Analytical modeling and numerical simulations of the offset voltage in silicon-on-glass vertical PNP’s

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***Abstract* — Silicon-on-glass vertical PNP’s are investigated with respect to the influence of the collector design on the offset voltage by means of electrical measurements, numerical simulations and analytical modeling. It is clarify why with Schottky collector contacts the offset voltage can be made both very low (≈0.05 V) and very high (≈0.28 V).**

***Index Terms* — Offset voltage, ohmic collector contact, Schottky collector contacts, silicon-on-glass, vertical PNP’s.**

I. Introduction

Substrate transfer processes are attracting attention as possible low-cost technologies enabling high-performance low-power RF integrated circuits with on-chip RF integration of active devices and high-quality passive components [1, 2]. From a device design point of view they are very attractive if, like the silicon-on-glass process used in this work [3], they give direct access to both sides of the device. Particularly for bipolar transistors, where the active current path is vertical to the surface from the emitter to the collector, the availability of the collector contact directly under the emitter eliminates the need for buried layers, the device size can be considerably reduced and the speed performance increased by the reduction of parasitic series resistance and capacitance.

Recently, fully-implanted vertical PNP’s (VPNP’s) have been added to a 25 GHz silicon-on-glass NPN process [3]. Different types of such devices were fabricated for example by varying the collector contact design. In addition to the conventional ohmic contacts, p-type Al/Si Schottky junctions were used as collector contacts. In Schottky-collector-contacted devices the implantation steps of the p^+ region at collector contact are eliminated, which results in cheaper fabrication then the silicon-on-glass VPNP’s with ohmic collector contact. The measurements show that the main device parameters are not significantly affected by the collector design except for the offset voltage.

The offset voltage is an important DC parameter of bipolar transistors. For high-frequency applications it is normally not an issue but in analog/power applications it can lead to undesirable extra power consumption and must be taken into consideration. In this paper the effect of the collector design on the offset voltage is investigated by means of electrical measurements, numerical simulations and analytical modeling.

II. Experimental Material

The doping profile of the intrinsic VPNP is shown in Fig. 1. Different collector designs were realized by varying both the thickness, t_{Si}, of the SOI silicon top-layer and the collector contacting method. Schematic cross sections of the fabricated devices are given in Fig. 2. Ohmic contacts were made by a 5×10^{15} cm^{-2} 5 keV BF_2^+ implantation and doping activation by laser annealing [4]. The metallization of these and the Schottky contacts was realized by standard Al/Si(1%) PVD as also used in [3]. A 3 hr anneal at 300°C was performed to dissolve any native oxide at the silicon-aluminum interface.

For the devices without the BF_2^+ implantation the Al/Si forms an Schottky diode to p-doped regions as shown in Fig. 3. When the region under the quasi-neutral base is depleted to the collector contact, the device is referred to as fully-depleted. The other devices have partly-depleted collectors. The nomenclature is given in Table I.

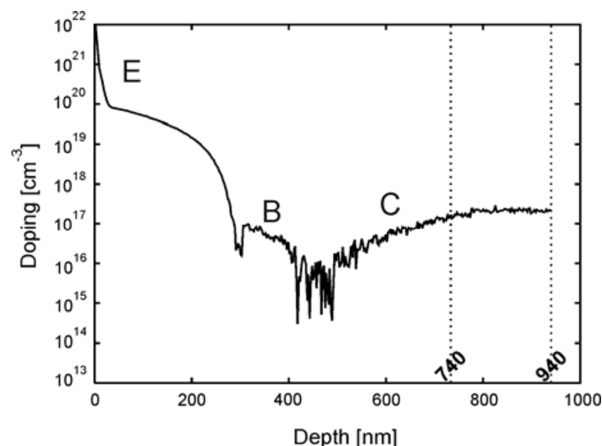


Fig. 1. SIMS profile of the intrinsic VPNP implantations after the 950°C thermal anneal. The distance to the collector contact is indicated for the two fabricated values of the silicon top-layer thickness: 740 and 940 nm.

