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BJT Application Expansion by Insertion of Superjunction

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Abstract — **In this paper, some high voltage Bipolar Junction Transistors are presented and compared in order to suggest a switch for household appliances with fully turn-on, turn-off control. For the first time, a comparative theoretical study, using 2D simulations, shows that concepts like the "superjunction" improve the static behaviour of conventional BJT. These new structures are compared with a SJMOSFET and an IGBT. The new BJT exhibits lower static losses than SJMOSFET and gives up an interest in bipolar structure.**

I. INTRODUCTION

The aim of this work is to improve the Bipolar Junction Transistor (BJT) behavior in saturation area to suggest a 5 A, 600 V, voltage and current bidirectional switch (BDS). Most common bidirectional components for household appliances are TRIACs. Although they are used in numerous AC/AC applications, their inability to be turned off restricts their field of application [1]. Moreover, their on-state performances are limited by their threshold voltage, as for IGBTs. A suitable solution would be MOS-based associations. However, due to their unipolar conduction mode, these devices require a large silicon area [2]. The only suitable device which remains for that bidirectional application is the BJT association [3].

An example of such solution is shown in Fig. 1 where current and voltage bidirectionality are ensured by the association of two groups "T1 / D1" and "T2 / D2" connected in anti-serial. To ensure an on-state voltage lower than 1 V, the BJT cannot exceed a voltage drop of 0.3 V.

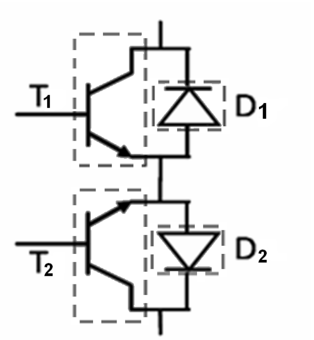


Figure 1. BJT + Diode" switch solution.

An example of such solution is shown in Fig. 1 where current and voltage bidirectionality are ensured by the association of two groups "T1 / D1" and "T2 / D2" connected in anti-serial. To ensure an on-state voltage lower than 1 V, the BJT cannot exceed a voltage drop of 0.3 V.

Nevertheless, the conventional BJT have a low current gain in high voltage (600 V, $N_D = 1.10^{14}$ cm^{-3}) due to the wide base needed to sustain voltage and the resistive epitaxial layer thus implying high drive current. On-state overall performances of such a device are defined by its current gain h_{FE} which value is set by the emitter efficiency γ_E, the base transport factor α_T, and the collector resistivity.

However, acting on the first two parameters will only lead to minor improvements. Indeed, the increase of γ_E, which basically is defined by the ratio between the emitter and the base doping concentrations, makes no really sense since the ratio is already high. Moreover, this approach is limited by the bandgap narrowing effect [4]. In order to improve α_T, previous studies suggested the possibility to shield a lowly doped and thin base to achieve higher current gain for a same breakdown voltage, thanks to P^+ caissons [5]. Nonetheless, this solution has a limited impact on high current density (more than 1 A.cm^{-2}) due to Rittner effect.

In order to observe the impact of the collector resistivity, several simulations are performed with different epitaxial doping concentrations. However, increasing epitaxial doping concentration reduces the base thickness due to Gaussian profiles. Consequently, to keep its thickness T_B at 1 µm, it is necessary to increase its doping concentration. Regardless to breakdown voltages, Fig. 2 presents the variation of the current gain versus collector current density for different epitaxial doping concentrations at $V_{CE} = 0.3$ V.

One can observe that increasing base doping concentration reduces the maximal current gain. This side effect is the result of the reduction of α_T. Moreover, the maximal current gain is shifted towards higher collector current densities due to higher epitaxial doping concentrations. At high collector current densities, h_{FE} sees a significant increase. Since the chip size reduction is one of the key factors of a switch design, increasing epitaxial layer doping concentration is a pertinent approach.

