Collector Design Tradeoffs for Low Voltage Applications of Advanced Bipolar Transistors

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***Abstract*—The values of BV_{ceo} are computed for transistors 1) with highly doped collectors and 2) with thin reach-through collectors, using various sets of ionization coefficients including new data. Computed values of BV_{ceo} are compared with experimental results. It is shown that transistors with thin reach-through collectors have higher current capability for any given BV_{ceo} compared to those with highly doped collectors. Tradeoffs in terms of BV_{ceo}, maximum collector current, and maximum frequency of operation are studied for transistors with highly doped and thin reach-through collectors and results are presented.**

I. INTRODUCTION

As DEVICE dimensions of advanced bipolar transistors are scaled down, it is desirable to increase the base and collector doping limits or use thin "reach-through" collector structures in order to realize the required high-speed performance goals. Consequently, these devices have rather low collector–emitter breakdown voltage BV_{ceo}. A precise knowledge of BV_{ceo} as a function of collector doping N_{epi} or collector region thickness W_{epi} is needed so that tradeoff in low-voltage circuits (analog or digital) may be accomplished. In the present study, values of BV_{ceo} are computed for transistors 1) with highly doped collectors (up to $10^{18}/\text{cm}^3$) and 2) with thin reach-through collectors, using the standard ionization coefficients [1], [2] and also a modified impact ionization formulation based on [3]–[5]. Computed values of BV_{ceo} are compared with experimental results.

At high collector currents, vertical base stretching (Kirk effect) is a limiting factor. It is shown in this paper that transistors with a thin reach-through collector structure give better high-current performance for a given BV_{ceo} than devices with a high collector doping level. Transistors with highly doped collectors and those with thin reach-through collectors are compared in terms of current handling capability, vertical-base stretching, and maximum frequency of operation in order to provide collector design tradesoff for low-voltage and high-speed applications.

II. BREAKDOWN VOLTAGE OF HIGHLY DOPED AND THIN REACH-TRHOUGH COLLECTOR STRUCTURES

When the transistor is biased as shown in Fig. 1(a), the collector–emitter terminal voltage V_{CE} can be written as

$$V_{CE} = V_{CB} + V_{BE} \tag{1}$$

where V_{CB} is the reverse voltage across the collector–base terminals and V_{BE} is the forward voltage across the base–emitter terminals. For the transistor of Fig. 1(a), if the base is open-circuited, the collector current I_C can be written as

$$I_C = \frac{\text{const}}{1 - \alpha M} \tag{2}$$

where $\alpha = \beta/(\beta + 1)$, M is the avalanche multiplication factor, and β is the dc current gain. Breakdown situation corresponding to zero base current or reversal of the sign of base current is reached if the condition $\alpha M = 1$ is satisfied and the corresponding collector–emitter breakdown voltage is referred to as sustaining voltage BV_{ceo}, as shown in Fig. 1(b). The multiplication factor M is obtained by numerically integrating the ionization integral (S_e) from the electric field solution to Poisson's equation [6]. Since the ionization integral value is $S_e = 1 - (1/M)$ and since $\alpha = \beta/(1 + \beta)$, the value of collector–emitter breakdown voltage BV_{ceo} is obtained by varying V_{CB} until the following condition, corresponding to BV_{ceo}, is satisfied [6]:

$$\beta = \frac{1 - S_e}{S_e}. \tag{3}$$

However, in transistors with a highly doped or a thin reach-through collector there is an important effect which influences the avalanche multiplication: when the width of the high-field region is comparable to the energy relaxation length λ_w, the profile of the electron energy $W(x)$ does not coincide with the distribution of the electric field $F(x)$. Since the ionization coefficients really depend on the electron energy and not on the local electric field, as assumed in the standard ionization models [1], [2], the electron never attains an energy corresponding to the maximum electric field when the space-charge region is narrow. This results in lower than otherwise expected multiplication factors. Thus when the collector region is thin or highly doped, it is essential that the nonlocal prop-

