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A New Circuit Model of Bipolar Junction Transistor

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Abstract: *Bipolar junction transistor or BJT is supposed to cost much more power and areas than MOSFET, but its frequency domain response seems better than MOSFETs. In this paper, a new circuit model for BJT is proposed, and the three-terminal circuit includes two MOSFETs and one Schottky diode, which can then be denoted by one MOSFET and a reversely-biased diode. If the new circuits are applied in technology processes for manufacturing, then MOS technology may be illuminated by early BJT to fabricate new devices.*

Keywords: *Bipolar, transistor, MOSFET, schottky junction, IGBT*

1. Introduction

Bipolar junction transistor (BJT) marks early mature semiconductor technologies before 2000, and is gradually replaced by Metal-Oxide-Semiconductor (MOS) technology in industry [1]. MOS field effect transistor (MOSFET) is supposed to be more area and power efficient than BJT. Meanwhile, BJT is superior to MOSFET in frequency domain response.

MOSFET is then faced with the problem of leakage currents and breakdown potential. Then a fin-like field effect transistor called FINFET is applied in technology to manufacture smaller MOSFET in deep submicron technology points [2]. Other ways in manufactures seeks high-resolution lithography machines. In fact, MOSFET is somewhat alike electromagnetic relay. The electromagnetic relay uses magnetic force to switch on the connection [3], while a MOSFET control electrons in the vertical direction to turn on a device. Also, there is a special semiconductor device called as insulated gate bipolar transistor (IGBT) for power electronics [4], which has MOS input characteristics and bipolar output characteristic.

In this work, a new circuit model for bipolar transistor is proposed to describe its behavior, which consists of two MOSFETs and a Schottky diode. In this way, the mechanism of channel modulation in MOS may be used to observe BJT, while the metal-semiconductor contacts in BJT may be used to improve the frequency response in MOSFETs.

The remaining parts of this brief paper are organized as follows: Sect. 2 is a short review of bipolar transistor, Metal-semiconductor diode, and MOSFET. Sect. 3 proposes a new point of view into bipolar junction, which can be considered as two MOSFETs and one conductor. The last section concludes this paper.

2. Bipolar Junction Transistor and MOSFET

2.1. Pn Junction

The pn junction in Figure. 1 is the basic unit of a semiconductor device, which is formed between two kinds of materials. By inserting impurity dopant into semiconductors, the materials will be filled of electrons or holes and become conductors of different polarities.

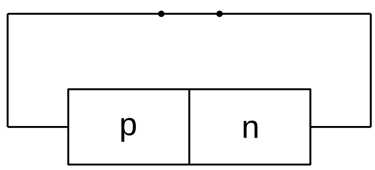

Figure 1: pn junction in a loop.

Suppose the acceptor and donation concentrations of p-type and n-type semiconductors are respectively N_a, N_d, then the built-in potential barrier of the p-n junction is [1]

$$V_{bi} = V_t \cdot \ln \frac{N_a \cdot N_d}{n_i^2}. \tag{1}$$

where n_i is the intrinsic carrier concentration, $V_t = k \cdot T/e$, k is the Boltzmann constant, and T is the junction temperature.

2.2. Bipolar Transistor

The device of a bipolar junction transistor is sketched in Figure 2, where the three terminals are base (B), emitter (E), and collector (C) [1].

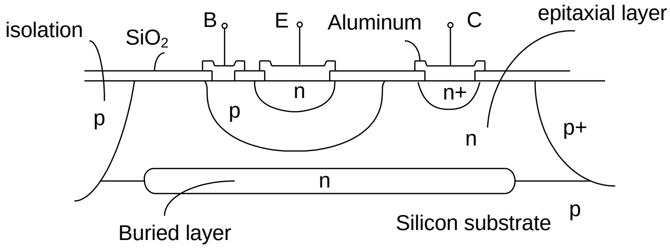

Figure 2: Bipolar junction transistor.

Usually, it seems that there are two currents out of the emitter, i.e., $I_e = I_{be} + I_{cb}$, where I_{be} is the forward-biased current from the base to the emitter, and I_{cb} is the diffusion current from the collector to the emitter. As a result, there is $I_e = I_s \cdot \exp\left(\frac{V_{be}}{V_t}\right)$, where $I_s = I_{c1} + I_{e2}$, with I_{c1} referring to diffusion currents I_{cb} and I_{e2} referring to base current I_{be}.

2.3. Metal-semiconductor Diode

The Metal-Semiconductor diode or Schottky barrier diode can be looked at as one-side p-n junction [1], as is shown in Figure 3. In fact, the electrodes are mostly connected to devices by metals like aluminum, copper and silver. The metals act as ideal boundary conditions for a pn junction, with the p-side of a junction omitted.

