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An Analytical Expression for Current Gain of an IGBT

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Abstract – A simple analytical expression for a current gain of IGBT is derived in terms of the device parameters as well as a gate length dependent parameter, which allows for the determination of the current components of the device as a function of its gate length. The analytical results are compared with those from simulation results. A good agreement is found.

Keywords: IGBT, Current Gain, Analytical Expression

1. Introduction

IGBTs (Insulated Gate Bipolar Transistors) are widely used in applications of high voltage and current, enjoying the high current handling capabilities of BJTs (Bipolar Junction Transistors) and the fast switching characteristic of the MOSFET [1]. The current gain defined as the product of the injection efficiency and the base transport factor is a fundamental quantity for the bipolar action of an IGBT. The well-known expression for the base transport factor of BJTs has been commonly used for the bipolar action of the device [2]. However, due to the conductivity modulation in the drift region of the device, the factor for IGBTs is expected to be different from that for BJTs.

In this work, based on the ambipolar diffusion equation, a simple analytical expression for the current gain of an IGBT is derived in terms of the device parameters including a gate length dependent one. Two-dimensional simulations are carried out using ATLAS. The simulation results of the gate length dependent electron current of an IGBT are compared with those obtained from the derived expression for the current gain of the device. Limitations of the value variation for the current gain are discussed. Physical principles involved in the present analysis can be applied to all types of IGBT structure.

2. Analytical Expression

At high-level injection the hole and electron current densities are given, respectively, by $J_p(x) = c'J(x) - qD_a dp/dx$ and $J_n(x) = cJ(x) + qD_a dp/dx$, where $J(x)$ is the total current density, $p(x)$ is the carrier density with x for the vertical distance measured from the anode $(x = 0)$ towards the gate edge in the middle of the accumulation region as shown in Fig.1, q is the electronic charge, and D_a is the ambipolar diffusion coefficient while $c' = 1/(1+b)$ and $c = 1 - c'$ are used with b for the ratio between the electron and hole mobilities. The carrier distribution in the drift region along the vertical path can be readily obtained from the ambipolar diffusion equation as $p(x) = p_0[\sinh(w-x)/L + k\sinh(x/L)]/\sinh[w/L]$, where L is the ambipolar diffusion length, p_0 is the carrier density at the anode junction, w is the thickness of the drift region, and $k = p(w)/p_0$ with $p(w)$ for the gate dependent carrier density near the gate edge.

The hole current density at $x = 0$ and $x = w$ may be written as

$$J_p(0) = c'J(0) + \bar{p}_0 J_{pd} \quad (1)$$

$$J_p(w) = c'J(w) + \bar{p}_0 J_{pd}[1/\cosh r - k]/[1 - k/\cosh r] \quad (2)$$

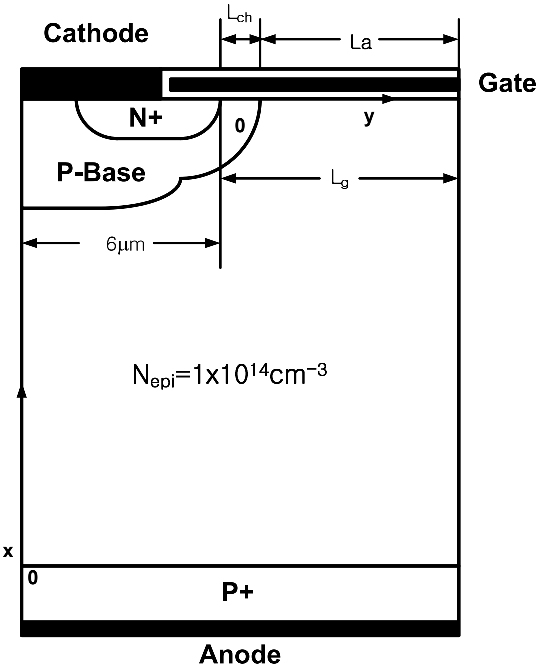

Fig. 1. The Cross section of a half unit cell of an IGBT with parameters

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with

$$J_{pd} = [qD_a N_{epi} / (L \tanh r)](1 - k / \cosh r) \qquad (3)$$

where $r = w / L$ and $\bar{p}_0 = p_0 / N_{epi}$ are used. Assuming that $J(w) \approx J(0)$ satisfies in Eq. (2), combination of Eqs. (1) and (2) gives an expression for the base transport factor of the IGBT, resulting in

$$\alpha_T = J_p(w)/J_p(0) = c'/\gamma + [1 - c'/\gamma](1/\cosh r - k)/[1 - k/\cosh r] \quad (4)$$

where $\gamma = J_p(0) / J(0)$ is the anode injection efficiency of the IGBT treated previously [3].

Eq. (4) reveals that the well-known expression of $\alpha_T \cong [1/\cosh r]$ for the base transport factor of BJTs is not valid for IGBTs and reduces to it only for the case of $c' \cong 0$ and $k \cong 0$, indicating no drift field for holes in the base region and a vanishing hole concentration in the proximity of the collector junction assumed generally for a P-N-P in active-region operation.

