MINORITY CARRIER INJECTION IN GaAs SCHOTTKY BARRIER DIODES

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ABSTRACT

A new treatment for minority carrier injection across Schottky barrier diodes is presented. This new treatment takes into account the barrier lowering effects due to quantum mechanical tunnelling and image force. Minority carrier current is composed of both the drift and diffusion components. Minority carrier injection ratios for different metallization contacts Al, Au and Ag on n-type GaAs (100) have been investigated as a function of current density and bias voltage. It is shown that even when the two barrier lowerings effects are taken into consideration, minority carrier injection ratio increases linearly with increasing current. The highest injection ratio is obtained from the diode with the highest barrier height. Minority carrier injection ratio up to 10^{-2} has been obtained.

INTRODUCTION

Schottky barrier diodes are devices particularly suitable for microwave mixing, detecting and switching applications in the picosecond. Their suitability for these applications is due to the fact, that charge transport is effected merely by majority carriers i.e by electrons, since n-type material is thoroughly used for Schottky barrier devices. In some cases, however, deviations from the pure majority carrier conduction behaviour are observed. i.e Schottky barrier diode will act as a majority carrier device under low - injection conditions, but at sufficiently large forward bias, the minority injection ratio (ratio of minority carrier current to total current) increases with forward current due to the enhancement of the drift - field component which becomes much larger than the diffusion current component.

At steady - state the one dimensional continuity and current density equations for minority carrier are given by [1]

$$0 = -(P_n - P_{no})/\tau_p - 1/q.\delta J_p/\delta x$$

$$J_p = q\,\mu_p\,P_n\,\epsilon - q\,D_p\,\delta P_n/\delta_x \qquad (2)$$

Where J_p is the minority current due to holes and consists of the drift and diffusion components, P_n is the minority carrier concentration, P_{no} is the equilibrium minority carrier concentration, μ_p is the hole mobility, q is the electronic charge, D_p is the minority carrier diffusion constant, τ_p is the minority carrier lifetime, ϵ is the electric field in the bulk semiconductor.

From the rectifying theory, the minority carrier density at x_1 is given by

$$P_n(x_1) = n_i^2/N_D\,[\exp(qV/KT)-1] \qquad (3)$$

as shown in Figure (1), where n_i and N_D are the intrinsic and doping concentrations, K is the Boltzman constant, T is the temperature, V is the applied voltage and ϕ_n is the barrier height.

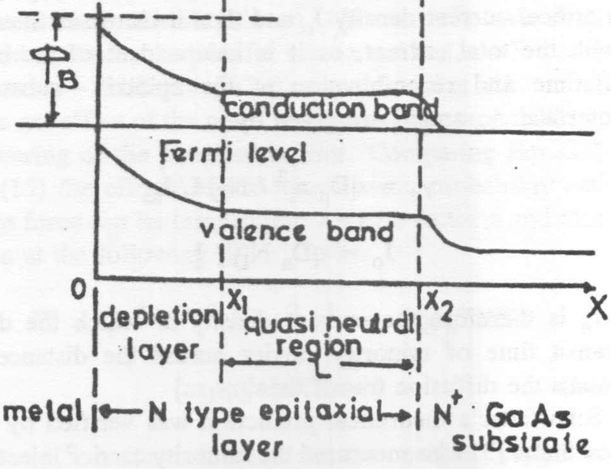


Figure 1. Energy band diagram of an epitaxial Schottky barrier [2].

The boundary condition on $P_n(x)$ at $x=x_2$ can be stated in terms of a transport velocity $v_T = D_p/L_p$ for minority carriers

$$J_p(x_2)=qv_TP_n= q(D_p/L_p)P_{no}[\exp(qV/KT)-1] \quad \text{for } L<<L_p \tag{4}$$

Where L_p is the minority carrier diffusion length and L is the distance of the quasi-neutral region.

The first theoretical prediction of minority carrier injection in Schottky barrier diodes was given by Scharfetter [2]. He found that the injection ratio increases linearly with current at high forward currents, because the current induced drift - field in the bulk - semiconductor affects the minority carrier current, but not the majority carrier current. In this range, the injection ratio was given by

$$\gamma = n_i^2 J / b N_D^2 J_{ns} \tag{5}$$

Where J is the diode forward current, J_{ns} is the Schottky diode saturation current, b is the mobility ratio μ_n/μ_p.

Scharfetter neglected the voltage drop across the heavily doped substrate and assumed the voltage drop across the Schottky barrier space charge region to depend upon the majority carrier current density J_n. His model includes minority carrier drift and diffusion transports, constant bulk lifetime, and surface recombination at the epitaxi-substrate interface. Recombination in the Schottky barrier space charge region and surface leakage current were neglected.

