Design Tradeoffs for Improved $V_{CE(sat)}$ versus I_C of Bipolar Transistors Under Forced Gain Conditions

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***Abstract*— Based on the quasi-saturation analysis of bipolar transistors and using numerical simulation, it is shown in this paper that the quasi-saturation performance of transistors under forced gain conditions can be improved by increasing the base-Gummel number if the emitter diffusion is also simultaneously altered to keep the active region current gain h_{FE0} constant. It is further shown that for a given h_{FE0}, if the ratio of h_{FE0} to the forced current gain β_f is below 10, the quasi-saturation performance of the transistors will be poor compared to those with $h_{FE0}/\beta_f \geq 10$. Design curves obtained using numerical simulation are also presented to choose the quasi-saturation current limit of the transistors as a function of breakdown voltage and for different reach-through collector structures.**

I. INTRODUCTION

WHEN a bipolar transistor is operated at high collector current densities, the collector epitaxial region introduces some important changes in the output characteristics of the transistor. Most predominant among these changes are 1) the presence of a "quasi-saturation region" in the output characteristics and 2) a fall in the common-emitter current gain at high collector currents as the collector-emitter voltage approaches zero. These effects have been well modeled in the literature [1]–[3]. In applications involving high current operation, the transistor is often characterized under forced gain conditions (e.g., $\beta_f = 5$) by increasing the base drive so that the ratio of collector current and base current remains constant. The saturation voltage drop $V_{CE(sat)}$ under these conditions limits the maximum collector current at which the transistor can be operated without resulting in undue power dissipation. Therefore, it is important to know how the physical parameters of the transistor control its operation at high collector current densities.

From the analysis of quasi-saturation operation of transistors [2] and using the BIPOLE device simulator [4] we show in this paper that the collector current I_{CQS}, at which the onset of quasi-saturation begins, can be improved by increasing the base-Gummel number. Our results also show that for a given collector epitaxial layer thickness and doping, the ratio of dc current gain h_{FE0} to the forced current gain β_f of the transistor should be at least 10 to keep the value of I_{CQS} reasonably high. We also present design curves for the quasi-saturation current limit of the transistor as a function of the breakdown voltage BV_{ceo} and for different reach-through collector structures.

II. THEORY

The total dc collector-to-emitter voltage drop $V_{CE(sat)}$ at the terminals of a n^+pvn^+ transistor operating in the quasi-saturation region is the sum of the various voltage drops:

$$V_{CE(sat)} = V_{CER} + V_{ox'} + V_{BE} - V_{CB} + I_C R_{sat} \quad (1)$$

where V_{CER} is the voltage drop across the nonconductivity modulated collector region, $V_{ox'}$ is the voltage drop in the conductivity modulated region of the collector, V_{BE} is emitter junction voltage, V_{CB} is the collector junction voltage and $I_C R_{sat}$ is the drop in the ohmic contacts of the n^+-collector and emitter. The ohmic voltage drop V_{CER}, however, is normally so high at high collector currents that it alone limits the maximum collector current density to such values at which voltage drops other than V_{CER} can be neglected. Therefore, the above equation can be simplified to

$$V_{CE(sat)} = V_{CER} + I_C R_{sat}. \quad (2)$$

When the transistor is operating in the quasi-saturation region, the collector-base junction is forward biased and hence electrons are injected from the collector into the base resulting in a back injected electron current. Similarly, there is a hole injection from the base into the collector causing a hole current that replenishes the holes recombined in the conductivity modulated region. By solving for the collector current in terms of these electron and hole currents, the voltage drop in the nonconductivity modulated collector region can be shown to be [2]

$$V_{CER} = I_C R_{epi} \times \left[1 - \sqrt{\frac{4D_{nc}^2 A_E (Q_B/D_{nb})}{\left[1 + \frac{D_{nc} A_E (Q_B/D_{nb})(1+h_{FE0})}{\tau_{epi}}\right] I_C W_{epi}^2} \left(\frac{h_{FE0}}{\beta_f} - 1\right)}\right] \quad (3)$$

where R_{epi} is the resistance of the metallurgical collector region, D_{nc} and D_{nb} are the electron diffusivities in the collector and base, A_E is the emitter area, W_{epi} is the epitaxial collector thickness, τ_{epi} is the collector recombination lifetime, β_f is the forced current gain (a ratio of the collector current I_C and the base current I_B) and h_{FE0} is the normal active region dc current gain given by

$$h_{FE0} = \frac{G_E}{Q_B/D_{nb}} \quad (4)$$

Manuscript received February 17, 1993; revised October 4, 1993. The review of this paper was arranged by Associate Editor P. J. Zdebel. This work was supported in part by a grant from NSERC and in part by a grant from ITRC.

