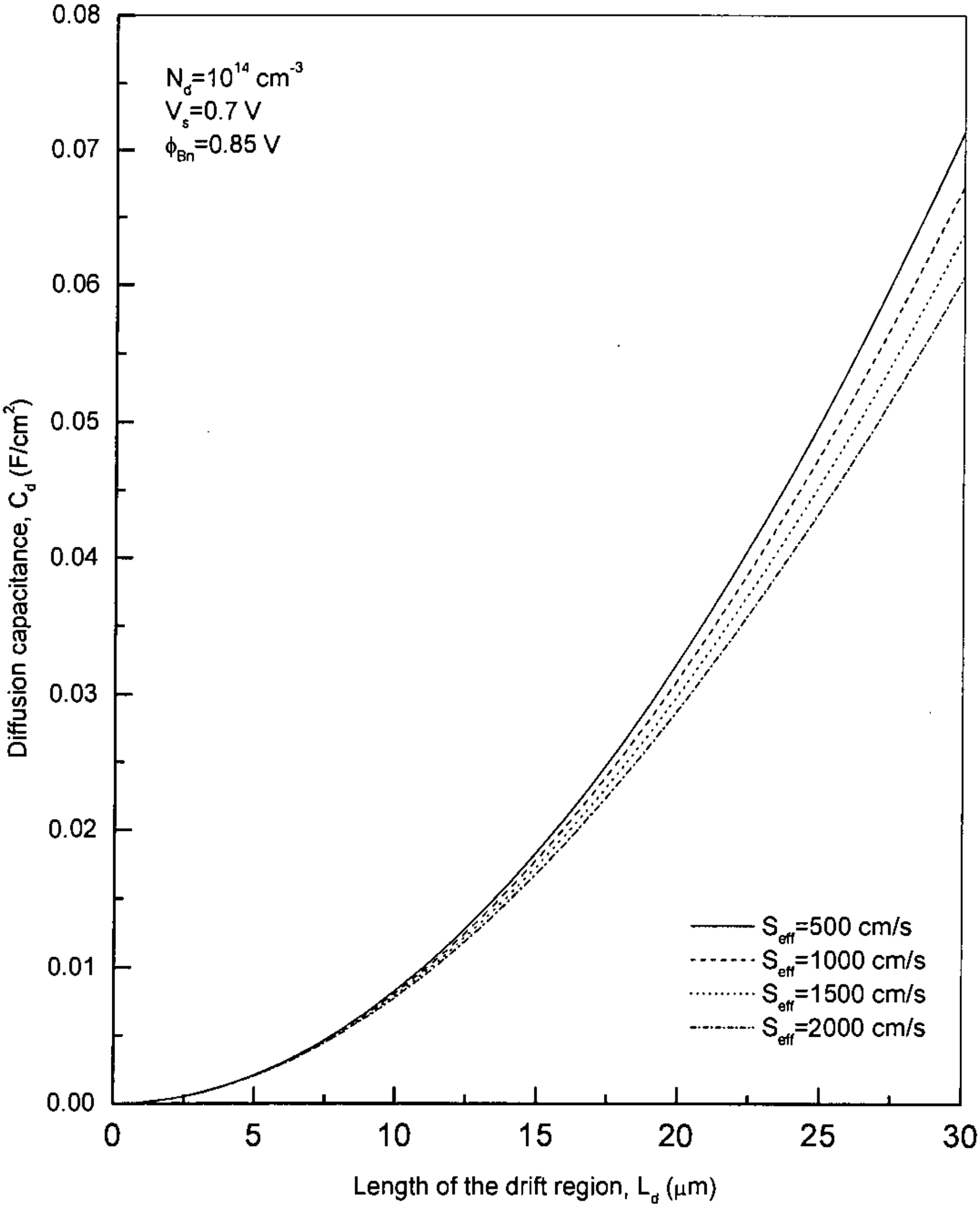

Fig 3.8 (c): Variation of diffusion capacitance as a function of drift region length for various effective surface recombination velocities.

