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Numerical Simulation of BJMOSFET on Current-Voltage Characteristics

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Abstract: A new power MOSFET Structure with a pn junction——Bipolar Junction MOSFET (BJMOSFET) has been proposed. The device has the advantages of both BJT and FET. The numerical model of the *I-V* characteristics of BJMOSFET has been obtained on the basis of both numerical and analytical methods. With the software package of Mathematic, we firstly calculate the gain factor, and then simulate the voltage tranmission, voltage output and voltage transfer's characteristic graphs of the BJMOSFET. The simulation result indicates that BJMOSFET has the current density, which is about 25% larger than the power MOSFET, under the same operating conditions and with the same structure parameters, except that the threshold voltage increase a little.

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1 Introduction

The MOSFET is a key device in high-fequency applications, such as swithing supplies, because of its high input DC impedance and the majority carriers participating in the

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current conduction. Unfortunately, owing to the limitation of the carrier's density in the channel, the output current and power capacity of MOSFET are very small. There are two kinds of carriers(hole and electron) in BJT in the current conduction, which can achieve large current flow and power output. However, the BJT suffers from long turn-off time due to the minority carrier storage and its input resistance, which is so low that it is difficult to coulpe directly. The ideal semiconductor device should exhibit a low forward voltage drop to decrease the on-resistance, so that it can operate at a high current density for any desired current handling capabilities. Therefore, various combinations of MOSFET and bipolar structures have been proposed, i. e. some different transistors, including MOSFET and BJT, have been incorporated into one IC[1-3]. But all of above makes the devices complicated, expensive and difficult to produce and integrate. A new device model of Bipolar Junction MOSFET(BJMOSFET)[4] has been proposed by Zeng, Yan and Chen *et al.*, which can solve the contradiction successfully.

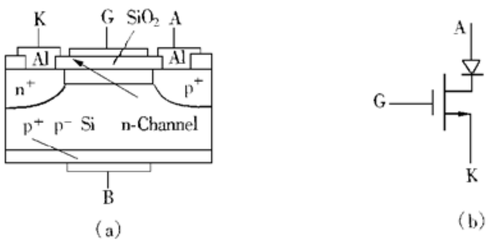

FIG. 1 (a) Cross Section of n-Channel BJMOSFET
(b) Schematic Circuit Diagram of BJMOSFET

Figure 1(a) shows the structure principle of the n-channel BJMOSFET, whose structure is similar to that of MOSFET's except that a p^+ region substituted for its n^+ regioning. It consists of a MOS structure and a p-n junction. Due to the introduction of the p-n junction injecting minority carriers into the n-channel, there are two kinds of carriers in BJMOSFET participating in the conduction, so that we can obtain large current capacity and output power. Furthermore, we adjust the voltage, the BJMOSFET has a high input impedance and its frequency response is better. Therefore the BJMOSFET has the advantages of both BJT and MOSFET. In addition, it is cheap and easy to produce.

In this paper, the numerical model is obtained for BJMOSFET's I-V characteristics, based on the numerical and analytical methods. With the software package of Mathematic, we firstly calculate the gain factor M, and then simulate the characteristic graphs of BJMOSFET about the voltage transmission, voltage output and the direct voltage transfer. The results show that the BJMOSFET has a large current density which is about 25% larger than the power MOSFET under the same operating conditions and with the same structure parameters, except that the threshold voltage increases a little.

2 Modeling BJMOSFET

The I-V relation between n-channel BJMOSFET and p-substrate should be taken into consideration before the channel's pinch-off. The schematic diagram of the analytical model for BJMOSFET's I-V characteristics is shown in Fig. 2.

For the sake of convenience, two assumptions were taken as follows: (1) Graded-channel approximation, i.e., the electric field parallel to the channel orientation is far larger than one normal to channel orientation ($\partial\epsilon_y/\partial y \gg \partial\epsilon_x/\partial x$). (2) Strong inversion approximation, i.e. when the potential at channel's surface equals to $2\Phi_F$, the current will flow through the channel.

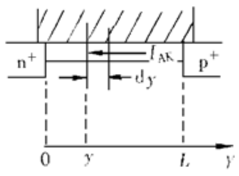

FIG. 2　Schematic Diagram of Analytical Model for BJMOSFET's I-V Characteristics

According to the Reference[5], the total charges in the inversion per unit layer area $Q(y)$ at point y in Fig. 2 can be obtained from (1) on the basis of the ideal MOS junction's theory just at the strong inversion:

$$Q(y) = -[V_{GK} - V_{FB} - \Psi_s(y)]C_{ox} + \sqrt{2\epsilon_s\epsilon_0 q N_{Ap}[V(y) + 2\Psi_F]} \qquad (1)$$

where V_{GK} denotes the gate voltage, $\Psi_s(y)$ the surface potential, $V(y)$ the potential drop along the y-orientation of n-channel, Ψ_F is the Fermi level during the p-substrate and V_{FB} is the flat band voltage, C_{ox} denotes the capacitance of the oxide per unit area and N_{AP} denotes the doping concentration in the p^+ region.