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IEEE Log Number 9214888.

where G_E is a constant defining the effective emitter Gummel integral including the effects of bandgap narrowing, recombination and diffusion coefficient and Q_B is given by

$$Q_B = q \int N_A dx \tag{5}$$

where N_A is the acceptor density in the neutral base region and D_{nb} is the effective average electron diffusion coefficient in the base.

If τ_{epi} in (3) is assumed to be large such that

$$\frac{D_{\mathrm{nc}} A_E (Q_B/D_{\mathrm{nb}})(1 + h_{\mathrm{FE0}})}{\tau_{\mathrm{epi}}} \ll 1 \tag{6}$$

then (3) can be simplified as

$$V_{\mathrm{CER}} = I_C R_{\mathrm{epi}} \left[1 - \sqrt{\frac{4D_{\mathrm{nc}}^2 A_E}{I_C W_{\mathrm{epi}}^2} Q^*} \right] \tag{7}$$

where

$$Q^* = \frac{Q_B}{D_{\mathrm{nb}}} \left(\frac{h_{\mathrm{FE0}}}{\beta_f} - 1 \right). \tag{8}$$

At high collector currents (obtained by large base drives), the voltage drop V_{CER} across the unmodulated collector region increases the collector-base forward bias and the current gain begins to fall when this forward bias exceeds about 0.5 V [3]. The collector current at which the current gain starts to decrease as a result of the onset of quasi-saturation is called the quasi-saturation current limit I_{CQS} of the transistor. Thus for collector currents greater than I_{CQS}, the saturation voltage drop $V_{\mathrm{CE(sat)}}$ increases dramatically limiting the high current operation of the transistor as a result of undue power dissipation.

From (7) and (8), it is rather obvious that the voltage drop V_{CER} can be reduced and hence the quasi-saturation current limit I_{CQS} of the transistor can be improved by choosing W_{epi} so as to be compatible with the required breakdown voltage $\mathrm{BV}_{\mathrm{ceo}}$. Since the breakdown voltage will normally dictate a minimum thickness and resistivity for the collector region, the tradeoff between $\mathrm{BV}_{\mathrm{ceo}}$ and I_{CQS} is difficult. We show below, however, that for a given W_{epi} and N_{epi} and therefore a given $\mathrm{BV}_{\mathrm{ceo}}$, the value of I_{CQS} can still be improved by increasing the factor Q^* in (8).

III. EFFECT OF INCREASING THE BASE-GUMMEL NUMBER

The value of Q^* can be made large by increasing either h_{FE0} or the base-Gummel number Q_B/D_{nb}. Large h_{FE0}, however, has the effect of decreasing BV_{ceo} and hence is unattractive if our aim is to improve I_{CQS} without affecting the breakdown voltage. The other parameter which can be adjusted to reduce V_{CER} is, therefore, the base Gummel number Q_B/D_{nb}.

For a given breakdown voltage, the key to improving the saturation performance of the transistor lies in reducing the forward and reverse injection current components $J_{\mathrm{nc}F}$ and $J_{\mathrm{nc}R}$, respectively. As mentioned in the preceding section, these two currents are a result of the back injected electrons and holes at the forward biased collector-base junction. The current components $J_{\mathrm{nc}F}$ and $J_{\mathrm{nc}R}$ can be expressed as [5], $J_{\mathrm{nc}F} = -e^{(V_{\mathrm{BE}}/V_T)}/K$ and $J_{\mathrm{nc}R} = e^{(V_{\mathrm{BC}}/V_T)}/K$, where $K = Q_B/(qD_{\mathrm{nb}}n_i^2)$ and V_{BE} is the internal base-emitter voltage, V_{BC} is the internal base-collector voltage, V_T is the thermal voltage and n_i is the intrinsic carrier concentration. Since both $J_{\mathrm{nc}F}$ and $J_{\mathrm{nc}R}$ are inversely proportional to the base-Gummel number, by increasing Q_B/D_{nb}, the reduction in total collector current due to the back injected current components can be minimized and hence the quasi-saturation current limit I_{CQS} of the transistor can be improved.