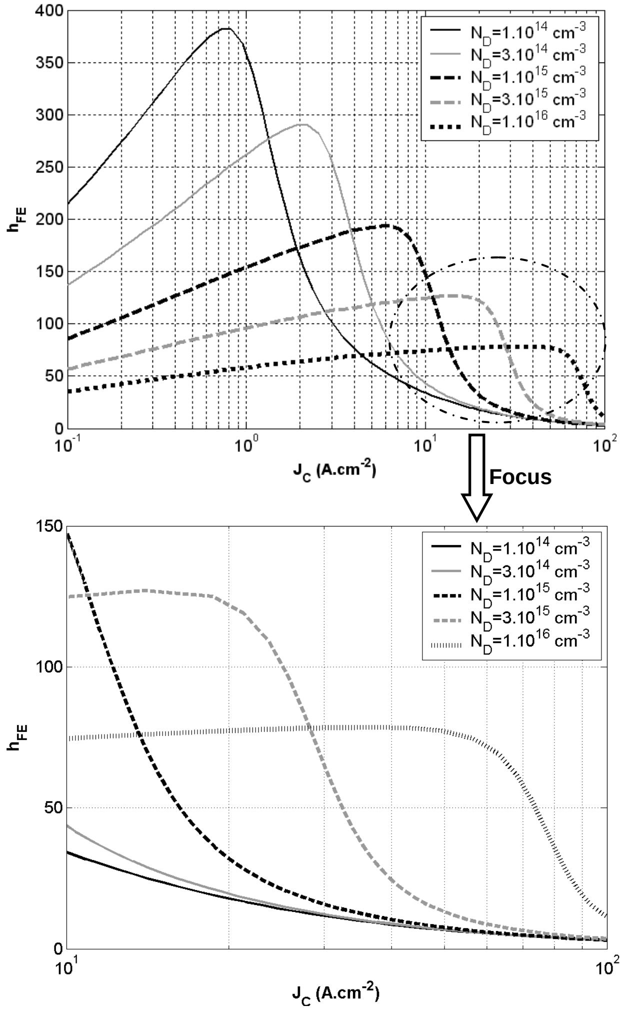


Figure 2. Simulated comparison of current gain versus collector current density for different epitaxial doping concentration at V_{CE} = 0.3 V.

In this work, we suggest to modify conventional structure with the concepts of SuperJunctions (SJ) [6] in order to increase the epitaxial layer doping concentration, thus moving the maximal current gain to higher collector current density in the saturation operating mode and keeping the breakdown voltage unchanged at 600 V.

II. DEVICE STRUCTURES

A. *The superjunction BJT concept*

Superjunction concept was first designed for unipolar devices. Replacing the epitaxial layer by a succession of n-pillars and p-pillars allows to drastically reduce the resistivity of the drift region, thanks to higher doping concentrations. In order to maintain a high breakdown voltage, one must respect the charge balance which implies a tight connection between the doping concentration and the width of such pillars. In fact, a SJ device is well designed if the condition below is respected:

$$N_D \cdot W_N = N_A \cdot W_P \qquad (1)$$

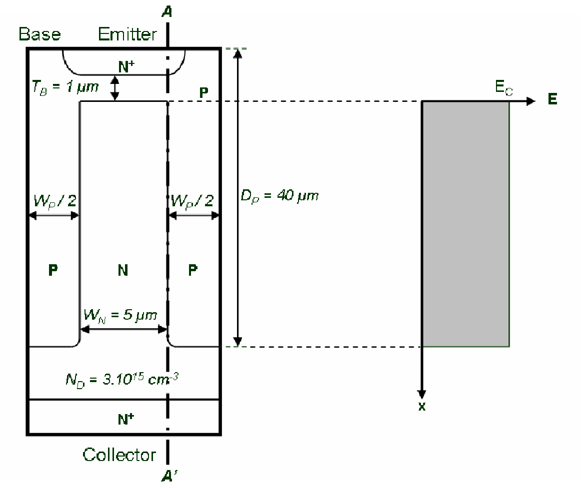
N_D and N_A are respectively the doping concentrations of n-pillars and p-pillars. W_N and W_P, respectively represent the pillar width.