The current gain of an IGBT is found accordingly to be

$$\alpha_{pnp} = \gamma \alpha_T = c' + [\gamma - c'](1 / \cosh r - k) / (1 - k / \cosh r) \; (5)$$

Eq. (5) reduces to $\alpha_{pnp} = c'[1 - 1/\cosh r] + [\gamma / \cosh r]$ for $k = 0$, showing that the current gain of the IGBT in this case is larger than that of the BJT given by $\alpha_{pnp} = \gamma / \cosh r$ and then decreases with the increase of k, approaching ultimately to $\alpha_{pnp} = c'$ for $k = 1/\cosh r$. The anode injection efficiency, γ in Eq. (5) depends also on k as will be discussed shortly. In the base of the P-N-P structure of an IGBT, both the diffusion and the drift of the carriers are so effective as to result in α_{pnp} as a function of the holes injected from the anode and the electrons injected through the accumulation layer under the gate as well as the carrier mobility.

3. Simulation Results and Discussions

A cross section of the half unit cell with a thickness of $w = 95\mu m$ for an IGBT with a blocking capability of 600V used in the simulation is shown in Fig. 1, where the drift region is assumed to be uniformly doped with an impurity concentration of $N_{epi} = 10^{14} cm^{-3}$ with $\tau_{n0} = \tau_{p0} = 1\mu s$ for the electron and hole lifetime, respectively, and a double diffused p body region has a diffusion depth of $5\mu m$ and peak concentrations of $2 \times 10^{19} cm^{-3}$ and $1 \times 10^{17} cm^{-3}$ at the cathode contact and the inversion layer, respectively. The p+ anode has a thickness of $W_A = 30\mu m$ and a uniform distribution of the impurity with a concentration of $N_A = 5 \times 10^{18} cm^{-3}$. The device has a total width of $(6 + L_g)\mu m$ with a fixed channel length of $L_{ch} = 2\mu m$ and an accumulation layer length of L_a varied from $4\mu m$ to $48\mu m$ in the simulation, resulting in $L_g = L_a + L_{ch}$ for the gate length, which allows investigation of the current components of the device as a function of its gate length.

Fig. 2 shows the carrier distribution in the drift region at $V_g = 15[V]$ as a function of the distance measured from the gate at $y = L_g$ along the vertical direction towards the anode with the gate length as a parameter. The carrier density remains almost unvaried in the drift region of the anode side with $p_0 \cong 6.6 \times 10^{16} [cm^{-3}]$, but increases significantly in the proximity of the gate with increase of the gate length. The values are found to be $p(w) \cong 5.3 \times 10^{15}$, $8.7 \times 10^{15}, 1.4 \times 10^{16} [cm^{-3}]$ with the corresponding values of $k = 0.08, 0.13, 0.21$ for $L_g = 6, 14, 26 [\mu m]$, respectively. The simulation results are fitted by $p(w) = 2.7 \times 10^{15} + 0.43 L_g(\mu m) \times 10^{15} [cm^{-3}]$.

The n-channel MOSFET supplies electrons through the gate of an IGBT that replaces electrons recombined with the injected holes in the drift region as well as that reach the anode junction. The values for $p(w)$ thus represent the electron injection capability of the accumulation layer.

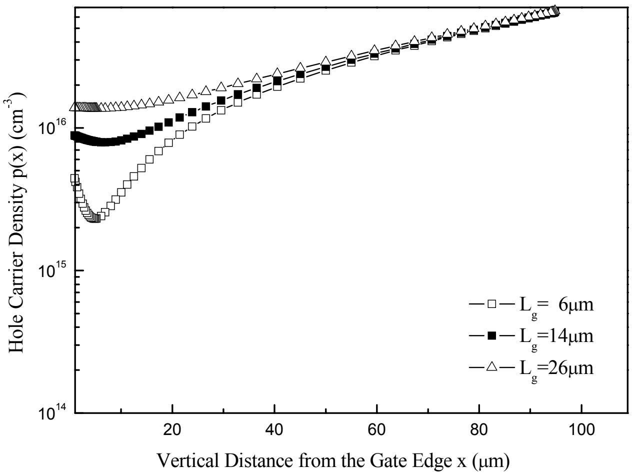

Fig. 2. Carrier distribution in drift region with gate length of IGBT as a parameter at $V_g = 15V$.

The injected carrier density, $\bar{p}_0$ can be calculated [3] by equating the expressions for the electron current density on either side of the anode junction given by $J_n(0) = cJ(0) - \bar{p}_0 J_{pd}$ from Eq. (1) and $J_n(0) = J_{n0} \bar{p}_0^{\,2}$. The result leads an expression for $\bar{p}_0 = \sqrt{(J_{pd} / 2J_{n0})^2 + cJ(0) / J_{n0}} - J_{pd} / 2J_{n0}$, where $J_{n0} = qgD_A N_{epi}^{\,2} / [N_A L_A \tanh(W_A / L_A)]$ with D_A and L_A for the diffusion constant and length for electrons in the anode, respectively, and with g for the band gap narrowing [4] in the heavily doped anode. The present anode structure with $D_A = 3.54 [cm^2 / s]$, $L_A = 1.88 [\mu m]$, and