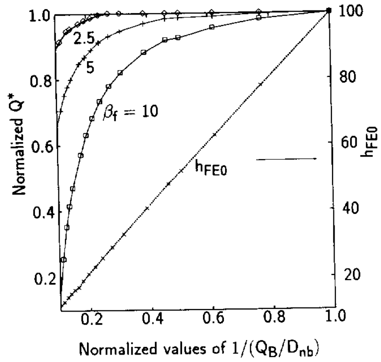

Fig. 1. Normalized values of Q^* and h_{FE0} as a function of normalized values of $1/(Q_B/D_{\mathrm{nb}})$ for $\beta_f = 2.5$, 5 and 10.

A. For a Fixed Current Gain h_{FE0}

For a fixed h_{FE0}/β_f, the value of Q^* in (8) increases linearly with increasing Q_B/D_{nb} and therefore, as can be noted from (7), this makes V_{CER} smaller. One way to increase the value of Q_B/D_{nb} is by having deep collector-base junctions. It should be noted from (4) that increasing the base-Gummel number alone will adversely affect the emitter injection efficiency resulting in a smaller h_{FE0}. Therefore, to keep h_{FE0} fixed with increasing Q_B/D_{nb}, the emitter-base junction has to be adjusted simultaneously. Using numerical simulation we will show in the next section that for a constant h_{FE0}, the quasi-saturation current limit of the transistor can be increased by increasing the base-Gummel number.

B. With Decreasing Current Gain h_{FE0}

If h_{FE0} is allowed to decrease with increasing base-Gummel number, (8) shows that the factor Q^* cannot be increased leading to no improvement in I_{CQS}. The normalized values of Q^* obtained from (8) are plotted in Fig. 1 as a function of the normalized values of $(Q_B/D_{\mathrm{nb}})^{-1}$ assuming a forced gain of $\beta_f = 2.5$, 5 and 10. This figure also shows the corresponding h_{FE0} as a function of $(Q_B/D_{\mathrm{nb}})^{-1}$. Fig. 1 shows that Q^* does not increase with increasing Q_B/D_{nb} as a result of decreasing h_{FE0}. It should therefore be noted that increasing the base-Gummel number will have no consequence in improving the quasi-saturation current limit of the transistor if h_{FE0} is allowed to decrease. In fact, as the base-Gummel number is further increased, the current gain continues to decrease. As a result, Q^* decreases and therefore results in a lower value of I_{CQS}.

TABLE I
DEVICE PARAMETERS IN BIPOLE SIMULATION

Case	E-B Junction Depth	C-B Junction Depth	Q_B/qD_{nb}	N_{epi}	W_{epi}	h_{FE0}	β_f	J_{CQS} at $V_{\mathrm{CE(sat)}} = 0.5$V
	μm	μm	cm^{-4} − s	cm^{-3}	μm			A/cm^{-2}
1	1.8	4.1	$1.61x10^{10}$	$2x10^{14}$	53.0	100	5	115
2	2.5	5.7	$2.25x10^{10}$	$2x10^{14}$	53.0	100	5	150
3	4.5	10.2	$3.91x10^{10}$	$2x10^{14}$	53.0	100	5	250

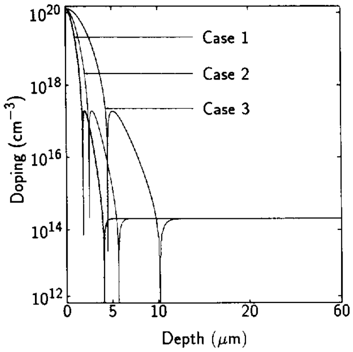

Fig. 2. The doping profile data of the transistors in Table I.