Due to the small distance between two pillars, the space charge region will spread laterally. Since the pillars are fully depleted, the vertical electric field profile is rectangular: the epitaxial layer behaves as a dielectric. Therefore, the breakdown voltage is defined by the equation below:

$$BV = E_C \cdot D_P \qquad (2)$$

BV, E_C and D_P are respectively the breakdown voltage, critical electric field and depth of a pillar. One can notice the breakdown voltage is no longer dependent on doping concentrations but on the charge balance.

In order to let the current flowing from the emitter to the collector, the n-pillars must be located under the active base. Built from these assumptions, a 600 V SJ-BJT (SuperJunction Bipolar Junction Transistor) is shown in Fig. 3 (a) with its schematic electric field distribution along the line A-A' at breakdown in Fig. 3 (b).



(a) (b)

Figure 3. (a) Schematic cross-section of a 600 V Superjunction BJT, (b) its theoretical electric field distribution using SENTAURUS tools.

The dimensions are based on the work of Saito *et al.* [7]. Each pillar is doped at 3.10^{15} cm^{-3} for a width W_N of 5 µm. The total depth of a p-pillar D_P and the base thickness T_B are respectively set to 40 µm and 1 µm. At V_{CE} = 600 V, the pillars are fully depleted and no base punch-through is observed.

III. SIMULATED RESULTS

A. *Output characteristics*

The Gummel plots presented in Fig. 2 are not useful to quantify the performances of a structure in use. For this, Fig. 4 exhibits the simulated output characteristics for the 600 V SJ-BJT with a 10 mm^2 active area. One can notice that the linear area presents a stable collector current for less than 50 mA base current. This let us to use this type of structure as a variable current limiter. In saturation area, one can observe two areas, especially for high base current (> 50 mA). The first one shows a strong slope in low voltage. The second one, named “quasi-saturation” area, has a lower slope. This part of the curve decreases the performance of the structure because the saturation voltage increase with the base current, so in order to keep a low voltage drop, near 0.3 V, the structure needs to absorb a higher current base, reducing the current gain for a fixed collector-emitter voltage.

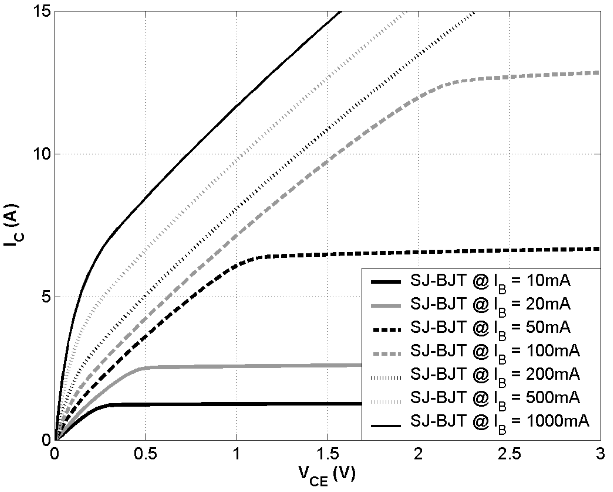
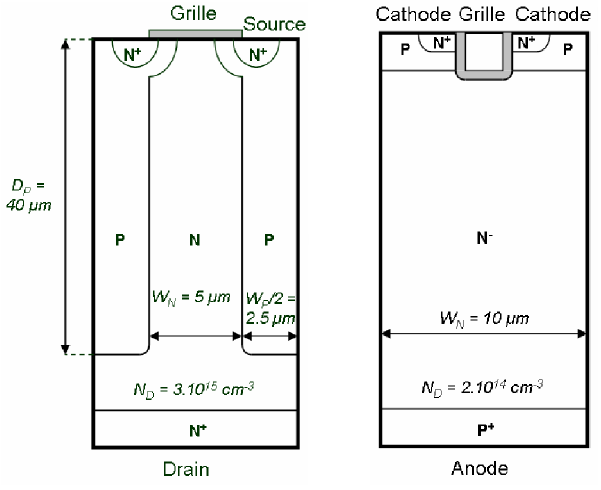


Figure 4. Simulated output characteristics for the 600 V SJ-BJT with 10 mm^2 active area.