The voltage-current relation of the metal-semiconductor junction is shown in Equ. 2, where V_{Bn} is the built-in potential, and V_a is the source voltage [1].

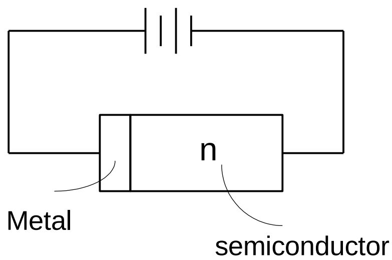

Figure 3: Metal-semiconductor junction.

The current is alike diffusion currents with ideal boundary conditions. Also, it can be found that if the source voltage $V_a = 0$, then the current $I_{ms} = 0$.

$$I_{ms} = I_0 \exp\left(-\frac{eV_{Bn}}{kT}\right) \cdot \left(\exp\left(\frac{eV_a}{kT}\right) - 1\right) \tag{2}$$

2.4. MOSFET

The MOS transistor is a three-terminal device, which is illustrated in Figure 4. Between the gate

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and the body is the oxide or insulator. The voltage between the gate G and the source S is positive, while the voltage between the drain D and the source S is also positive. The current is controlled by the voltage between S and G. For long-channel MOS device, its I-V relation is:

$$I_D = \frac{W\mu_n C_{\text{ox}}}{2L}[2(V_{GS} - V_T)V_{DS} - V_{DS}^2] \tag{3}$$

In saturation region, there is V_{GS}-V_T= V_{DS},, and the current is determined by the gate voltage in the following:

$$I_D = \frac{W\mu_n C_{\text{ox}}}{2L}(V_{GS} - V_T)^2 \tag{4}$$

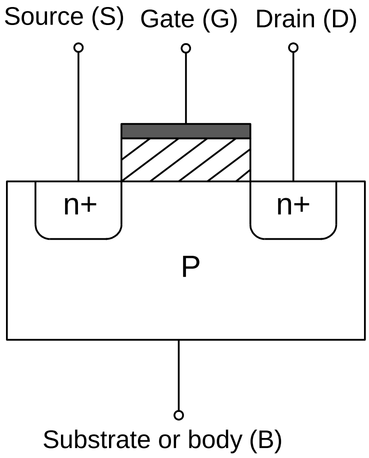

Figure 4: Schematic of MOS transistor.

The oxide brings out a large capacitance between the gate and the body due to large contact area and high insulation media, which results in power consumption and time delay for charging and discharging the capacitance.

3. New Model of Bipolar Transistor

The bipolar transistor in Figure. 2 can be viewed as two MOSFET together with a Schottky barrier junction, as is shown in Figure 5.

In Figure. 5, the area below the base (B) can be divided into three areas:

(1) a positively biased MOSFETs between E and B, which is marked by Area 1. The electron concentration is n_p= n_{p0}·exp(V_{be}/V_t), where V_t= k·T/e. Then if B-E is positively biased or V_{be}>0, then B and E is connected.

(2) a negatively biased MOSFET between B and C, which is marked as Area 2. The electron concentration is n_p= n_{p0}·exp(-V_{cb}/V_t), where V_t= k·T/e. Then if B-C is negatively biased or V_{bc}<0, then B and C is cut off.

(3) the middle Area 3 denotes electron concentration of a Schottky diode. First, the free electrons sufficiently exist in the metal along the side of Area 3. Second, if the base is positively biased, then area 3 is like a conductor. Otherwise, if the base is negatively biased, then the area 3 is a depletion region of electrons.

Obviously, the bipolar junction includes 2 MOSFETs and 1 Schottky junction. For bipolar junction, it is supposed that the current from C to E is constant when V_{cb}> V_t. This current Ice is determined by the voltage V_{be} in Area 1, which is a voltage-controlled current in the device. The area 2 is a depletion region for electrons, with the junction negatively biased. Compared with MOSFET circuit model, the middle area along the channel is minorly affected by the voltage V_{be} and V_{bc}. The modulation or control then happens around the edges on both sides of the base, which is appropriate for electronic or electric movements. In other words, the electronic devices can be locally controlled by signals.

The base current I_b is mainly due to the current from the base to the n-well in vertical direction,

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where the n-well is shown in Figure 2. Therefore, I_b is also proportional to $\exp(V_{be}/V_t)$ as well as I_{cb}. The conduction area 3 makes the transportation of electrons very fast from E to C, which denotes a high velocity or mobility of carriers. Also, the contact areas of the MOSFET are much smaller than traditional MOSFETs, and the related capacitance between the gate and body gets smaller. As a result, it has high performance in frequency domain response. However, the effective channel is much shorter, which decreases the threshold voltage.