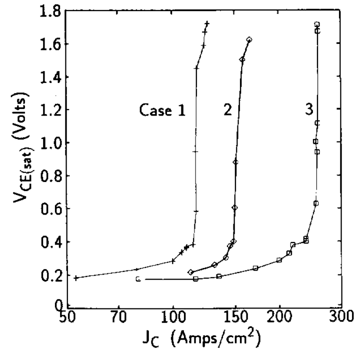

Fig. 3. $V_{\mathrm{CE(sat)}}$ as a function of collector current density $J_C$obtained using BIPOLE for a forced gain of 5 for the transistors of Table I.

An important observation can be made from Fig. 1, namely, that the parameter Q^* remains constant as long as $h_{\mathrm{FE0}}/\beta_f \geq 10$. However, Q^* decreases for $h_{\mathrm{FE0}}/\beta_f < 10$. From (8), we note that this result is true irrespective of the collector doping N_{epi} and the collector epitaxial layer thickness W_{epi} of the transistor. If h_{FE0}/β_f is below 10, as is usually the case for most power transistors, Fig. 1 suggests that the quasi-saturation current limit of these transistors will be very poor compared to those with $h_{\mathrm{FE0}}/\beta_f \geq 10$. Thus it is clear that for a given h_{FE0}, to achieve a higher quasi-saturation current limit, the ratio h_{FE0}/β_f of the transistor should be at least 10. This result will further be verified using numerical simulation in the following section.

IV. SIMULATION OF $V_{\mathrm{CE(sat)}}$ VERSUS I_C

We have used the device simulation program BIPOLE [4] to calculate the saturation voltage $V_{\mathrm{CE(sat)}}$ as a function of collector current I_C under forced gain conditions. A forced gain of 5 is used in all our simulations. BIPOLE has been shown to predict the $V_{\mathrm{CE(sat)}}$ versus I_C values very close to that of experimental results [6].

A. Increasing the Base-Gummel Number With $h_{\mathrm{FE0}} = $ *Constant*

The physical parameters of the transistors used in the BIPOLE simulation are shown in Table I and the corresponding doping profile data is shown in Fig. 2. The emitter-base and collector-base junction depths are adjusted such that all three transistors have equal h_{FE0} but different Q_B/D_{nb} values. The collector epitaxial layer thickness W_{epi} of these transistors is chosen such that at the breakdown voltage $\mathrm{BV_{ceo}}$(for a forced gain of 5), the collector depletion layer width is equal to W_{epi}.

The $V_{\mathrm{CE(sat)}}$ versus J_C curves obtained using BIPOLE for a forced gain of 5 are shown in Fig. 3. As can be seen from this figure, the maximum current limit of the transistor improves with higher Q_B/D_{nb}. As discussed above, this improvement can be realized only if the dc current gain is maintained constant with increasing Q_B/D_{nb}. It can be seen that I_{CQS} can be increased by the proper choice of the emitter-base and collector-base junction depths. The curves in Fig. 3 are obtained for transistors with a dc current gain of 100. However, we got similar improvement in the $V_{\mathrm{CE(sat)}}$ versus J_C even at a lower value of dc current gain as long as it is maintained constant with increasing base-Gummel number. It should be noted that there is a limit to which the base-Gummel number can be increased. From (7), we notice that the maximum limit on base-Gummel number is when V_{CER} becomes zero. Thus equating the right hand side of (7) to zero and substituting I_{CQS} for I_C, it can be shown that

$$\left[\frac{Q_B}{D_{\mathrm{nb}}}\right]_{\max} = \frac{J_{\mathrm{CQS}} W_{\mathrm{epi}}^2}{4D_{\mathrm{nc}}^2} \frac{1}{\left(\frac{h_{\mathrm{FE0}}}{\beta_f} - 1\right)}. \tag{9}$$

Thus for a given collector current density J_{CQS} at which the onset of quasi-saturation begins, the maximum value of Q_B/D_{nb} depends only on the collector region epitaxial width W_{epi} and h_{FE0}/β_f and is independent of collector doping.

Normally deep collector-base junctions are used in high voltage transistors to minimize the curvature effects on the breakdown voltage. It is clear from the above that deep emitter-base and collector-base junctions are also needed to increase Q_B/D_{nb} while keeping h_{FE0} constant so as to improve the quasi-saturation current limits of the transistor.