When the current channel is formed between the positive electrode (A) and the negative electrode (K), a forward current will flow through the positive electrode junction and the holes in the positive(p^+) region to inject into the n-channel. At this moment, the current consists of the electron and the hole current. The total charge in the channel is

$$Q(y) = Q_n(y) + Q_p(y) \qquad (2)$$

Based on the p-n junction theory, the hole density is

$$P_n = P_p e^{-qV_D/kT} \qquad (3)$$

where V_D is the potential drop at the positive electrode junction.

According to $n_n p_n = n_i^2$, we can obtain $\frac{P_n}{n_n} = \frac{N_{AP}}{n_n^2} e^{-qV_D/kT}$. Neglecting the generation and recombination of carriers, we believe the current in channel is only drift current. Hence, $\frac{Q_p(y)}{Q_n(y)} = -\frac{P_n}{n_n}$. That is to say,

$$Q_p(y) = \frac{N_{AP}^2}{N_i^2} e^{-qV_D/kT} Q_n(y) \qquad (4)$$

Substituted Eq. (4) into Eq. (2), we obtain

$$Q_n(y) = \frac{1}{1 - A} Q(y) \qquad (5)$$

where

$$A = \frac{N_{AP}^2}{n_i^2} e^{-qv_D/kT}$$

For the same reason, $Q_p(y)$ is

$$Q_p(y) = \frac{-A}{1 - A} Q(y) \qquad (6)$$

Considering the modulation of gate voltage V_{GK}, the current density in the channel is not well distributed. According to the Ohm's law, the current density is

$$J(x,y) = \delta(x,y)\epsilon_y = n(x,y)q\mu_n\epsilon_y + P(x,y)q\mu_p\epsilon_y \tag{7}$$

According to the assumption (1), the electric field is uniformly distributed paralleling to the channel orientatin, i.e., $\epsilon_y = -\frac{dV}{dy}$. If the channel is labeled as W, and both μ_n and μ_p are content, we obtain the total current in the channel as:

$$I(y) = - W[\mu_n Q_n(y) + \mu_p Q_p(y)]\frac{dv}{dy} \tag{8}$$

Though the holes and electrons in the channel move along opposite direction, their current direction is consistent. In the light of the current continuity's theory, $I_{AK} = -I(y)$, comparing the depletion layer's thickness and the channel's length L, we can neglect the former. Substitute (5) and (6) into (8), we obtain the integration of y from 0 to L, and V from 0 to $(V_{AK} - V_d)$:

$$I_{AK} = \frac{W}{L}\frac{\mu_n - A\mu_p}{1 - A}\int_0^{V_{AK} - V_p} Q(y)\,dv \tag{9}$$

Substitute Eq.(1) into Eq.(9), the integration yields

$$I_{AK} = \frac{WC_{ox}\mu_n}{L}M\left\{\left(V_{GK} - V_{FB} - 2\Psi_F - \frac{V_{AK} - V_D}{2}\right)(V_{AK} - V_D) - \frac{2}{3}\frac{\sqrt{2\epsilon_s\epsilon_0 qN_{Ap}}}{C_{ox}}[(V_{AK} - V_D + 2\Psi_F)^{3/2} - (2\Psi_F)^{3/2}]\right\} \tag{10}$$

where $M\left(= \frac{1 - A\frac{\mu_p}{\mu_n}}{1 - A}\right)$ is the gain factor. From (10), we find the BJMOSFET's channel current increases M greatly, compared with traditional MOSFET's[5].

While the V_{GK} keeps constant and V_{AK} increases to V_{GKsat}, the channel just pitches off and I_{AK} reaches the saturated value I_{AKsat}. Assuming $V(L) = V_{AKsat}$, and $Q(L) = 0$, I_{AKsat} is given as follows.

$$I_{AKsat} = \frac{W\mu_n C_{ox}}{L}M\left\{\left(V_{GK} - V_{FB} - 2\Psi_F - \frac{V_{AKsat} - V_D}{2}\right)(V_{AKsat} - V_D) - \frac{2}{3}\frac{\sqrt{2\epsilon_s\epsilon_0 qN_{Ap}}}{C_{ox}}[(V_{AKsat} - V_D + 2\Psi_F)^{3/2} - (2\Psi_F)^{3/2}]\right\} \tag{11}$$