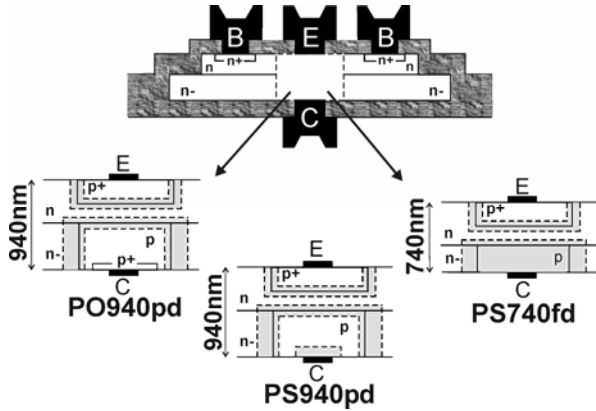


Fig. 2. Schematic cross section of the silicon-on-glass VPNP's with implanted and laser-annealed ohmic collector contact (PO940pd), and with p-Schottky collector contact (PS940pd and PS740fd). Depletion regions are indicated by grey areas.

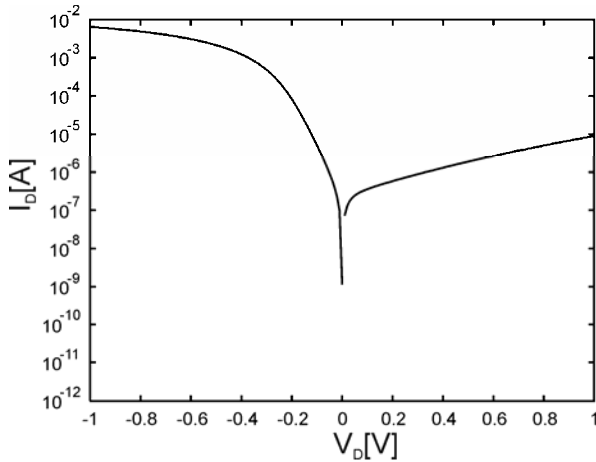


Fig. 3. Measured I-V characteristic of p-Schottky diode with a junction doping of about 10^{17} cm^{-3} and area 4 x 4 μm^2.

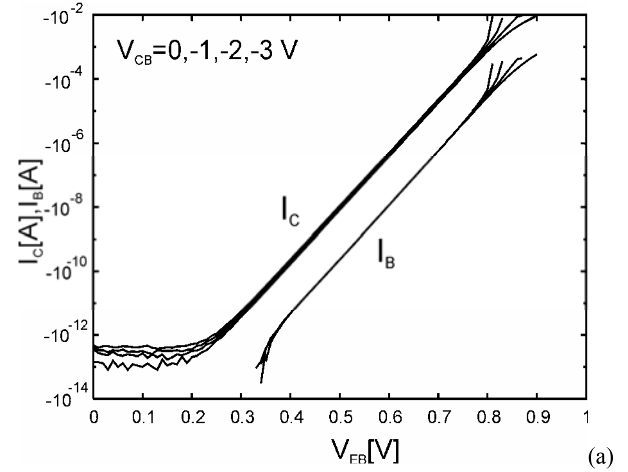
III. EXPERIMENTAL MEASUREMENTS

An example of typical I-V characteristics for the Schottky-collector VPNP's is shown in Fig. 4. At high I_C or high V_{EC} the observed excessive increase in I_C is due to selfheating [3], but this is of no consequence for the present study. Measured reverse Gummel plots of the devices listed in Table I are shown in Fig. 5.

