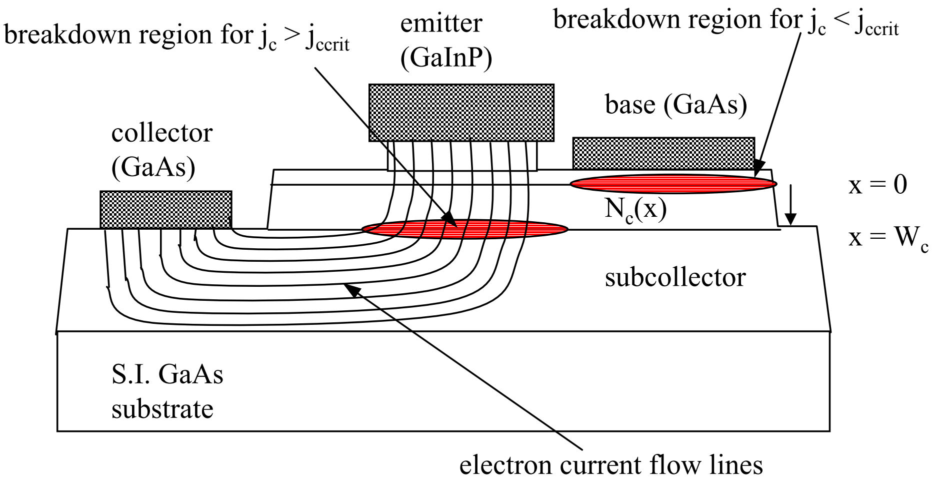
Avalanche Breakdown in GaInP/GaAs HBTs

Overview

- device description to identify high electrical field regions

  (Emax=4*10^{7}V/m in GaAs until avalanche breakdown occurs)
- pulsed versus dc measurements
- electrical field and avalanche current calculations
- prediction of maximum output power (class A)
- thermal induced breakdown in multifinger devices
- summary of problems with breakdown voltage measurement and simulation

Device description



some equations for 1D-Model

$N_c \approx 1 \cdot 10^{16}/cm^3$; $W_c \approx 1\ \mu m$

$j_{ccrit} = N_c \cdot q \cdot v_{sat} = 1.6 \cdot 10^4\ A/cm^2$

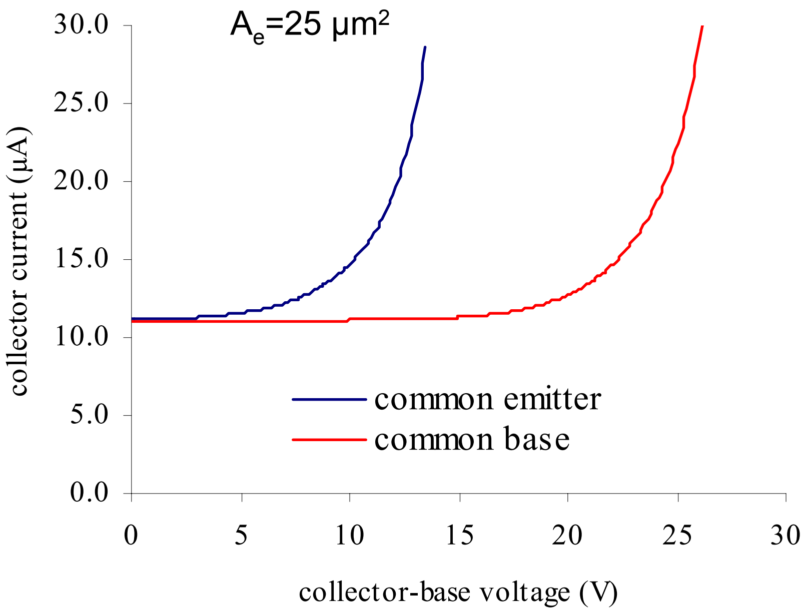
$j_c \approx I_c / A_e$

$$V_{cbkb}(j_c) = V_{cbkb}(0) + \frac{W_c^{\,2}}{2 \cdot \varepsilon \cdot v_{sat}} \cdot j_c \quad \text{for } j_c < j_{ccrit}$$

$$\Delta V_{cbkbmax} = V_{cbkb}(j_{ccrit}) - V_{cbk}(0) = 6.4\ V$$

N_c : collector doping density
W_c : collector thickness
j_c : collector current density
I_c : collector current
A_e : emitter area
V_{cbkb} : common base breakdown voltage
v_{sat} : saturation velocity of electrons in GaAs
ε : dielectric constant of GaAs
q: electron charge