The injection ratio was found to be a constant γ_o up to a critical current density J_o and then it increases linearly with the total current, as it is independent of the bulk lifetime and recombination at the epitaxi - substrate interface. γ_o and J_o are given by

$$\gamma_o = qD_p n_i^2 / N_D L J_{ns} \tag{6}$$

$$J_o = qD_n N_D / L \tag{7}$$

J_o is therefore the current density at which the drift transit time of minority carrier across the distance L equals the diffusion transit time.

Scharfetter's theoretical prediction was verified by Yu and Snow [3] who measured the minority carrier injection ratio for metal / silicon contacts. Four different metals with barrier heights ranging from 0.65 to 0.85 eV on n-type Si with doping levels from 10^{14} - $6*10^{16}$ cm^{-3} were examined. Their results showed that the injectio efficiency is constant at low current levels. For small bias voltage, the injection ratio was given by

$$\gamma_{yu} = J_p/J_p+J_n \sim J_p/J_n = (qD_p N_v/A LT^2) \exp[-q(\phi_p-\phi_n)/KT] \tag{8}$$

Where N_v is the effective density of states in the valence band, ϕ_n is the barrier height for electrons, ϕ_p is the barrier height for holes, and A is the Richardson constant for free electrons = 120 A/cm^2/K^2.

From eq.(8) Yu and Snow deduced that:

i. γ_{yu} depends on the barrier height of the metal semiconductor ϕ_n.
ii. γ_{yu} depends on the semiconductor doping as reflected by ϕ_p
iii. γ_{yu} is higher for larger ϕ_n and lower ϕ_p i,e lower doping
iv. γ_{yu} is not a function of the applied bias (this is a consequence of the assumption that all the applied voltage is dropped across the depletion region).

However their measurements were not continued to sufficiently high current densities to establish whether γ_{yu} increases linearly with J in agreement with Scharfetter's theory or passes through a maximum as predicted by Green and Shewchun [4].

Henish [5] proposed a minority carrier injection ratio under low injection. He neglected the minority carrier drift component in eq.(2) in comparison with the diffusion component. Assuming thermionic-emission theory, the minority carrier injection ratio was thus given by

$$\gamma_{He}=J_p/J_p+J_n=qn_i^2D_p/N_DLA^{**}T^2\exp(-q\phi_n/KT) \tag{9}$$

Where A^{**} is the effective Richardson constant

Henish concluded that the injection ratio increases with ϕ_n because of the reduction in J_n and decreases with N_D because of the decrease in P_{no} and consequent reduction in J_p.

Hargrove and Anderson [6] proposed a minority carrier injection ratio at low currents, where the field in the quasi neutral region is negligible, and was given by

$$\gamma_{HA} = qD_p n_i^2 / L N_D.J_{ns} \exp[(n-1/n)(qV/KT)] \tag{10}$$

where n is the diode quality factor.

THEORETICAL APPROACH

In the present paper a new approach is presented where the effect of both the quantum mechanical tunnelling and image force lowerings are taken into consideration. Quantum mechanical tunnelling is important in semiconductor with small effective masses, e.g, GaAs, it causes ideal Schottky diode to exhibit a larger than unity ideality factor.

1. *Image force barrier lowering*

Image force lowering of the barrier arises from the electrostatic attraction between an electron and its image in the metal. The attractive potential, $V_i = -q/16 \pi \epsilon_{si} x$, where ϵ_{si} is the image dielectric constant and x is the distance from the metal semiconductor surface, gives rise to a barrier lowering

$$\Delta\phi_i = [q^3 N_D / 8 \pi (\epsilon_{si})^2 \epsilon_s]^{1/4} [V_{bi} - V - KT/q]^{1/4} \qquad (11)$$

where ϵ_s is the static dielectric constant, and V_{bi} is the built - in voltage. A detailed discussion of the image force can be found in [1].

2. *Quantum mechanical effects*

Current transport across the metal semiconductor interface depends strongly on the energy band profile. Figure (2) shows the energy band profile resulting from the superposition of the Schottky field, the image field and the applied bias.