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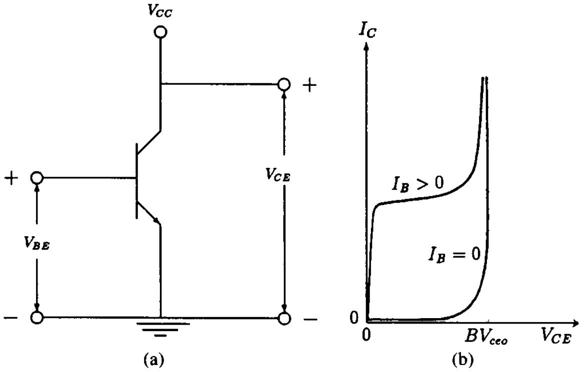


Fig. 1. (a) Schematic diagram of a transistor biased in active mode. (b) Breakdown characteristics of the transistor of Fig. 1(a).

erties of the avalanche multiplication are taken into account. We used the equation from [3]

$$W(x) - W_O = q\frac{3}{5}\int_0^x F(z)\exp\left(\frac{x-z}{\lambda_w}\right)dz \qquad (4)$$

to calculate $W(x)$ distribution. Then we calculated the *effective field* F_{eff} using the equation

$$F_{\text{eff}}(x) = \frac{5}{3q\lambda_w}(W(x) - W_O) \qquad (5)$$

which coincides with the real electric field for homogeneous silicon, i.e., for negligible energy flux gradients [5]. Finally, this field was used for ionization coefficient calculations instead of the real field. Choosing $\lambda_w = 55$ nm in (4) and (5) together with the set of ionization coefficients from [4] gives good agreement with a variety of experimental data for BV_{ceo} values as will be shown below.

We have estimated the breakdown voltages using the standard ionization models [1], [2] and the new ionization formulation [5] based on the ionization data of [4] for transistors with highly doped as well as reach-through collector structures. A schematic of the doping profiles used in our simulation is shown in Fig. 2. The numerical integration is performed using BIPOLE [7] on an abrupt collector–base junction with a uniform base doping at $3 \times 10^{19}/\text{cm}^3$ with the collector doping varied from $10^{17}/\text{cm}^3$ to $10^{18}/\text{cm}^3$. For $N_{\text{epi}} = 10^{18}/\text{cm}^3$, the zero bias space-charge layer width on the collector side of the junction is 360 Å and on the base side of the junction is 10 Å. Since the space-charge layer width on the collector side is 36 times that of the width on the base side, it ensures that the values of breakdown voltage are mainly dependent on the collector side space-charge layer width.

The reverse breakdown voltage of the collector–base junction with the emitter open (BV_{cbo}) is first calculated using the standard ionization coefficients [1], [2] and the new ionization model based on [4] and are compared in Fig. 3 as a function of collector doping for non-reach-through conditions. The collector–emitter breakdown voltage (BV_{ceo}), calculated using the above ionization coefficients, is shown in Fig. 4 as a function of current gain and for various collector dopings N_{epi}. Similarly, the values of BV_{ceo} as a function of current gain for different narrow collector region widths W_{epi} are shown in Fig. 5. These values are calculated assuming $N_{\text{epi}} = 10^{15}/\text{cm}^3$. It may be noted from Figs. 4 and 5 that since the new ionization model accounts for the nonlocal nature of the impact ionization, the estimated values of BV_{ceo} for both the highly doped and reach-through collector structures are higher than those obtained using the standard models.

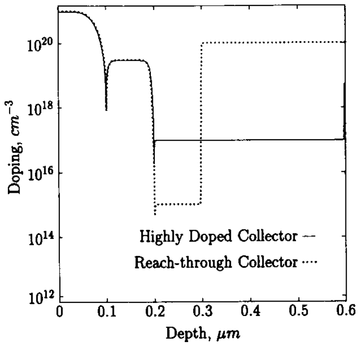


Fig. 2. Schematic diagram of the doping profile used in the simulation.

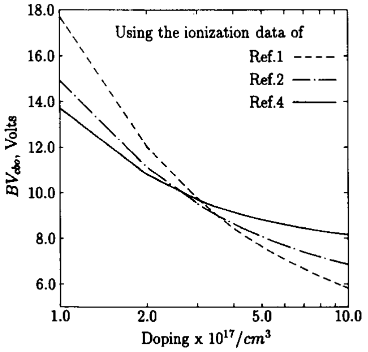


Fig. 3. Breakdown voltage BV_{cbo} as a function of collector doping for the ionization rates of [1], [2], and [4].