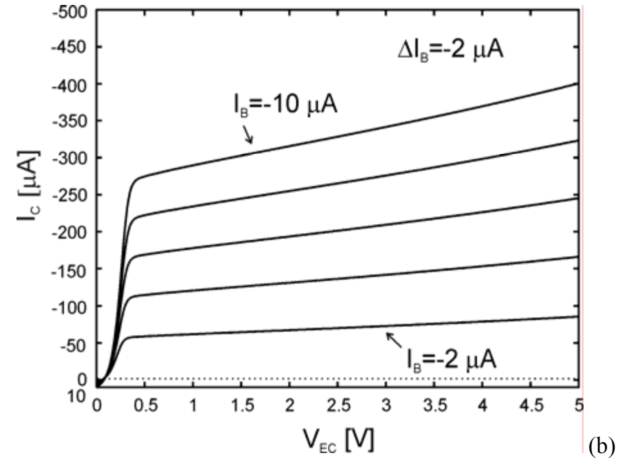
The offset voltage, V_{offset}, is the V_{EC} for which $I_C = 0$ when both the e-b and c-b junctions, for a forced I_B in the common-emitter configuration, are forward biased. The measured V_{offset} for the studied devices is shown in Fig. 6 and an overview of the main device parameters is given in Table II.

TABLE I
DESCRIPTION OF DIFFERENT COLLECTOR DESIGNS

Device type	Collector region	t_{Si} (nm)	Contact type
PO940pd	P, partly-depleted	940	Ohmic
PS940pd	P, partly-depleted	940	Schottky
PS740fd	P, fully-depleted	740	Schottky



(a)



(b)

Fig. 4. Measured (a) forward Gummel plots and (b) output characteristics of PS940pd device with emitter area 40 × 1μm^2.

TABLE II
OVERVIEW OF THE MAIN DEVICE PARAMETERS

Collector type	h_{FE} (V_{CB}=0, V_{EB}=0.65V)	V_{offset} (V)	V_A (V)	f_T (GHz)
PO940pd	19	0.1-0.12	10.5	3.6
PS940pd	23	0.05-0.08	8.5	5.0
PS740fd	20	0.28	10.5	4.0

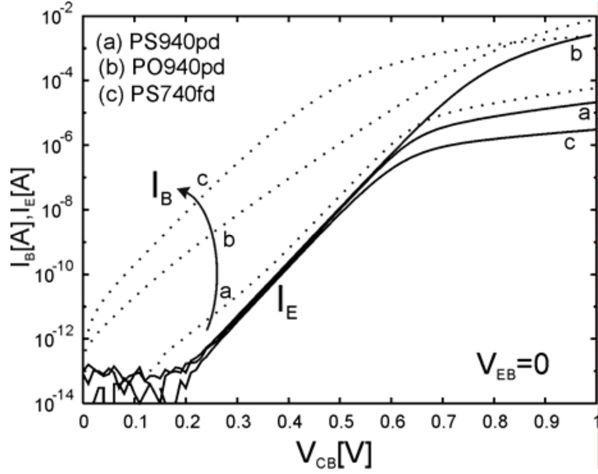


Fig. 5. Measured reverse Gummel plots of the devices listed in Table I with emitter area 40 × 1 μm^2.

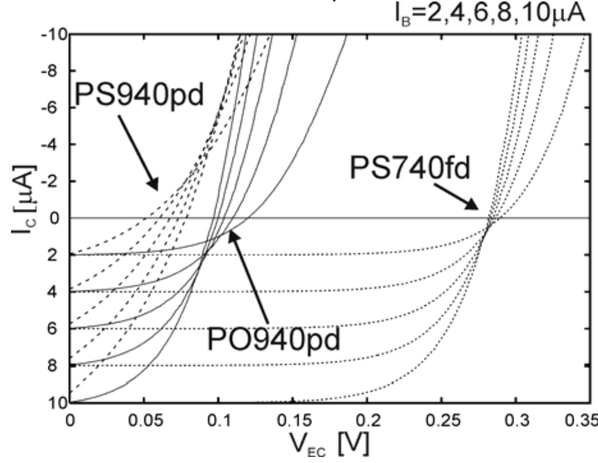


Fig. 6. Measured output characteristics around the offset voltage (at $I_C = 0$) for the devices listed in Table I with emitter area 40 × 1 μm^2.