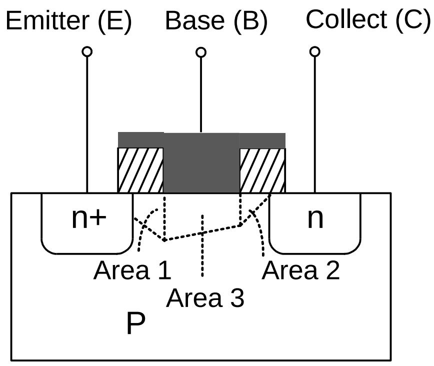

Figure 5: Equivalent circuit of a bipolar junction transistor.

In addition, the multi-emitter structure can be applied to realize a long channel device. First, it makes the control or modulation of the channel more effective compared to one-emitter structure. This is analogous to a double-pole double-throw switch, which is more efficient and secure than single-pole single-throw switch. Figure 6 shows a double-emitter and double-base bipolar junction transistor.

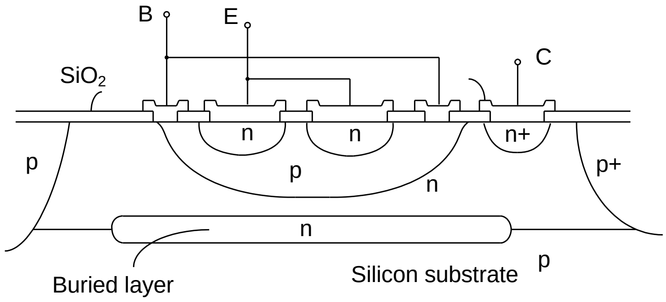

Figure 6: Multi-emitter and multi-base bipolar transistor.

In Figure 6, the BJT with two emitters and two bases is like a double-pole double throw switch. The Aluminum or metal provide a short path from E to C that constrains the carrier channel. In the situation, if the voltages of B and E are not exerted, then 2~4 isolated areas exist between E and C, which is more effective to cut off currents.

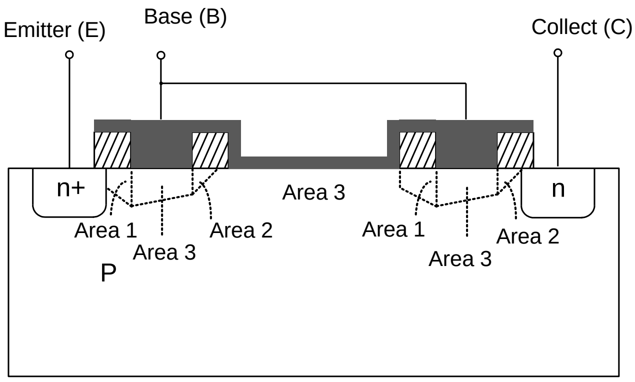

Figure 7: Bipolar transistor with two bases.

In Figure 7, Area 1 and Area 2 are like two insulated areas and are controlled by the two bases, looking like 2~4 serial switches of the drain currents. Meanwhile, Area 3 denotes the conduction areas.

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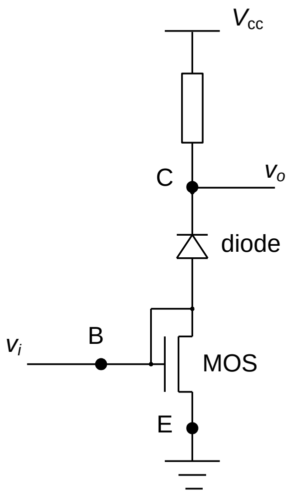

Figure 8: Equivalent circuit of the BJT.

Figure 8 is the equivalent circuit of the schematic in Figure 5, in which the BJT is analogous to a MOS and a reversed diode. Especially, the drain and the gate voltages are connected in together.

4. Conclusions

The bipolar junction transistor can be also looked at as a channel-modulated device. Along the channel from E to C the path can be divided into 3 areas, one positively biased MOSFET, one negatively biased MOSFET, and one Schottky barrier diode. The current in saturation area of a BJT is mainly determined by the positively biased MOSFET. The Schottky diode is in parallel with a metal plane, so that area 3 can be considered as a conducted area with sufficient electrons.

The circuit model of a bipolar junction transistor can be simplified as a MOSFET and a reversely-biased diode. It seems that the new circuit model of BJT can be used to improve the accuracy of BJT models in circuit simulations. Also, the metal-semiconductor junction may be applied in MOSFETs to improve its frequency domain response in the future.

Acknowledgments

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