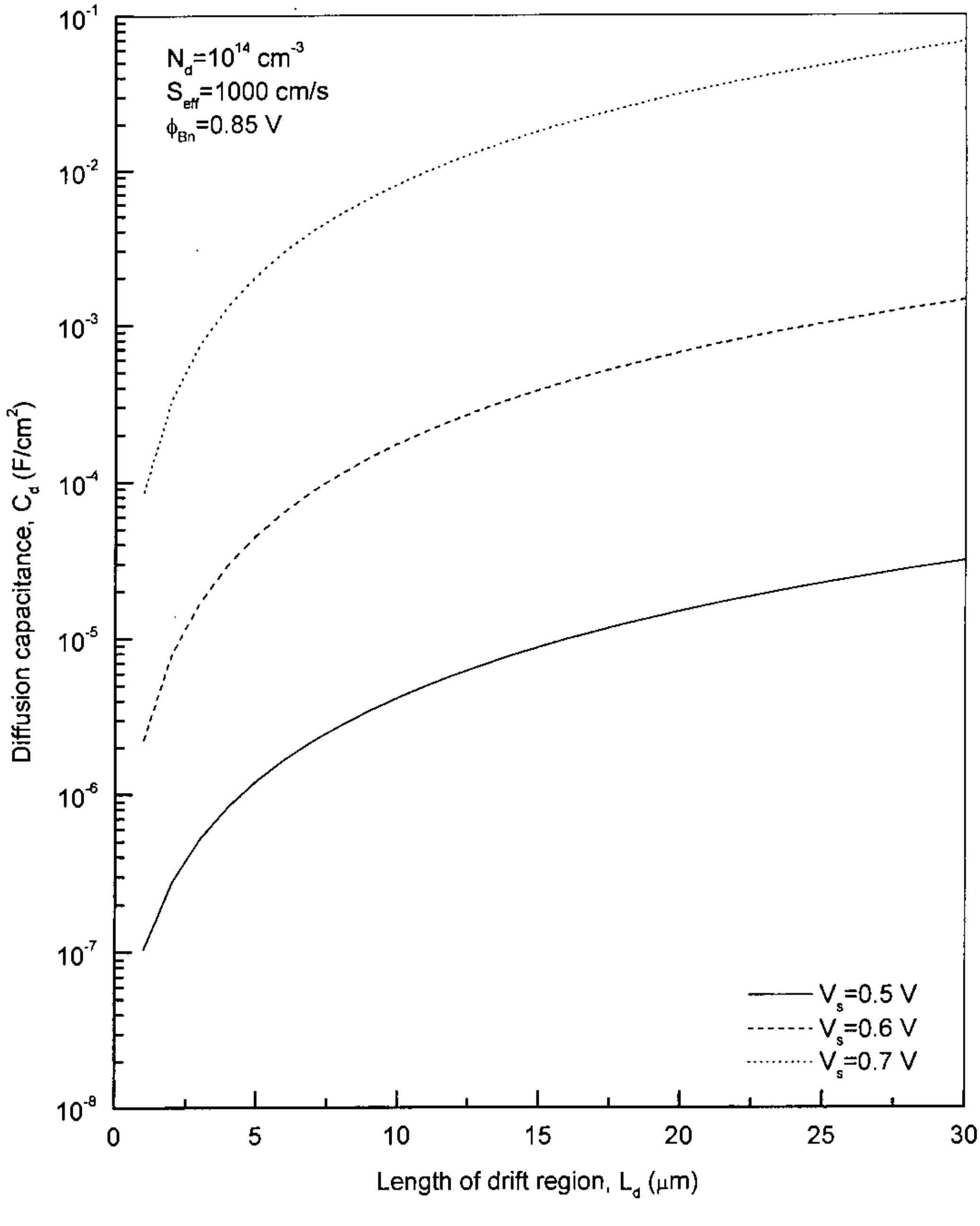

Fig 3.9: Variation of diffusion capacitance as a function of drift region length for various junction voltages.