We have also estimated the values of BV_{ceo} at $\beta = 10$ and 100 as a function of W_{epi} and for different collector dopings using the new ionization model and the results are shown in Fig. 6. It should be noted from Fig. 6 that in the case of reach-through collector transistors, BV_{ceo} becomes independent of collector doping if $W_{\text{epi}} \leq 0.5$ μm and $N_{\text{epi}} \leq 10^{16}/\text{cm}^3$. Specifying high-speed circuit applications, Fig. 6 can be used to choose the appropriate collector thickness and doping concentration.

The calculated I_C–V_{CE} breakdown characteristics of a transistor with highly doped collector structure are plotted in Fig. 7(a) and (b) for $\beta = 10$ and $\beta = 100$, respectively. These characteristics are obtained assuming $V_{BE} = 0.7$ V and $I_B = 1$ nA. It should be noted from Fig. 7(a) and (b) that the standard ionization models overestimate the multiplication factor in the collector–base space-charge layer and thus underestimate the breakdown voltage BV_{ceo}.

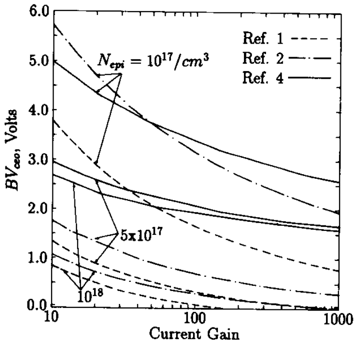


Fig. 4. Collector-emitter breakdown voltage BV_{ceo} as a function of current gain for highly doped collector structures.

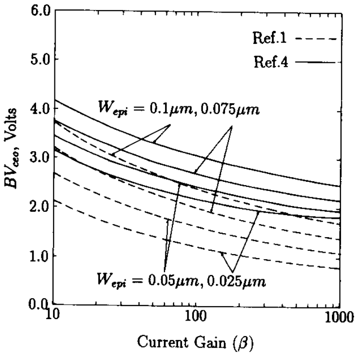


Fig. 5. Collector-emitter breakdown voltage BV_{ceo} as a function of current gain for reach-through collector structures.

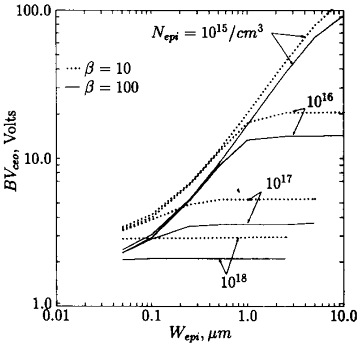
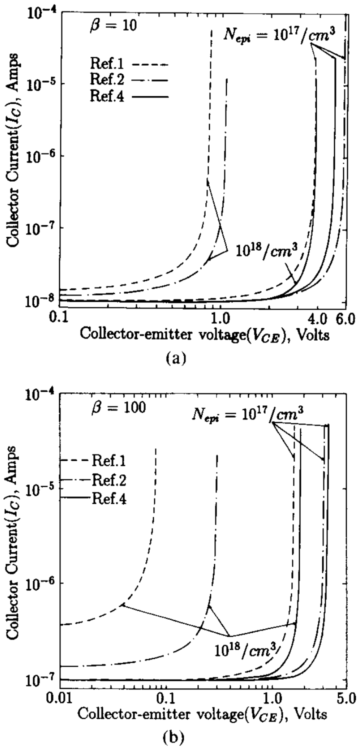


Fig. 6. BV_{ceo} as a function of W_{epi} of reach-through collector structure for different collector dopings.

However, the new ionization model predicts higher values of BV_{ceo} than those obtained using the standard models. Fig. 7 thus provides information on the range of collector dopings that give the BV_{ceo} values of interest for digital circuit applications when the current gain is in the range of 10 to 100.



(a)

(b)

Fig. 7. Calculated I_C–V_{CE} characteristics of a transistor with heavily doped collector (a) for $\beta = 10$ and (b) for $\beta = 100$.