Determination of breakdown voltages with constant bias current



measurement of collector IV data

common emitter $V_{cbke}(0)$ =15.8 V

common base $V_{cbkb}(0)$ =28.4 V

extraction with Millers empirical formula:

$$M = \frac{I_c(x = W_c)}{I_c(x = 0)} = \frac{1}{1 - \left(\frac{V_{cb}}{V_{cbk}}\right)^n}$$

theoretical correspondence between breakdown voltages:

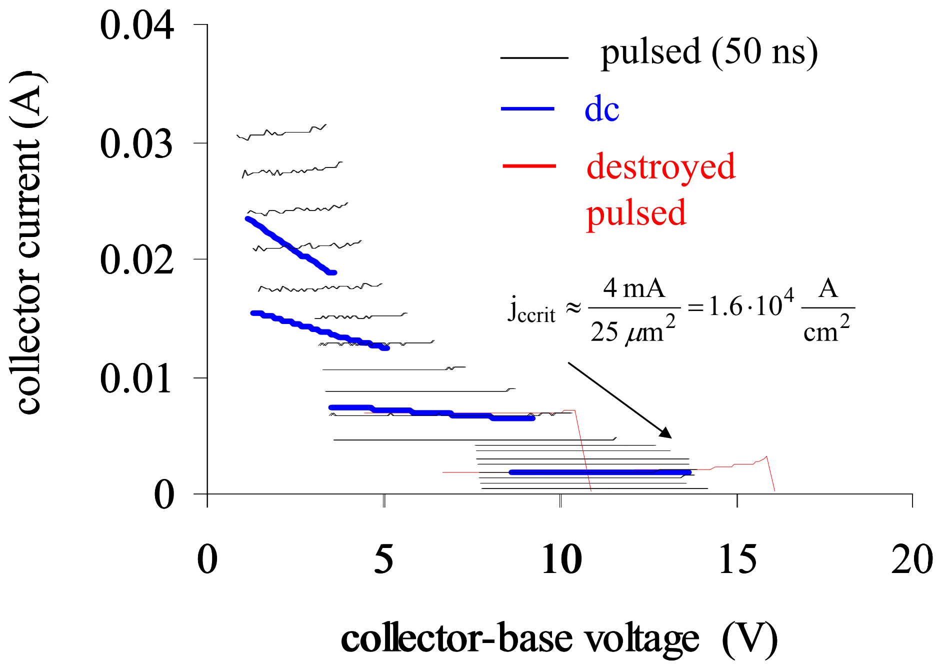
$$V_{cbke} = V_{cbkb} \cdot (1 - \alpha)^{\frac{1}{n}}$$

$$n = 8$$

M: collector multiplication factor

α : common base current gain

Pulsed versus dc IV data single finger HBT (A_e=25 µm²)



$$j_{ccrit} \approx \frac{4\,\text{mA}}{25\,\mu\text{m}^2} = 1.6 \cdot 10^4\,\frac{\text{A}}{\text{cm}^2}$$

pulsed stop criterion:

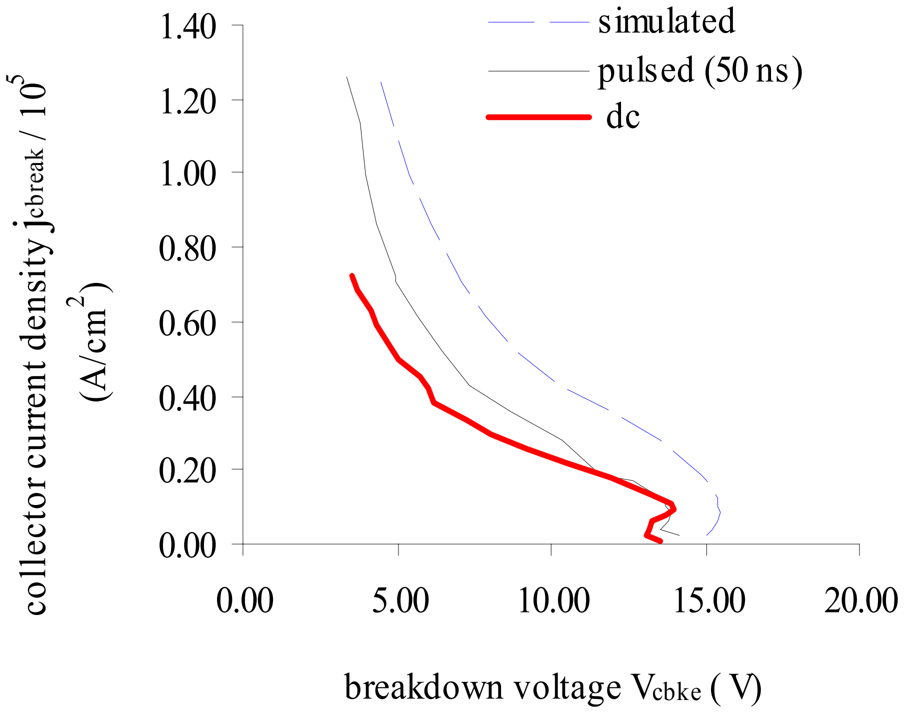
$$\frac{\Delta I_c}{I_{c0}} > 0.01 \text{ with } \Delta V_{cb} = 100\,\text{mV}$$

dc stop criterion

$$\frac{\Delta I_c}{I_{c0}} > 0.01 + \text{slope} \cdot \Delta V_{cb} \text{with } \Delta V_{cb} = 100\,\text{mV}$$

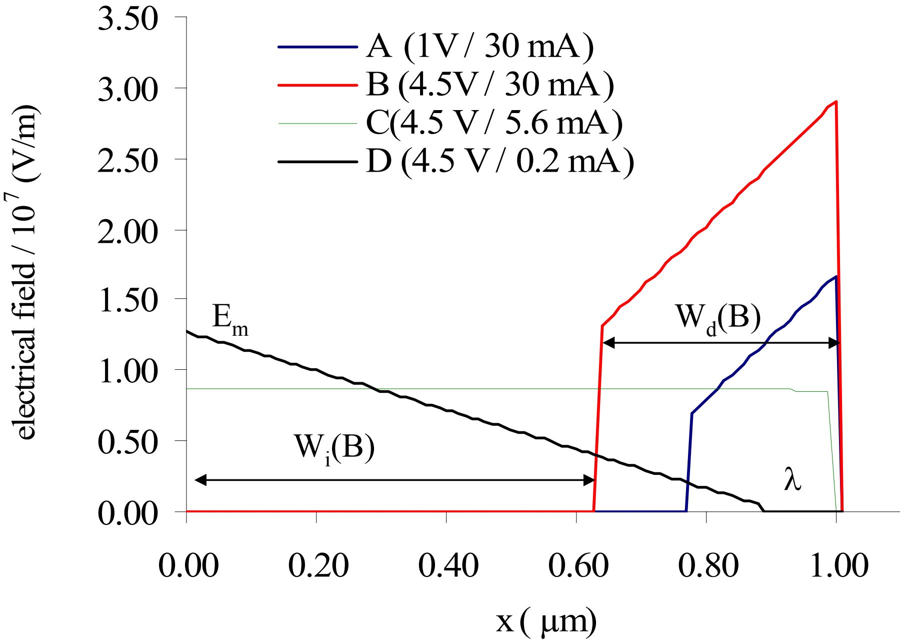
common emitter configuration with constant base current to avoid thermal runaway

Contourplot
single finger HBT (A_e=25 µm²)