Despite this phenomenon, the current gain for the SJ-BJT stays higher than a conventional one as presented in Fig. 2. For example, for a 5 A collector current at V_{CE} = 0.5 V, the SJ-BJT needs a current base of 200 mA while the conventional one needs 500 mA.

B. Characteristics comparison with other structures

In order to confirm the interest of the SJ-BJT, a comparison with other simulated structures is necessary. For this, the SJ-BJT is already presented in Fig. 3. The conventional BJT have the same top geometry and cell width in order to confirm the diminution of the current gain with the modification of the doping concentration epitaxial layer. The SJMOSFET is based on the work of Saito *et al.* [7] and their specifications are reminded in Fig. 5 (a). The only variation with the SJ-BJT is the nature of the current conduction and the top of the structure to realize a MOSFET. The last device is a trench-gate IGBT based on the work of Nakano *et al.* [8] and their specifications are reminded in Fig. 5 (b).



(a) (b)

Figure 5. (a) Schematic cross-section of a 600 V SJMOSFET, (b) Schematic cross-section of a 600 V trench-gate IGBT.

The Figure 6 presents the simulated output characteristics comparison for these different 600 V structures with 10 mm^2 active area.

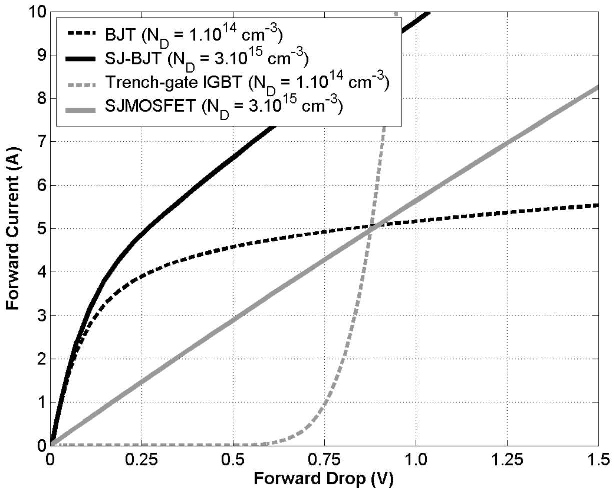


Figure 6. Simulated output characteristics for different 600 V structures with 10 mm^2 active area.

One can observe that the SJMOSFET have the same on-resistance than given in the original publication, or 155 mΩ for 10 mm^2. The trench-gate IGBT, also respects the performance of the original paper. The difficulty for comparing a bipolar structure is to fix the base current. So it was fixed to 500 mA because at this current, the conventional BJT output characteristics meet the SJMOSFET and IGBT ones. With this current, the conventional BJT is better than the other structures for a current less than 5 A. Nevertheless, these three structures propose a 5 A collector current for an on-state voltage at 0.88 V which is higher than the 0.3 V hoped. The SJ-BJT exhibits an on-state voltage at 0.27 V for 5 A. With these conditions, the SJ-BJT presents a collector current three times higher than a SJMOSFET. Nevertheless, it is necessary to compare the static power losses accounting for the base current, which is not insignificant.

C. Conduction power losses comparison

In order to compare the power losses for the ON state of the different structures, it is necessary to remind the expression of the conduction power losses for MOSFET (3), IGBT (4) and for bipolar transistor devices (5):

$$P = I_D \cdot R_{DSon}{}^{2} \tag{3}$$

$$P = I_A \cdot V_{AK} \tag{4}$$

$$P = I_B \cdot V_{BE} + I_C \cdot V_{CE} \tag{5}$$

These expressions take part of the output losses, but the expression (5) put the input power forward for the current controlled devices. For the gate controlled devices, the input power can be ignored, especially for low frequencies.