TABLE I

COMPARISON OF EXPERIMENTAL RESULTS WITH THE CALCULATED VALUES OF BV_{ceo}

Ref.	N_{epi} $10^{17}/cm^3$	β	Measured BV_{ceo}	Calculated BV_{ceo} Using the Ionization Rates of [1]	[2]	[4]
[9]	1.5	20	3.4 V	2.147 V	3.447 V	3.75 V
[9]	1.5	36	3.0 V	1.747 V	2.950 V	3.42 V
[9]	3.0	51	2.7 V	0.829 V	1.529 V	2.65 V
[10]	6.0	135	2.0 V	0.245 V	0.560 V	2.12 V
[11]	6.0	18	2.6 V	0.424 V	0.527 V	2.70 V

A. Comparison with Experimental Results

The calculated values of BV_{ceo} are compared with experimental results in Table I. It should be noted that there is an excellent agreement between the computed and experimental values of BV_{ceo} if the ionization data based on [4] are used. There is considerable discrepancy between calculated and experimental results if the standard ionization coefficients [1], [2] are used in the calculation of breakdown voltage because in these models the ionization coefficients are an exponential function of local electric field. However, for narrow space-charge regions, the nonlocal properties of impact ionization become important [3] and should be taken into account for a precise prediction of BV_{ceo} as shown in Table I.

III. COMPARISON BETWEEN REACH-THROUGH AND HIGHLY DOPED COLLECTORS

If the collector current density J_C exceeds a critical value J_K, the effective base width increases from W_b to W_b

+ W_K due to the Kirk effect and W_K can be written in terms of the collector current density J_C as [8]

$$W_K = W_{\text{epi}}\left[1 - \frac{1}{\sqrt{[(J_C/J_K) - 1](V_{pt}/V_{CB}) + J_C/J_K}}\right] \tag{6}$$

where J_K is the critical current density and is given by [8]

$$J_K = qv_sN_{\text{epi}}\left(1 + \frac{V_{CB}}{V_{pt}}\right) \tag{7}$$

where v_s is the saturation velocity, N_{epi} is the doping of the collector, V_{pt} is the collector–base terminal voltage required under low-current conditions to make the depletion layer extend from the base–collector junction up to the n-n$^+$ junction and can be written from the solution to Poisson's equation as

$$V_{pt} = \frac{qN_{\text{epi}}}{2\epsilon}W_{\text{epi}}^2 \tag{8}$$

where W_{epi} is the thickness of the collector region. When $V_{pt} << V_{CB}$, (6) and (7) reduce to

$$W_K = W_{\text{epi}}[1 - \sqrt{J_K/J_C}] \tag{9}$$

and

$$J_K = 2\epsilon v_s\frac{V_{CB}}{W_{\text{epi}}^2}. \tag{10}$$

Thus (9) and (10) show that if a thin reach-through collector is used, J_K and W_K become independent of doping.

A. Critical Current Density J_K

By computing J_K from (7) with BV_{ceo} for a given value of N_{epi}, we calculate J_K versus BV_{ceo}. This is repeated for the reach-through structure using (10) for J_K. We assume that W_{epi} of the highly doped collector is 0.5 μm and N_{epi} of the reach-through collector is $10^{15}/\text{cm}^3$. BV_{ceo} values are computed using the new ionization formulation [5] based on the data of [4], for $\beta = 10$ and 100 by varying N_{epi} of the highly doped collector and W_{epi} of the reach-through collector. The values of J_K are computed assuming $V_{CB} = BV_{ceo}$ for a given N_{epi} or W_{epi} and the results are shown in Fig. 8. It may be noted that the reach-through collector structure has a higher current capability than the highly doped collector structure for any given BV_{ceo}.

B. Vertical Base Stretching W_K

Fig. 9 shows the values of W_K, computed using BIPOLE [7], as a function of collector current density. The doping N_{epi} of the highly doped collector structure and the collector region width W_{epi} of the reach-through collector structure are chosen such that both the devices have identical BV_{ceo} of 3 V at $\beta = 100$. Both structures have identical base width $W_b = 0.075$ μm. The W_K values are calculated for $V_{CB} = 2$ V and 0.5 V. It should be noted from Fig. 9 that the increase in base width due to vertical base stretching is more predominant in transistors with highly doped collectors. For example, at $J_C = 5 \times 10^5$ A/cm^2, W_K of the reach-through structure is only 0.01 μm whereas that of the highly doped collector structure is 0.36 μm. This large increase in base width due to vertical-base stretching will limit the maximum operating current of transistors with highly doped collectors as will be shown below.