Simulation - electrical field calculation single finger HBT (A_e=25 µm²)

$$I_{aval} = I_c(x=0) \cdot \int\limits_{x(E \neq 0)} P_n(x)\,dx$$



base | collector | subcollector

Chynoweth´s empirical law for the ionisation coefficient:

$$P_n(x) \approx \alpha_n \cdot \exp\left(\frac{-b_n}{E(x)}\right)$$

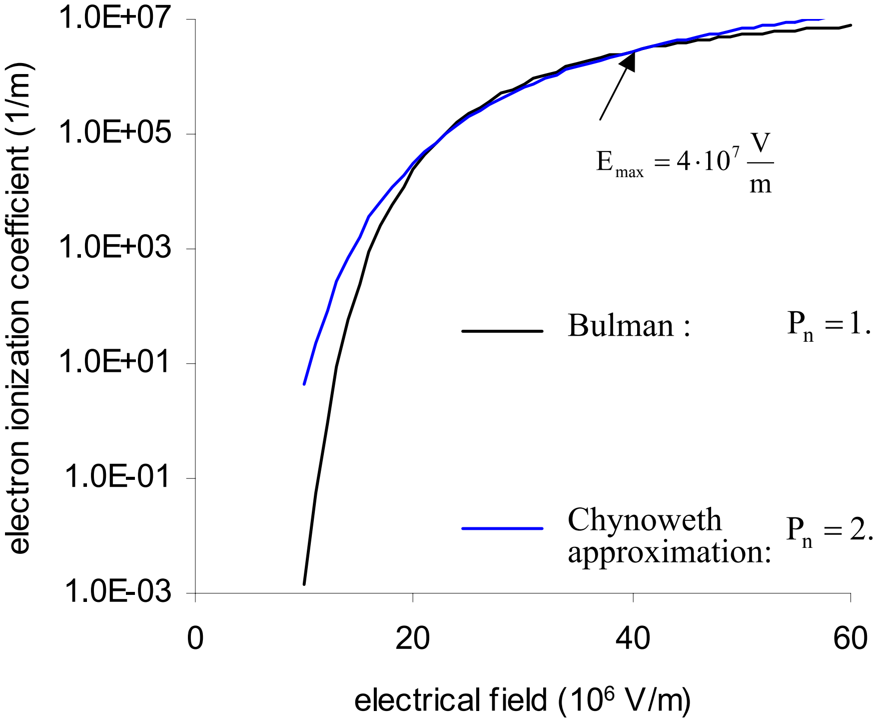
Kloosterman BCTM 2000 p.172

$$E(x) = E_m \cdot \left(1 - \frac{x}{\lambda}\right) \approx \frac{E_m}{1 + \frac{x}{\lambda}}$$

$$M - 1 = \frac{I_{aval}}{I_c(x=0)} =$$

$$= \frac{\alpha_n}{b_n} \cdot E_m \cdot \lambda \cdot \left\{ \exp\left(\frac{-b_n}{E_m}\right) - \exp\left(\frac{-b_n}{E_m} \cdot \left[1 + \frac{W_d}{\lambda}\right]\right)\right\}$$

Simulation - determination of ionization coefficient



$$E_{max} = 4\cdot10^{7}\,\frac{V}{m}$$

Bulman :