B. Increasing the Base-Gummel Number With $h_{\mathrm{FE0}} = $ *Nonconstant*

We have also simulated the $V_{\mathrm{CE(sat)}}$ versus I_C characteristics using BIPOLE to examine the effect of decreasing h_{FE0} on

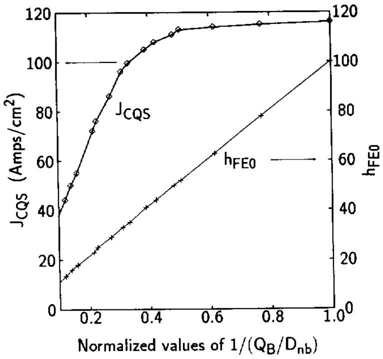

Fig. 4. The quasi-saturation current density limit J_{CQS} and h_{FE0}as a function of normalized values of $1/(Q_B/D_{nb})$ for the transistor # 1 of Table I for a forced gain of 5.

the quasi-saturation limit of the transistor as the base-Gummel number is increased. The transistor of Table I, with E-B junction depth of 1.8 μm and C-B junction depth of 4.1 μm, is used in the simulation. The collector-base junction of this transistor is increased while keeping the emitter-base junction constant. This has the effect of increasing the base-Gummel number while the dc current gain falls. The quasi-saturation collector current density J_{CQS} and the dc current gain h_{FE0} are plotted in Fig. 4 as a function of normalized $(Q_B/D_{nb})^{-1}$. It should be noted that J_{CQS} remains constant for values of $h_{FE0}/\beta_f \geq 10$. However, with increasing base-Gummel number, h_{FE0}/β_f falls below 10, resulting in a lower value of J_{CQS}. Therefore, to keep J_{CQS} high, the ratio of h_{FE0} to β_f should be greater than or equal to 10. This is in accordance with the results obtained from (8) of the quasi-saturation analysis discussed previously.

Thus our numerical simulation results confirm that for better quasi-saturation performance of the transistor under forced gain conditions, the value of h_{FE0}/β_f should be at least 10 and that for a given h_{FE0}, the value of J_{CQS} can be improved by increasing the base-Gummel number.

V. QUASI-SATURATION CURRENT LIMIT OF TRANSISTORS WITH REACH-THROUGH COLLECTORS

We also have simulated the $V_{CE(sat)}$ versus I_C of transistors with different collector dopings and collector epitaxial region widths. The collector current density J_{CQS} at which the onset of quasi-saturation becomes predominant, is plotted in Fig. 5 as a function of the collector-emitter breakdown voltage BV_{ceo} at a forced gain of 5. The current density values are plotted for three different cases (a) with W_{epi} equal to the collector depletion layer width at breakdown (b) with $W_{epi}/2$ and (c) with $W_{epi}/4$. Fig. 6 shows BV_{ceo} as a function of the collector doping N_{epi} and for the above three cases of W_{epi}. The breakdown voltages in Figs. 5 & 6 are calculated for a forced gain of 5 using BIPOLE as described in [7] using the ionization coefficients of [8], [9]. The values of W_{epi} (equal to the collector depletion layer width at breakdown for a forced gain of 5) are also shown in Fig. 6 as a function of collector doping.

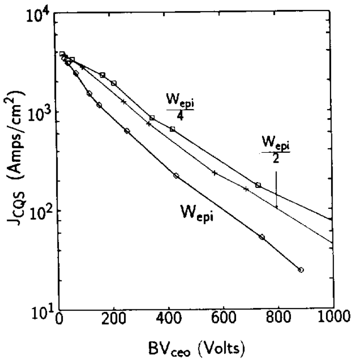

Fig. 5. J_{CQS} as a function of BV_{ceo}. Both J_{CQS} and BV_{ceo} are calculated for a forced gain of 5 by changing the collector doping N_{epi}.