Therefore, the diffusion capacitance will increase with the length of drift region. Fig. 3.2 shows that as S_{eff} increases, $p(x)$ decreases due to more recombination at the n-n+ interface and therefore C_d will decrease with the increase of S_{eff}. The plots show that the value of diffusion capacitance is higher for higher voltage. Fig. 3.3 shows that the hole concentration increases with the junction voltage, therefore the diffusion capacitance will be higher for higher voltage.

The variation of C_d with respect to the L_d for various junction voltages is shown in fig. 3.9. The plots show that the diffusion capacitance increases with the junction voltage. Fig. 3.3 shows that as V_s increases, $p(x)$ increases due to more hole injection and therefore C_d will increase with increase of V_s.

3.5 CONCLUSIONS

The analytical equation derived in chapter 2 is used in this chapter to study the hole density profile, electric field distribution and diffusion capacitance of the epitaxial high barrier Schottky diode. The effect of drift region length, effective surface recombination velocity and junction voltage on the hole concentration has been studied in this chapter. It is found that the hole concentration increases with the distance from the Schottky contact. The value of hole concentration at $x=L_d$ is higher for higher drift region length device. The hole concentration has been found to be decreased for increased S_{eff}. The hole concentration within the drift region increases with the junction voltage.

In this chapter, we have also studied the effect of drift region length and effective surface recombination velocity on the electric field. The electric field at x=0 is higher for higher epitaxial thickness because hole current density is higher for higher epitaxial thickness. Electric field with higher L_d decreases more rapidly than for lower L_d. The electric field has been found to be increased with increased S_{eff}.

The diffusion capacitances as a function of junction voltage and total current density are studied. The diffusion capacitance of an epitaxial high barrier Schottky diode is significant under high level of injection. This is due to considerable amount of minority carrier injection at high-level injection of an epitaxial high barrier Schottky diode. For the same value of junction voltage or total current the diffusion capacitance is found to be increased with increase of L_d and decrease with increase S_{eff} respectively.

The variations of diffusion capacitance with the drift region length have also been studied. It has been found that the diffusion capacitance increases with the length of drift region. The effect on the effective surface recombination velocity and the junction voltage on the plots are studied. The diffusion capacitance is found to be decreased with increased effective surface recombination velocity and decreased junction voltage respectively.

CHAPTER 4

Conclusions

4.1 CONCLUSIONS

A low barrier Schottky diode is a majority carrier device. On the other hand, when the barrier height is high minority carrier injection takes place within the drift region under forward bias. Due to this minority carrier injection, the minority carrier charge is stored in the drift region. The stored charge in the drift region gives rise to diffusion capacitance at the forward bias. In this work, the diffusion capacitance of an epitaxial high barrier Schottky diode has been studied. Neglecting recombination within the drift region, an analytical expression for total charge stored within the drift region is obtained. The total stored charge is a function of junction voltage; therefore the expression for the diffusion capacitance is obtained by taking first derivative of the stored charge with respect to junction voltage. The calculated result shows that the diffusion capacitance depends strongly on the junction voltage and on the total current density. At high-level injection, the value of diffusion capacitance is considerable and should be take into account. The dependency of diffusion capacitance on the effective surface recombination velocity is not so significant. The diffusion capacitance varies exponentially with the drift region length. For low drift region length device the value of diffusion capacitance is low. But, it increases exponentially with the increase of drift region length. The effect of effective surface recombination velocity on the diffusion capacitance is ignorable for low drift region length device but it increases somewhat with the drift region length of the SBD.

4.2 SUGGESTIONS FOR FUTURE WORK

In the present work, uniformly doped Si is considered in the drift region. In practical devices, the doping profile is not uniform. In the future work, non-uniformly doped drift layer can be considered. The work may also include distance depended mobility.

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