1) *SJ-BJT losses for different base currents*

The Figure 7 presents the simulated static power losses for different base currents with 10 mm^2 active area and a load current of 5A.

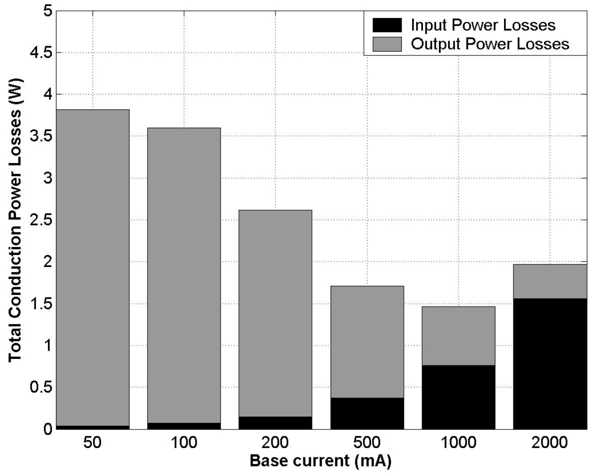


Figure 7. Simulated conduction power losses for a load current of 5A at different base current with 10 mm^2 active area.

The reduction of the power losses is not only based on the reduction of the on-state voltage, but is a trade-off between the input and the output losses. Thankfully, for I_C = 5 A, the lower power losses are obtained with a 1 A base current. A higher base current increases the input losses, while a lower one increases the output losses. Nevertheless, the conduction power losses between a base current of 500 mA and 1 A is 250 mW. A base current of 500 mA have been keeping in order to reduce the power losses of the driver. It is interesting to compare this result with the other structures power losses.

2) *Comparison between different structures*

The Figure 8 presents the simulated static power losses versus direct current with 10 mm^2 active area for the different structure. One can observe an intersection of the curves for the IGBT, the SJMOSFET and the BJT at I_C = 5 A. This confirms the Figure 6 results. However for lower currents, like 1.5 A, the two BJT structures are not attractive comparatively to the IGBT and SJMOSFET due to the input power losses. The SJ-BJT structure proposes a lower power losses about 1.8 W for 5 A. This result is nearly three times lower than for the other structures, reducing the losses at 360 mW.A^{-1}, opening the possibility to recess the switch in a wall, which has a high thermal resistance.

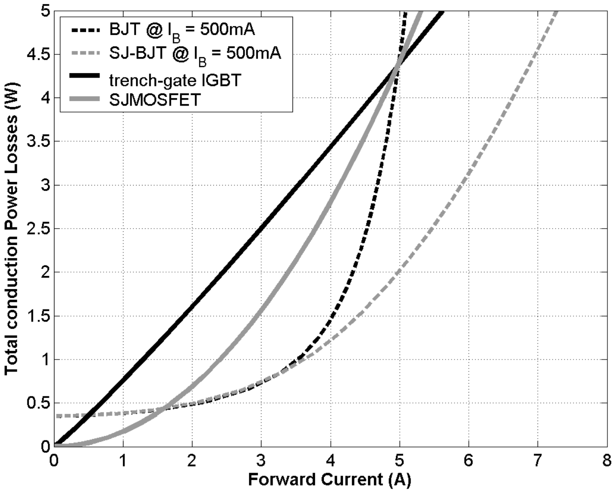


Figure 8. Simulated static power losses versus direct current with 10 mm^2 active area.

IV. CONCLUSION

SJ-BJT, as a new design of high voltage (600 V range) power BJT is presented. Besides, the output characteristics of an IGBT, SJMOSFET, BJT and SJ-BJT are compared. Simulation results show that the SJ-BJT is the only structure presenting an on-state voltage of 0.3 V and a base current of 500 mA for a 5 A load current and 10 mm^2 active area. In terms of power losses, the SJ-BJT is disadvantaged by the input losses compared to IGBT and SJMOSFET, but for a load current of 5 A, the losses are divided by three. The interest for the superjunction bipolar structure is then confirmed.

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