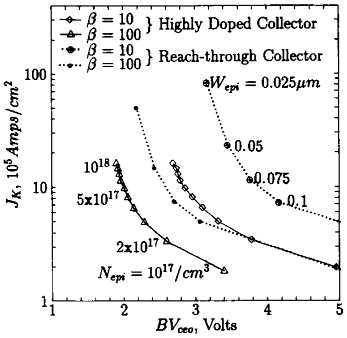


Fig. 8. J_K as a function of BV_{ceo} for heavily doped and reach-through collector structures.

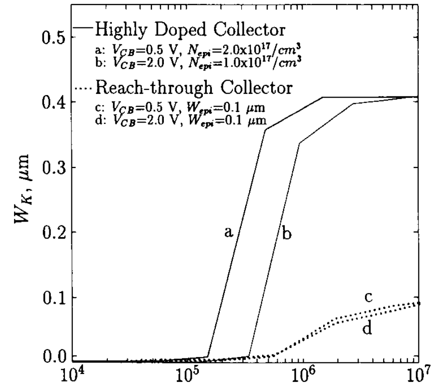


Fig. 9. W_K as a function of collector current density for the highly doped and reach-through collector structures.

C. Maximum Oscillation Frequency $f_{\max}$

The maximum oscillation frequency or unity power gain frequency $f_{\max}$ is a good measure of transistor operation at high frequencies and can be written as [8]

$$f_{\max} = \sqrt{\frac{f_t}{8\pi C_{jc}r_{bb}}} \tag{11}$$

where f_t is the transition frequency, r_{bb} is the base resistance, and C_{jc} is the collector–base space-charge layer capacitance. The values of $f_{\max}$, computed using BIPOLE [7], are shown in Fig. 10 for both the reach-through and highly doped collector structures. Both structures have identical neutral base width $W_b = 0.075$ μm and the peak doping in the base is $N_B = 10^{19}/\text{cm}^3$. The values of N_{epi} of the highly doped collector structure and W_{epi} of the reach-through structure are shown in Fig. 10. These val-

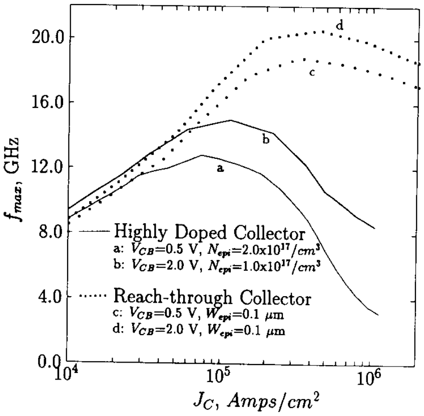


Fig. 10. The maximum oscillation frequency $f_{\max}$ as a function of collector current density for the highly doped and reach-through collector structures.

ues are chosen such that for a given V_{CB}, the collector space-charge layer width of the highly doped structure is the same as W_{epi} of the reach-through collector structure. This ensures that both devices have identical C_{jc} and t_{scl} (space-charge layer delay time) for a given V_{CB}. It should be noted from Fig. 10 that $f_{\max}$ of the highly doped collector structure decreases rapidly as the collector current is increased. This rapid fall in maximum oscillation frequency is because at high collector currents, f_t decreases and C_{jc} increases due to vertical-base stretching. However, in the case of the reach-through collector structure, the fall in $f_{\max}$ is not significant because of less pronounced vertical-base stretching at high collector currents.

IV. CONCLUSIONS

In conclusion, we have shown that standard ionization rates reported in literature underestimate the breakdown voltages at high collector dopings. However, excellent agreement between computed and experimental values of BV_{ceo} can be obtained using the new ionization data which include the nonlocal properties of impact ionization. We have further shown that transistors with reach-through collector structures have higher current capability and less vertical-base stretching, thus offering better switching performance compared to the transistors with highly doped collector structures.

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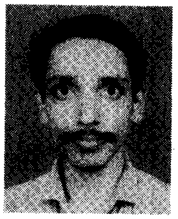

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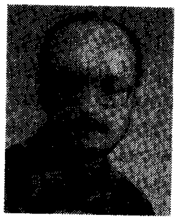

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