IV. NUMERICAL SIMULATIONS OF V_{OFFSET}

The difference in the measured offset voltages is investigated in this section by means of MEDICI numerical simulations. The doping profiles of the active E-B-C regions were defined according to the SIMS measurements from Fig. 1. The ambient temperature was set to 300 K. The devices with p-Schottky collector contact were simulated by selecting an appropriate value for the metal work function at the collector electrode. This value was tuned in order to achieve a good agreement for all the measured data. Moreover, an infinite value of the recombination velocities at the collector contact was assumed. Several simulated characteristics are shown in Figs. 7, 8 and 9, which agree well with the measurements from Figs. 4(b), 6 and 5, respectively.

Basing on these simulations, the carrier flows, distribution of electric field and band diagrams for different device configurations were studied. This yields the following theoretical analysis of the offset voltage.

V. THEORETICAL ANALYSIS OF V_{OFFSET}

The currents that play a role for determining V_{offset} are depicted in Fig. 10. Parasitic generation-recombination currents are extremely small in the investigated devices and are therefore neglected. The perimeter currents can also be neglected since the special collector design places the collector contact directly under the emitter. Thus the effective collector area, A_{CBeff}, is about the same as the effective emitter area, A_{EBeff}. Therefore, for calculating V_{offset}, only the intrinsic junction currents need to be taken into consideration. The I_C can be expressed as

$$I_C = I_{p,C\text{-}B} - I_{p,E\text{-}B} + I_{n,B\text{-}C} \quad (1)$$

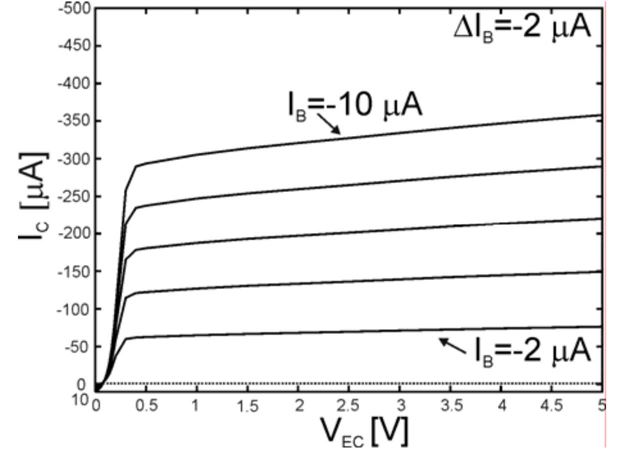


Fig. 7. Simulated output characteristics of PS940pd device with emitter area 40 × 1μm^2

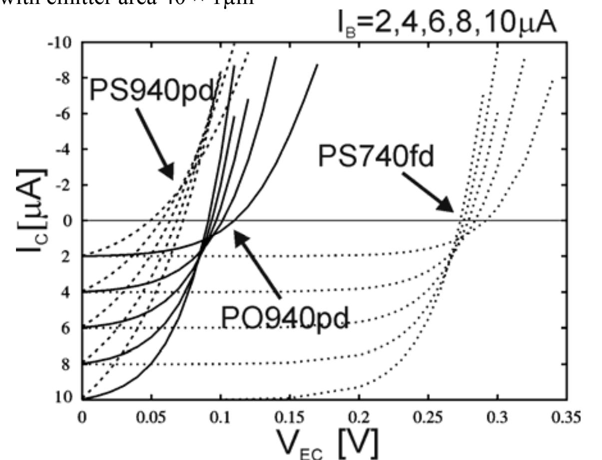


Fig. 8. Simulated output characteristics around the offset voltage (at $I_C = 0$) for the devices listed in Table I with emitter area 40 × 1 μm^2.

