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Impact of Work function Engineering in Charge Plasma Based Bipolar Devices

Lokesh Bramhane¹, Suresh Salankar¹, Mahendra Gaikwad¹, Meena Panchore²

Abstract—In this paper, we have explored and justified the reason behind the degradation in the cutoff frequency of the bipolar transistors evolved from the charge plasma concept. It has been observed that if the work function difference present between the emitter metal contact and silicon is greater than or equal to 0.68 eV ($\phi_m - \phi_{SI} = 4.05 \text{ eV} - 4.73 \text{ eV}$), it results in increment in the base width which is the inverse of the cutoff frequency. On top of this, two dimensional TCAD simulations of the different bipolar devices also demonstrate the same basewidth widening effect into the intrinsic region which is present between the base region and collector region. Apart from this, if this difference is exactly equal to 0.5 eV ($\phi_m - \phi_{SI} = 4.23 \text{ eV} - 4.73 \text{ eV}$) then the base width widening effect can be completely eliminated from the bipolar devices base on the charge plasma.

Keywords - Horizontal Electric field; Base Width Widening Effect; Cut-off frequency; Charge plasma; Silicon-on-insulator.

I. INTRODUCTION

Bipolar junction transistors are the best suitable devices to integrate with the CMOS and as a result, BiCMOS emerged as a device that has both the characteristics of analogue as well as digital. Inclusion of high speed and amplifying characteristic of the bipolar devices with switching mechanism of MOSFET devices have enhances the importance of BiCMOS [1]. Apart from this, to reduce the cost of the fabrication of these devices, the charge plasma concept was proposed to simplify the fabrication steps and to eliminate the post ion-implementation [2]-[5]. In addition, bipolar charge plasma transistors (BCPTs) in symmetric nature have also been proposed to make it compatible with symmetric MOSFETs [6], [7]. Moreover, polarity controlled reconfigurable BCPTs that can switch from NPN type to PNP type and vice versa also have contributed to this [8]–[10]. But bipolar devices based on the charge plasma concept have had reported comparatively very large current gain [7], [8] and half of the cutoff frequency compared to its counterparts [5]. Hence, to enhance the cutoff frequency many efforts have been made by introducing different architectures like extruded base BCPTs, schottky-collector and hetero-junction type BCPTs [11]–[17]. These devices poses the high cut-off frequency but lower current gain compared to the devices that were previously proposed using the concept of charge plasma. However, proposed structures of these devices are not compatible with the MOSFETs hence not suitable for the integration process with CMOS devices that is why; lateral structures

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of BCPTs which does not contained the extruded base and heterojunction are preferred more and found best candidates for the integration process with CMOS to form the BiCMOS devices. On top of this, it had been said that cutoff frequency degradation of these devices may be due to the inclusion of the intrinsic region between the base-emitter region and basecollector region [4], [6], [7]. But none have concentrated on the effects like Kirk or base width widening effect that implicate severe impact on the performance of the devices based on the charge plasma. Moreover, in charge plasma concept, it is stated that the minimum work function difference between the contact metals and silicon should be 0.5 eV in order to induce the electrons or holes in a particular region [2]–[6]. But have not incorporated about the maximum work function difference that should be maintained to avoid the aforementioned effects in the bipolar devices.

Considering the above said, we have exploring and justifying the reason behind the degradation in the cutoff frequency by simulating and calibrating the bipolar charge plasma transistors using the different emitter work function metals contacts. In this paper, a way to limit the horizontal electric field induced at the emitter region due to different emitter work function is presented and explored to avoid the degradation in cut-off frequency. Our work is calibrated with both fabricated and simulated devices that are presented in [3].

II. DEVICE STRUCTURE AND PARAMETERS

Figure 1 - Crosssectional view of lateral BCPT with different emitter metal contacts [3].

Charge plasma concept has been proposed to eliminate the doping process from the different semiconductor devices. In these devices, to induce the electrons and holes in a particular regions, work function difference between the metal contacts and silicon should have to put equal or higher than the 0.5 eV [2], [3]. Electrons and holes can be accumulated using the metal contacts having work function lower and higher compared to the silicon. In this process, there is an

Name of the device	Emitter Metal	$\phi_{m,E}$ (eV)	$\phi_{m,E} - \phi_{si}$ (eV)
Asymmetric BCPT (3.9 eV)	Hafnium	3.9	-0.83
Asymmetric BCPT (4.05 eV)	Zirconium	4.05	-0.68
Proposed Asym. BCPT (4.23 eV)	laterally extended Al(111)	4.23	-0.5