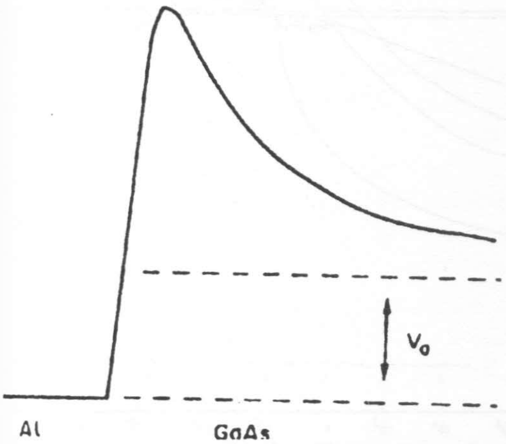


Figure 2. Energy band profile of the Schottky diode resulting from the superposition of the Schottky field, the image force field and the applied bias.

The current density from the semiconductor to the metal using Fermi - Dirac statistics is given by [7]

$$J = qm^* KT/2 \pi^2 h^3 \, |T_a(E_x)|^2$$

$$* \, \mathrm{Ln} \, [1 + \exp (E_F - E_x)/KT)] dE_x \qquad (12)$$

Where m^* is the electron effective mass, E_x is the energy related to the motion of the electrons perpendicular to the metal - semiconductor interface, $|T_a(E_x)|^2$ is the transmission probability, h is the reduced Planck's constant and E_F is the Fermi energy. The transmission probability is not only a function of E_x but also of the barrier height, applied bias and effective mass. In the thermionic emission theory due to its classical nature $|T_a(E_x)|^2$ is 0 for electrons with energy below the barrier and 1 for electrons with sufficient energy to surmount it. When the Boltzmann approximation to the Fermi function is valid i,e in the low doping regime or in the depletion region, Eq. (12) reduces to the well known J-V relationship for an ideal Schottky diode.

$$J^{te} = qm^{*3} K^2 T^2 / 2 \pi^2 h^3$$

$$* \exp(-q \phi_b / KT)[\exp(qV/KT-1] \qquad (13)$$

The reverse saturation current has been taken into account in the above equation. It should be evident that the approximations used in thermionic-emission theory for the transmission probability are not valid for Schottky diodes especially for semiconductors with small effective masses eq.(12) should be used instead of Eq.(13). The transmission probability in eq.(12) can be obtained by several methods; the transfer matrix method, the Wentzel - Kramers - Brillowin (WKB) approximation [8].

The net effect of the non - zero tunnelling probability is a lowering of the potential barrier. Comparing Eqs.(12) and (13) the effects of the transmission probability and image force can be lumped into a single factor n and Mui arrive at the following [9].

$$J^{te} = qm^* K^2 T^2 / 2 \pi^2 h^3 \exp (-q\phi_b{}^e/KT)$$

$$[\exp(qV/nKT)--1] \qquad (14)$$

where $\phi_b{}^e$ is the effective barrier height, which is assumed to be bias independent.

To a good approximation Mui[9] expressed the effective barrier height as

$$\phi_b^e = \phi_b - C(V_{bi} - V)^a \tag{15}$$

where a is a constant and equal 1/3 for tunnelling [10] and 1/4 for image force, C is a constant. For an applied bias smaller than the built in voltage eq.(15) is reduced to

$$\phi_b^e = \phi_{bo}^e + \beta V \tag{16}$$

Where ϕ_{bo}^e is the zero effective barrier height and β is a constant given by aCV_{bi}^{a-1}

Although the two barrier lowering effects are considered separately in Eqs.(15) and (16). They can be combined in a straight forward manner. With the barrier height corrected for barrier lowering effects, Eq.(14) can now be written as [11].

$$J^{te} = J_s\,[1-\exp(-qV/KT)]\exp(qV/nKT) \tag{17}$$

where J_s is a constant given by

$$J_s = qm^* K^2\, T^2/2\,\pi^2\, h^3 \exp\,(-q\phi_{bo}^e\,/KT) \tag{18}$$

and

$$n = 1/(1-\beta\,) \tag{19}$$

In my approach, the minority carrier injection ratio is calculated first by taking only the diffusion component of the hole current and this is given by

$$\gamma_d = J_p/J^{te} = q.D_p/L.n_i^2/N_D[\exp(qV/KT)-1]/J^{te} \tag{20}$$

Second by taking only the drift component of the hole current and this is given by

$$\gamma_H = \gamma_{drift} = J_p/J^{te} = (q.\mu_p.n_i^2/N_D)\epsilon.[\exp(qV/KT)-1]/J^{te} \tag{21}$$

It is to be noticed that γ_{drift} takes into account, the variations of the electric field in the space charge region as well as in the neutral region, together with the variations of the barrier height with the bias voltage, and the doping concentration.