At the offset point $I_C = 0$ and thus

$$I_{p,E\text{-}B} = I_{p,C\text{-}B} + I_{n,B\text{-}C} \tag{2}$$

Expressing the currents in terms of the Gummel numbers has been applied by Chand [5] to analyze conventional bipolar transistors with ohmic collector contacts. This gives

$$V_{offset}(I_B)=V_{EBoff}(I_B)-V_{CBoff}(I_B)= \\ =V_T \ln\left[\frac{A_{BCeff}}{A_{BEeff}}\left(1+\frac{G_B(V_{EBoff},V_{CBoff})}{G_C(V_{CBoff})}\right)\right]+R_E\left|I_B\right| \tag{3}$$

where $V_T = kT/q$ is the thermal voltage, G_B and G_C are the base and collector Gummel numbers, respectively, and $V_{EBoff}(I_B)$ and $V_{CBoff}(I_B)$ are the voltages across e-b and c-b junctions in the offset point. Here the voltage and implicitly the I_B dependence of G_B and G_C is explicitly included because both the integral doping of the base and of the collector are low and readily voltage dependent. Moreover, in the present devices R_E is very low so the term $R_E/I_B/$ is neglected in the following.

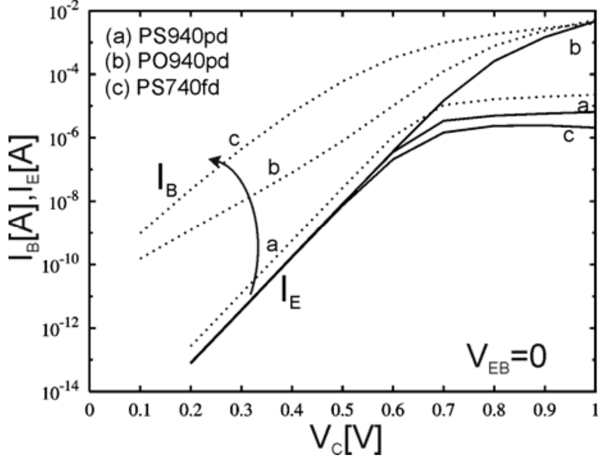
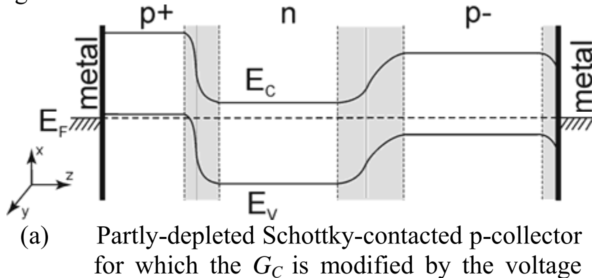
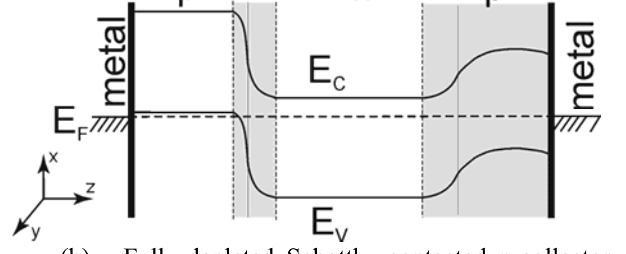


Fig. 9. Simulated reverse Gummel plots of the devices listed in Table I with emitter area 40 × 1 μm².

For the Schottky devices this formulation cannot be directly applied as becomes clear from the band diagrams:



(a) Partly-depleted Schottky-contacted p-collector for which the G_C is modified by the voltage drop over the Schottky contact, $V_{p\text{-}SH}(I_B)$, and the holes injection from emitter to collector pulls the Schottky diode in forward.



(b) Fully-depleted Schottky-contacted p-collector where the built-in voltages deplete the whole collector region. This lowering the barriers for electrons and holes injection.