TABLE I. WORK FUNCTION OF THE EMITTER METAL CONTACT AND ITS DIFFERENCE FROM THE SILICON WORKFUNCTION

induction of the high horizontal electric field at the emitter region near the interface of the emitter metal contact and silicon [4]. Apart from this, width of the silicon should be within the Debye length [2]–[4]. But, none of the restriction on the maximum work function difference between the metal contact and silicon has been imposed nor stated to consider such effects on priority basis. To impose the restriction on the horizontal electric field at the emitter which is due to the work function difference between the emitter metal contact and silicon, we have proposed a structure having emitter metal contact of 4.23 eV that is also calibrated with the bipolar charge plasma transistors (lateral n-p-n BCPT). Cross-sectional view of the proposed structure is shown in Figure 1. In order to accumulate the charge (electrons and holes) in a particular region, all these BCPT devices having different emitter metal contact have maintained the minimum work function difference between the emitter metal contact and silicon. All the parameters of these devices are same except the work function of the emitter metal contacts that are also listed in Table 1 [4], [5]. In the proposed device, laterally extended Al (111) metal contact having the work function of 4.23 eV is used as an emitter metal contact [18]. The device parameters employed in our simulation are: Silicon having 15 nm (t_{si}) is lightly doped ($N = 1 \times 10^{13}/\text{cm}^3$) and layer below the silicon is 375 nm (t_{BOX}) wide. While intrinsic gap between emitter-base regions and base-collector regions are 100 nm (L_S) wide. Insulation layer between the base contact metal and silicon is 5 nm (t_{ox}). The dimension of the emitter region is 0.2 μm while the base and collector region are just half and twice the emitter region, respectively. To maintain the uniform distribution of carriers, the silicon film thickness is under the Debye length. Apart from this, different BJT Models are included during the 2D simulation of these devices [21]–[24].

III. RESULTS AND DISCUSSION

An exploration and justification behind the degradation in the cut-off frequency of the bipolar charge plasma transistors have been discussed in this paper. However, in [5], it has been proposed that in the absence of oxide thicknesses which are located below the emitter and collector metal contact electrodes, there is no degradation in the cut-off of the device (7.5 GHz) and reported current gain also with in the practical range. Moreover, the current gain of the device can be increased further by making the work function difference larger than the previous one. But this high work function difference between the emitter metal contact and silicon is the

main reason of the base width widening effect, also, responsible for the high horizontal electric field towards the base region that exerts a force onto the electron-hole pairs. Due to this, the electrons which are present in the emitter region are now accelerated and under the forward active bias condition, all are collected by the collector region. As a result, the collector current increases further just because of the higher accumulation of electrons and becomes the dominating factor for the increment in the base width (base width widening effect). In npn type transistor when B-E junction is in the forward biased condition, the excess holes, Q_F , distribute in the three regions (base region, depletion layer regions, and in the emitter region). In this case, the emitter-to-collector transit time (τ_F) [19] can be expressed as

$$\tau_F = (Q_F/I_C)V_{rms} = V_m/\sqrt{2} \quad (1)$$

where, Q_F is the sum of all the excess holes, and I_C is the collector current. But the base transit time (τ_{FB}) has the major contribution and it is about the half of τ_F [19], and can be expressed as

$$\tau_{FB} = Q_{FB}/I_C = (W_B)^2/2D_B \quad (2)$$

where, base width W_B , Q_{FB} is the excess hole charge and D_B is the minority carrier (electron) diffusion constant in the base. Moreover, cut-off frequency f_T is inversely proportional to τ_F [19],

$$f_T = 1/2\pi\tau_F \quad (3)$$

Hence, to reduce τ_{FB} , it is important to reduce W_B . Apart from this, at the saturation velocity (v_{sat}), the collector current can be defined as

$$I_C = qnv_{sat}A_E \quad (4)$$

where, A_E is the area of the emitter region, q is the electric charge, and n is electron concentration.

$$\rho = qN_C - qn \quad (5)$$

$$\rho = qN_C - I_C/A_E v_{sat} \quad (6)$$

$$dE/dx = \rho/\epsilon_s \quad (7)$$

In Figure 2, electric field between the base and collector region (depletion region) has been shown that demonstrating the widening of the effective base width with increment in collector current. Also the shaded area demonstrates the potential across the junction. Since, base region is heavily doped comparatively to collector region hence depletion region is more towards the collector side and can be further divided into lightly and heavily doped collector region. From the above, it can be concluded that increment in collector current will result in decrement in electric field and it is almost zero near the lightly doped collector region. But still there is no change in the shaded area as shown in Figure 2 (b) and is equal to shaded area in Figure 2 (a). Voltage across the base-collector junction is kept constant. If we further increase the collector current then there is a change in the sign of the electric field but shaded area remains constant as