EXPERIMENTAL PROCEDURE

The GaAs [100] crystals used in these calculation were n-type, the doping concentration was $2.7 * 10^{18}$ cm^{-3}. The Schottky diodes parameters shown in Table I were taken from a previous work done by the author [12].

Table I. Schottky diodes parameters.

	Al	Au	Ag
ϕ_b	0.6068	0.5727	0.4460
n	1.43	1.283	1.4

RESULTS AND DISCUSSION

Computer calculations have been carried out for the different expressions of minority carriers with different metallization contacts Al, Ag and Au.

Minority carrier injection ratio for low injection, calculated by the different expressions for Al, Ag and Au metallization are shown in Figure (3). These graphs show that the minority carrier current ratio proposed by Yu and Snow and by Henisch are constant; whereas the minority current ratio proposed by Hargrove increases linearly with forward current. Minority current ratios obtained by my approach increases exponentially with the forward current.

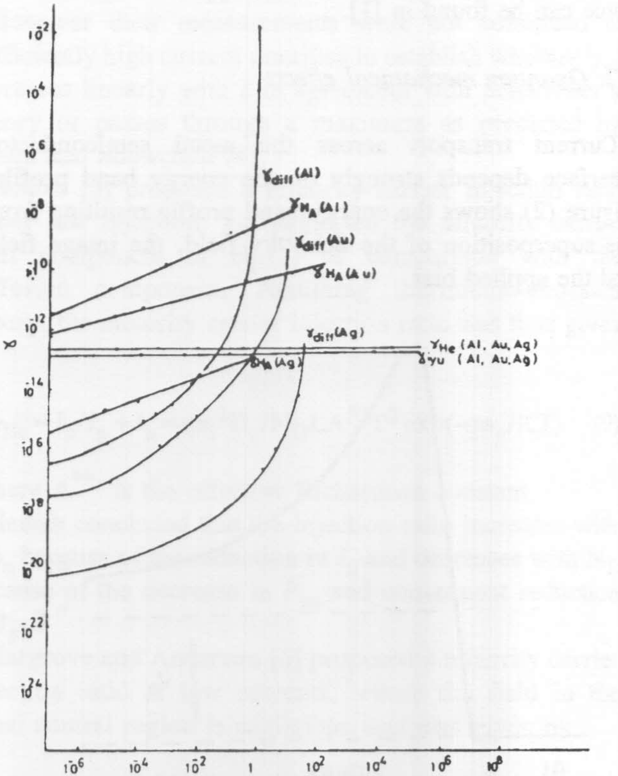


Figure 3. Minority carrier injection ratio calculated by the different expressions for the different metallization, under low - injection.

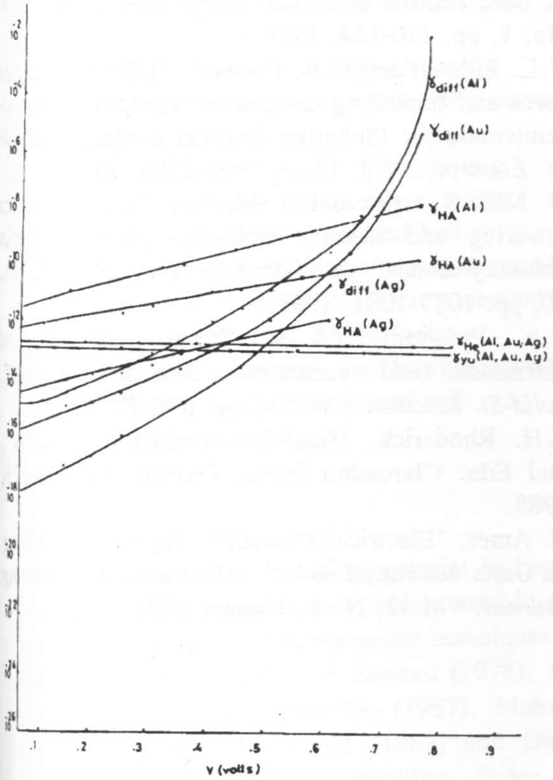
Table II. shows the various minority current ratio for a forward current of 1 A/cm^2. Calculated by my expression eq.(20) and by Hargrove expression eq.(10).

Table II. Various minority current ratio

J	γ_d(Al)	γ_d(Au)	γ_d(Ag)	γ_{HA}(Al)	γ_{HA}(Au)	γ_{HA}(Ag)
1 A/cm^2	10^{-2}	10^{-13}	10^{-18}	10^{-9}	10^{-12}	10^{-14}

It is to be noticed from table II, that minority carrier injection ratios proposed by my method are higher than those proposed by Hargrove for Al metallization.