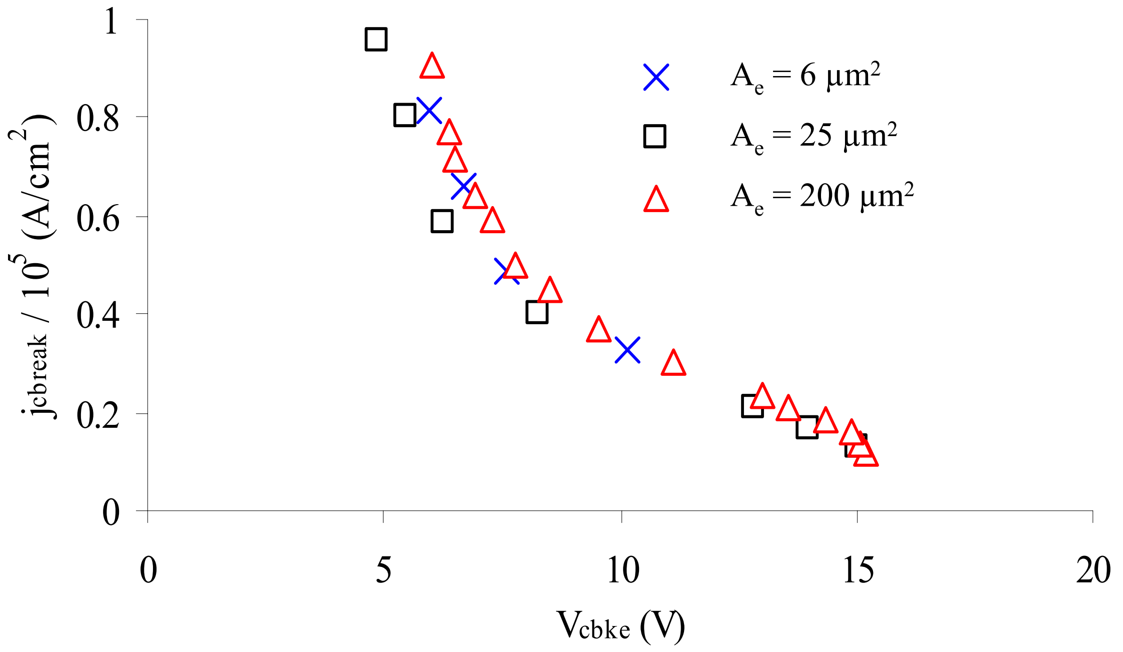
$$P_n = 1.899\cdot10^{7}\,\frac{1}{m}\cdot\exp\left(-\left(\frac{5.75\cdot10^{7}\,\frac{V}{m}}{E}\right)^{1.8}\right)$$

Chynoweth approximation:

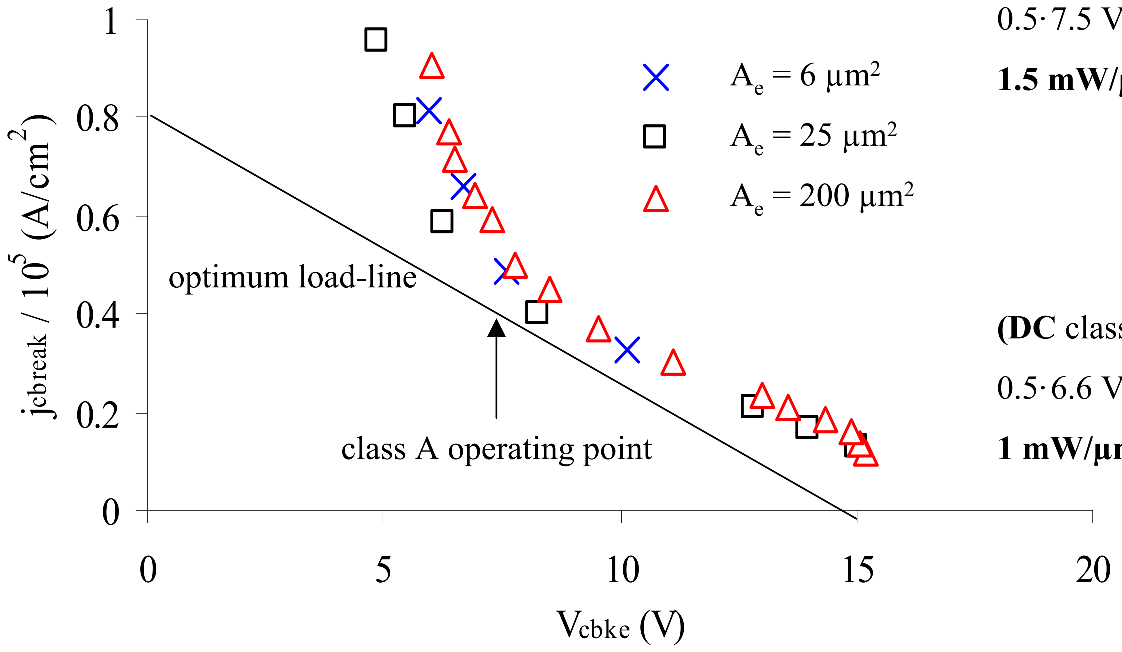
$$P_n = 2.403\cdot10^{8}\,\frac{1}{m}\cdot\exp\left(-\frac{1.782\cdot10^{8}\,\frac{V}{m}}{E}\right)$$