$g = 15.5$ gives $J_{n0} = 0.93 \times 10^{-4} [A/cm^2]$. In the present device structure $\mu_p = 493[cm^2/V \cdot s]$ is used for the hole mobility, giving $c' = 0.266$, $D_a = 18.74[cm^2/s]$ with $\tau_a = 2\mu s$ leads to $L = 61\mu m$, resulting in $1/\cosh r \cong 0.4$ and $J_{pd} \cong 53.7(1-0.4k)$ $[mA/cm^2]$ obtained from Eq.(3). Thus we obtain $J_{pd} \cong 53.7, 50.4, 48.7$ $[mA/cm^2]$ and $\overline{p}_0 = 645, 658, 664$, which yield in turn $\gamma = 0.61, 0.6, 0.59$ for $k = 0, 0.13, 0.21$, respectively, showing that the effects of the gate length on the anode injection efficiency are limitedly small as expected. These values are found to be in excellent agreements with the numerical ones obtained from Fig. 2 within 0.5% in error. The results show that the electron injection increases with an increase of the gate length, calling an increase of the hole injection from the anode junction, which results in an increase in the electron current density accordingly as $J_n(0) = J_{n0}\overline{p}_0{}^2$ and decrease in $J_p(0)$ by the same amount. This brings about a decrease in the anode injection efficiency and the current gain as well.

The current gain for the present IGBT structure calculated from Eq.(5) is found to be $\alpha_{pnp} \approx 0.4, 0.354, 0.33$ for $k \cong 0, 0.13, 0.21$, respectively, indicating that α_{pnp} decreases with increase of L_g, reducing to $\alpha_{pnp} \approx 0.33$ at $k \approx 0.21$ for $L_g \geq 26[\mu m]$. An approximate expression for $\alpha_{pnp} \cong 0.266 + 0.334(0.4-k)/(1-0.4k)$ may be found for the present IGBT when, for simplicity, $\gamma \cong 0.6$ is taken in Eq.(5), which would yield $\alpha_{pnp} \cong 0.24$ for the BJT case of $c' \cong 0$ and $k \cong 0$.

Assuming that $I_{mos} = (1-\alpha_{pnp})I_{anode}$ holds in the bipolar transistor-MOSFET model of IGBT[2], we finally arrive at $I_{mos} \cong 3.9 + 0.65L_g(\mu m)$ $[\mu A]$ for $k = 0.13$ and $I_{mos} \cong 4 + 0.67L_g(\mu m)$ $[\mu A]$ for $k = 0.21$, whereas $I_{mos} \cong 4.6 + 0.76L_g(\mu m)$ for the BJT case.

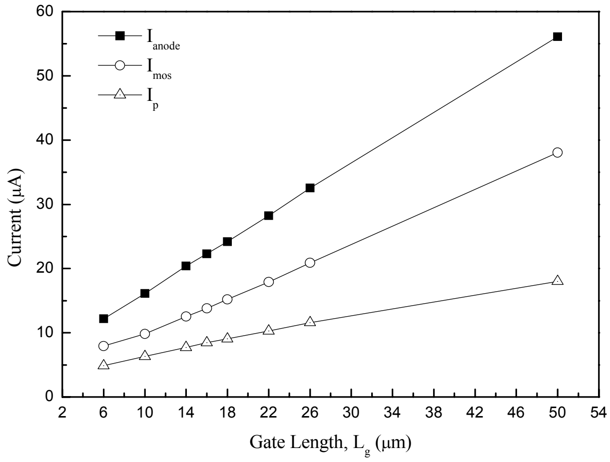

Fig. 3. Variation of electron, hole, and total current vs. gate length of IGBT at $V_g = 15V$.

The simulation results for the electron, hole, and total current denoted as I_{mos}, I_p and I_{anode}, respectively, are represented as data points in Fig.3 as a function of the gate length at $V_g = 15[V]$. With $J(0) = 100[A/cm^2]$ fixed, the total current for the present device is given by $I_{anode} = I_p + I_{mos} = 6 + L_g(\mu m)$ $[\mu A]$, whereas the electron current is found to be fitted by $I_{mos} = 4 + 0.66L_g(\mu m)$ $[\mu A]$ at least for $L_g \geq 6[\mu m]$, which shows a fair agreement with the calculated results of $I_{mos} \cong 3.9 + 0.65L_g(\mu m)$ $[\mu A]$ for $k = 0.13$ and $I_{mos} \cong 4 + 0.67L_g(\mu m)$ $[\mu A]$ for $k = 0.21$, given above, supporting the validity of Eq.(5). The similar simulation results are also obtained at $V_g = 10[V]$ and $V_g = 20[V]$. The V_g effects on I_{mos}, I_p and I_{anode} are found to be negligible.

4. Conclusion

In conclusion, it has been demonstrated that a simple analytical expression is derived for the current gain of the IGBT, which gives a good agreement with the simulation results for the gate length dependent MOSFET current of the IGBT. The analytical expression for the current gain of the IGBT provided in the present work, though approximate with one-dimensional treatment, will be useful in IGBT design calculations.

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