3 Numerical Simulatiuon and Discussion

At room temperature, a BJMOSFET structure is considered to be constructed on a p-Si substrate, with the channel length L of 5μm, channel width W of 20μm and oxide thickness C_{ox} of 0.025μm. The following are the main parameters of device used in the numerical simulation in this paper. The intrinsic carrier concentration n_i is 2.5×10^{10}cm^{-3}. The electron charge q is 1.602×10^{-19}C. The electron mobility μ_n and hole mobility μ_p are 10×10^4 and 5×10^4cm^2/(V·s), respectively. The doping concentration N_{AP} in the positive region is 10^{16}cm^{-3}. The product of the dielectric constant of oxide(ϵ_{ox}) is 38 and the permittivity of the free space(ϵ_0) is 3.45×10^{-3}F/cm.

3.1 Calculating Gain Factor *M*

At thermal equilibrium and under the condition of forming the channel, we calculated:

The thermal voltage: $V_T = kT/q = 0.026$V.

The coefficient A: $A = 0.3248$.

The gain factor M: $M = 1.2405$.

The calculating result shows that the BJMOSFET has a current density about 24% larger than the power MOSFET under the same operating conditions and with the same structure parameters.

3.2 Numerical Simulation and Discussion

Mathematic[6] is a kind of software package about mathematical analysis, used in the following numerical simulation. Figure 3 is the BJMOSFET's transfer characteristic graph when $V_{AK} = 5$V. Two conclusions have been drawn from the simulating results: (1) When gate voltage(V_{GK}) approximately equals to 2.2V, the channel comes into being. In this case, the value of V_{GK} is the threshold voltage of BJMOSFET. During modeling the BJMOSFET, we neglect the current contributin due to the electron and hole's recombination. In practice, the recombining current also play a role in the channel current. Therefore, the threshold voltage of BJMOSFET is much larger than the excepcted value. (2) The gate voltage has linear relations with the channel current, which is the reason for the BJMOSFET's current density increasing linearly with the grid voltage increasing. Therefore, the BJMOSFET operates in the linear region at this time.

Figure 4 shows the BJMOSFET's I-V characteristic graph, from which, we know BJMOSFET's characteristic graph can be divided into cutoff, linearity and saturation. But BJMOSFET's linear is so narrow that is very easy to enter to the saturation. At the same, the I-V characteristic graph of the power MOSFET with the same structure parameters are also displayed in Fig. 4. The comparative results indicate that the BJMOSFET has the larger current density, which is about 25% larger than the power MOSFET under the same operating conditions and with the same parameters, as agrees with the gain factor M.

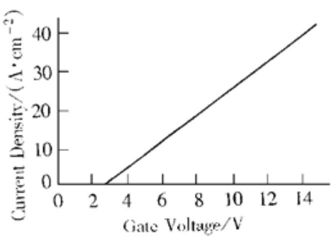

FIG. 3 Transfer Characteristic Graphs for BJMOSFET's

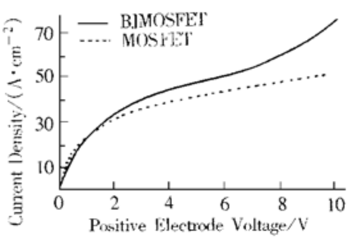

FIG. 4 I-V Characteristic Graph for BJMOSFET's

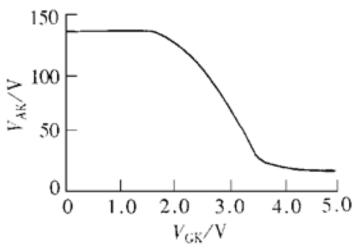

FIG. 5 Direct Voltage Transfer´s Characteristic Graph of BJMOSFET

The voltage transfer´s characteristic graph of BJMOSFET is shown in Fig. 5. When the input voltage (V_{GK}) is less than the threshold, the BJMOSFET wil operate in the cut-off region. Should the V_{GK} be increasing below 3.5V, the BJMOSFET is operating in the linear region, while V_{GK} increasing above 3.5V, it operating in the saturation region.

4 Conclusion

Under the condition of the reasonable assumptions, we analysed in details the I-V characteristies of BJMOSFET and obtained its DC numerical model. With the software package of Mathamatic, we firstly calculate the gain factor M, and then simulate the voltage transmission , voltage output and the direct voltage transfer´s characteristic graphs of the BJMOSFET. The BJMOSFET is proved to have the current density, which is about 25% larger than the power MOSFET under the same operating conditions when the structure parameters are same except that the threshold voltage increases a little, as indicates that the BJMOSFET is a kind device of high current capacity.

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