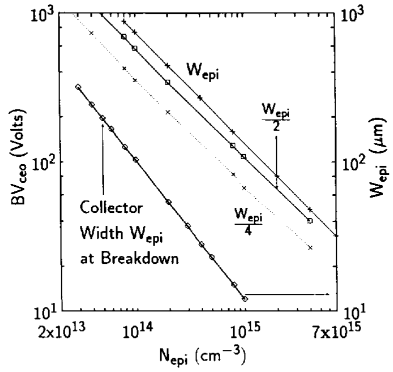

Fig. 6. The collector epitaxial layer thickness W_{epi} and the breakdown voltage BV_{ceo} for different reach-through collector cases obtained using BIPOLE for a forced gain of 5. W_{epi} is equal to the collector depletion layer width at breakdown.

Figs. 5 and 6 are useful to predict J_{CQS} values for any given N_{epi} and W_{epi}. As suggested by (3), the BIPOLE results of Fig. 5 confirm that J_{CQS} increases with decreasing W_{epi}. For example, for $N_{epi} = 10^{14}/\ \text{cm}^3$, when the collector epitaxial layer thickness is reduced from W_{epi} to $W_{epi}/4$, the breakdown voltage BV_{ceo} falls from 750 V to 350 V. Fig. 5 shows that the value of J_{CQS} for $BV_{ceo} = 750$ V and with the full collector epitaxial layer thickness W_{epi}, is 50 A/cm². For $W_{epi}/4$, and $BV_{ceo} = 350$ V, the corresponding value of J_{CQS} is 875 A/cm². We note from (3) that the voltage drop V_{CER} in the nonconductivity modulated collector region is directly proportional to the resistance R_{epi} of the metallurgical collector region given by

$$R_{epi} = \frac{W_{epi}}{q\mu_0 N_{epi} A_E}. \tag{10}$$

Therefore, for a given N_{epi}, the value of J_{CQS} increases when the epi-layer thickness is reduced from W_{epi} to $W_{epi}/4$. This is because, as can be seen from (10), the collector resistance reduces by 4 times improving the value of J_{CQS}. However, there is a corresponding reduction in the breakdown voltage BV_{ceo}.

Figs. 5 and 6 can also be used for choosing the collector doping and the collector epitaxial layer width to get higher

J_{CQS} for a given breakdown voltage $\mathrm{BV}_{\mathrm{ceo}}$. From Fig. 6 we notice that a given $\mathrm{BV}_{\mathrm{ceo}}$ can be obtained by choosing the collector doping N_{epi} and the collector thickness W_{epi} equal to the collector depletion layer width at breakdown or by choosing a reach-through collector with reduced N_{epi} and reduced collector thickness (e.g., $W_{\mathrm{epi}}/4$). For example, a $\mathrm{BV}_{\mathrm{ceo}}$ of 500 V can be obtained with either 1) $N_{\mathrm{epi}} = 1.8{\times}10^{14}$ cm^3 and W_{epi} or 2) $N_{\mathrm{epi}} = 7 \times 10^{13}$ cm^3 and $W_{\mathrm{epi}}/4$. Thus in the later case, since the collector doping is smaller and the epi-layer thickness is reduced from W_{epi} to $W_{\mathrm{epi}}/4$, two advantages accrue. First, the breakdown voltage is held constant and secondly, as we can see from (10), the value of R_{epi} is reduced thus resulting in a higher J_{CQS}. Thus Figs. 5 and 6 are useful for choosing the desired collector doping and collector epitaxial thickness to realize a given quasi-saturation current limit I_{CQS} and the breakdown voltage $\mathrm{BV}_{\mathrm{ceo}}$ of the transistor.

VI. CONCLUSION

In conclusion, we have shown that the collector current I_{CQS} of the transistor at which the onset of quasi-saturation begins, can be improved by increasing the base-Gummel number provided that the emitter-base junction is simultaneously altered to keep the ratio of emitter-Gummel number to base-Gummel number a constant. We have also shown that transistors operating at high collector current densities, independent of their collector doping and collector epitaxial layer thickness, should have a minimum h_{FE0}/β_f of 10 to keep I_{CQS} reasonably high. Finally, we have provided design curves for predicting the quasi-saturation current limit of the transistors as a function of the breakdown voltage $\mathrm{BV}_{\mathrm{ceo}}$ and for different reach-through values of the collector epitaxial layer thickness.

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