Figure (4) shows the various minority carrier injection ratios as a function of the applied bias. Minority carrier injection ratio of 10^{-2} has been obtained for Al metallization. Same argument applied on Fig.3 can be applied on Figure (4).



igure 4. Minority carrier injection ratio as a function of pplied bias, calculated by the different expressions for he different metallizations under low - injection.

Figure (5) shows the minority carrier injection ratio as function of the applied bias, calculated by the two expressions which takes into account the effect of the drift field in the bulk of the semiconductor. These are γ_{sch}, γ_H. (Notice that $\gamma_H = \gamma_{drift}$). It is to be noticed that the minority carrier injection ratio calculated by Scharfetter expression γ_{sch} for the different metallizations lie on each other, whereas minority carrier injection ratio γ_H calculated by my approach are distinct for each metallization. Minority carrier injection ratio calculated by my approach have higher injection ratio than Scharfetter's one.

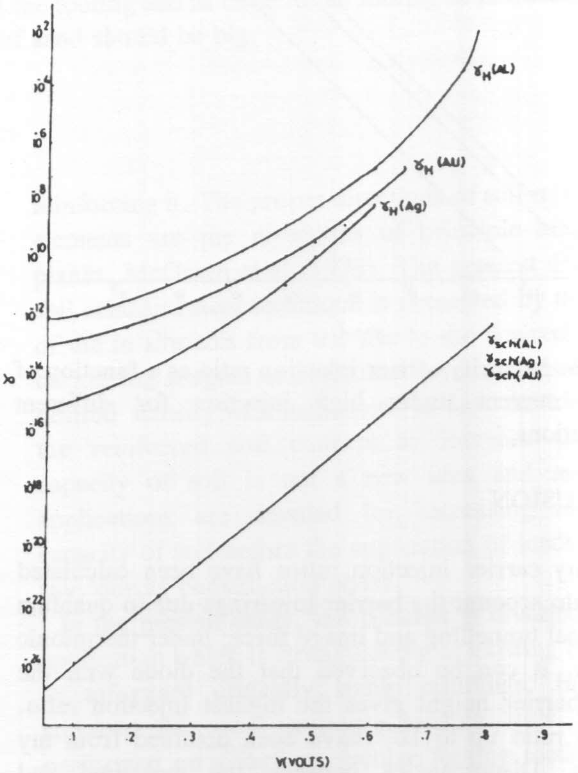


Figure 5. Minority carrier injection ratio for high injection as a function of the applied bias for different metallizations.

Figure (6) shows the minority carrier injection ratio as a function of forward current calculated by γ_{sch} and γ_H. Here minority carrier injection ratio calculated by Scharfetter's expression γ_{sch} are distinct for each metallization. Minority carrier injection ratio calculated by my expression γ_H are also shown and are higher than those of Scharfetter.

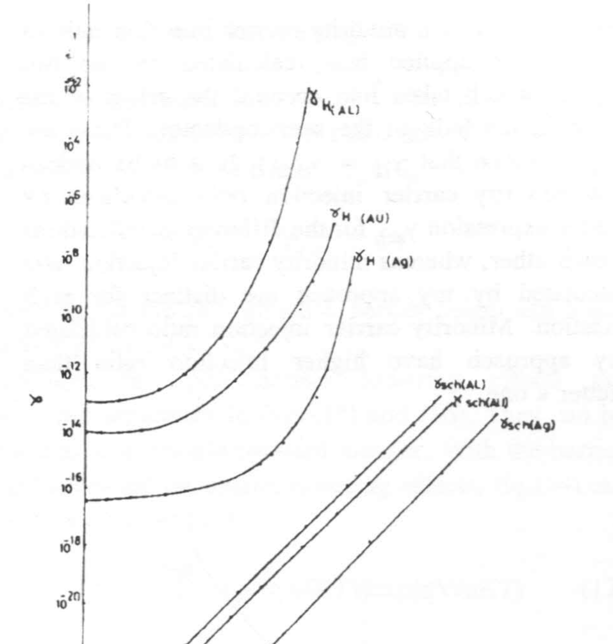


Figure 6. Minority carrier injection ratio as a function of forward current under high injection for different metallizations.

CONCLUSION

Minority carrier injection ratios have been calculated taking into account the barrier lowerings due to quantum mechanical tunnelling and image force; under thermionic emission. It can be observed that the diode with the highest barrier height gives the highest injection ratio. Injection ratio up to 10^{-2} have been obtained from my approach. Discrepancies between the measured and theoretical I-V characteristics of Schottky diodes can be attributed to the minority carrier injection currents.

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