For the Schottky-contacted partly-depleted collector devices (PS940pd) the holes injection from the emitter to the collector pulls in forward the Schottky junction at the contact. Therefore, taking into account the voltage drop $V_{p\text{-}SH}(I_B)$ over the collector contact, the (2) gives

$$V_{offset}(I_B) = V_{p-SH}(I_B) + \\ +V_T \ln\left[\frac{A_{CBeff}}{A_{EBeff}}\left(1+\frac{G_B(V_{EBoff},V_{CBoff})}{G_C(V_{CBoff},V_{p-SH})}\right)\right] \tag{4}$$

The G_C is now also dependent on V_{EB} due to the importance of the e-c holes injection in the collector for the biasing over the Schottky diode. This dependence is expressed through the $V_{p\text{-}SH}(I_B)$.

For the Schottky-contacted fully-depleted collector devices the equation (4) is not applicable because the collector Gummel number cannot be defined if the collector is fully depleted. In this case the electrons injection from the base to the collector $I_{n,B\text{-}C}$ is decades larger than the holes current, $I_{p,C\text{-}B}$, so equation (2) gives $I_{p,E\text{-}B} = I_{n,B\text{-}C}$. Basing on the last observation, research is in progress to develop an appropriate model for this case too.

VI. Discussion

Since the emitter and base regions in all the studied devices are the same, the analytical formulas (3) and (4) show that the measured V_{offset}'s are predominantly determined by the difference in electrons injection from the base to the collector, which is seen in Fig.5 as the reverse base current. For the device PO940pd, this reverse I_B is determined by the G_C. In the case of the device PS940pd, the I_B is more than a decade lower. In

this case the applied V_{CB} falls over both the b-c pn junction and the Schottky diode at the collector contact, thus reducing the effective forward biasing of the b-c junction. The voltage drop over the Schottky collector contact $V_{p\text{-}SH}$ increases V_{offset} both by reducing G_C and because the voltage drop itself must be taken into account as given in (4). The resulting V_{offset} is measured to be low, 0.05-0.08 V, as compared to 0.1– 0.12 V for the ohmic-contacted devices. The variation in V_{offset} with I_B seen in these partly-depleted devices is in agreement with the expected depletion regions width variations.

In the fully-depleted devices the reverse I_B is very high. Correspondingly, the V_{offset} of about 0.28 V is measured. Since in the present situation the V_{CB} falls over a depleted region of more than 200 nm wide, as seen in Fig. 1, the I_B dependence of the V_{offset} is in this case very low.

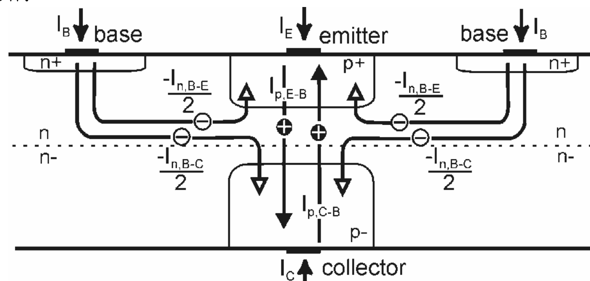


Fig.10. Diagram of the currents that play a role for determining the offset voltage.

VII. Conclusions

It has been demonstrated that the collector design has a large impact on the offset voltage. A very low offset of about 0.05 V can be obtained for a partly-depleted-collector device with p-type Schottky collector contact. This is much lower than the 0.1V offset of the comparable ohmic-contacted collector device. A very high offset of about 0.28 V is seen for fully-depleted-collector device with p-type Schottky collector contact because of the very high current of the base-to-Schottky diode.

In view of the relaxed dimensions of the experimental devices, the other main device characteristics are not significantly affected by the collector design. In more aggressively down-scaled devices it is, however, expected that the low collector resistance and compact collector design of the fully-depleted devices will give a clear speed advantage. Moreover, the process complexity is considerably reduced.

Acknowledgements

The authors are grateful to I. Hajas and DIMES ICP, in particular H. Schellevis and S. Milosavljevic, for processing and measurement support. This work has been supported by the Philips PACD project.

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