Figure 2. Electric field at the base-collector junction with respect to device length of the devices named (a) (b) (c) (d) bipolar junction transistor under forward bias condition [8], (e) BCPT under both thermal and forward bias conditions, and (f) All the three devices under forward bias.

shown in Figure 2 (c). Also, in Figure 2 (d), with increment in collector current, high electric field peak point is now shifted to near the lightly doped collector region. As a result, effective base width is wide enough and responsible for the decrement in the cut-off frequency [19], [20]. Using the TCAD SILVACO 2D simulator [25], we have extracted the horizontal electric field at the base-collector junction of the asymmetric bipolar charge plasma transistor (BCPT) having emitter metal work function of 3.9 eV that is elaborated in Figure 2 (e). In which, under the forward bias condition ($V_{BE} = 0.7$, $V_{CE} = 1.0$), base width widening effect is exhibited due to large work function difference 0.83 eV ($\phi_{Si} - \phi_E = 4.73 - 3.9$ eV) causing base width widening effected as depicted in Figure 2 (e). In Figure 2 (f), we also have extracted the horizontal electric field at the same base-collector junction for the asymmetric BCPT having emitter metal work function of 4.23 eV (proposed) and 4.05 eV. Asymmetric BCPT (4.05 eV) that demonstrate no degradation in cut off frequency due to elimination of the SiO₂ layer present between the emitter metal contact and silicon and have the same cutoff frequency equivalent to traditional BJTs (7.5 GHz) but in the proposed Asymmetric BCPT (4.23 eV) cutoff frequency is further improved and it is 9.75 GHz due to elimination of the base width widening effect. Although with the increment in work function difference, base width widening effect appears at the base-collector junction of these devices. Moreover, large work function difference between the emitter metal contact and silicon high horizontal electric field at the emitter region near the interface that accelerate the electrons of emitter towards the collector region via base region. Hence, accumulation of these electrons results increment in collector current. From Equation 6 and 7, it is clear that continuous increment or large collector current causes the shifting of the peak electric field at base-collector junction towards the lightly doped collector and responsible for the widening of the base width. From Equation 2, widening of the base width enhances the time travel by the electrons from the emitter to collector (transit time) which is inversely proportion to the cutoff frequency (Equation 3). Hence, it becomes necessary to set or define the maximum work function difference between

the emitter metal contact and silicon to avoid the base width widening effect. For this, it must be 4.23 eV as it is explored and justified by using the TCAD SILVACO 2D simulation and calibrated well before the extraction of the cutoff frequency of these devices.

IV. CONCLUSION

In this endeavor, we have explored and justified the reason behind the degradation in the cut-off frequency that is because of the high work function difference between the emitter metal contact and silicon. Due to this, high accumulation of the electrons at the collector region enhancing the collector current and the peak electric field at base-collector junction is shifting more towards the lightly doped collector region. As a result, base width is increased. Moreover, it is also explored and demonstrated using the SILVACO TCAD 2D simulation that how increment in work function difference of the emitter metal contact and silicon causing base width widening effect at the base-collector junction. Hence, to avoid this effect, work function difference must be kept equal or less than the 0.68 eV (4.05 eV - 4.23 eV). Moreover, the proposed structure having emitter work function of 4.23 eV is free from the base width widening effect.

V. DECLARATIONS

A. Funding Statement

Authors declare that for this work, we have not got any funding from anywhere.

B. Conflict of Interest

The authors declare that they have no competing or conflict of interests

C. Author contributions

Lokesh Bramhane have analyzed and interpreted the problem statement and suggested a solution. Along with Meena, we have calibrated and simulated the different results and concern with the Mahendra Gaikwad and Suresh Salankar. After evaluation, we all have equal contribution in preparing the manuscript. All authors read and approved the final manuscript.

D. Availability of data and material

Data sharing is not applicable to this article.

E. Compliance with ethical standards

Not Applicable

F. Consent to participate

Not Applicable

G. Consent for Publication

Not Applicable

H. Acknowledgments

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Figures

Figure 1

Crosssectional view of lateral BCPT with different emitter metal contacts [3].

Figure 2

Electric field at the base-collector junction with respect to device length of the devices named (a) (b) (c) (d) bipolar junction transistor under forward bias condition [8], (e) BCPT under both thermal and forward bias conditions, and (f) All the three devices under forward bias.