Scaling

pulsed (200 ns) common emitter breakdown characteristic of 3 single finger HBTs



Maximum class A output power



pulsed class A power density=

$0.5 \cdot 7.5\ V \cdot 4*10^4\ A/cm^2 =$

1.5 mW/μm^2

(**DC** class A power density=

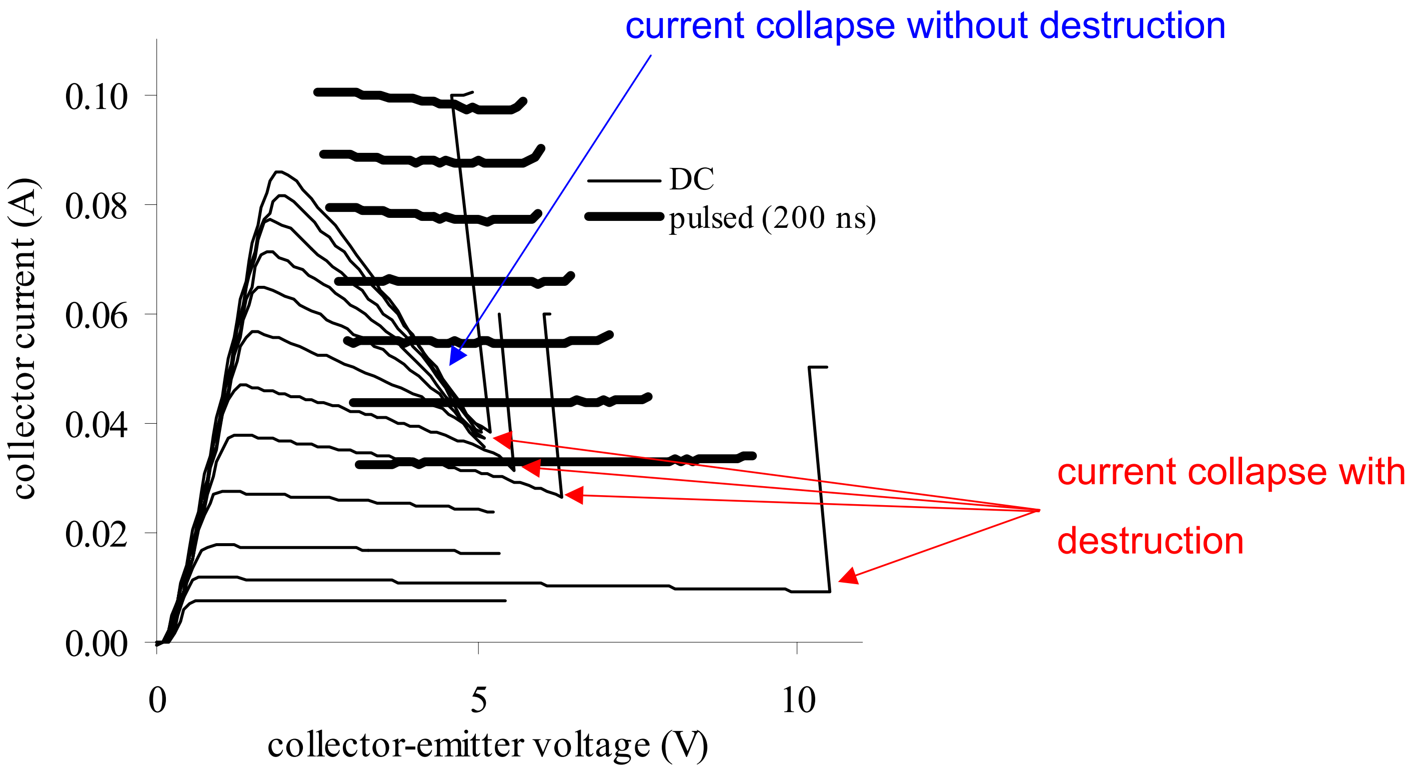
$0.5 \cdot 6.6\ V \cdot 3*10^4\ A/cm^2 =$

1 mW/μm^2 only for A_e=25 μm^2)

Thermal induced avalanche breakdown in multifinger transistors with constant base bias current

4 finger HBT

$A_e = 100\ \mu m^2$



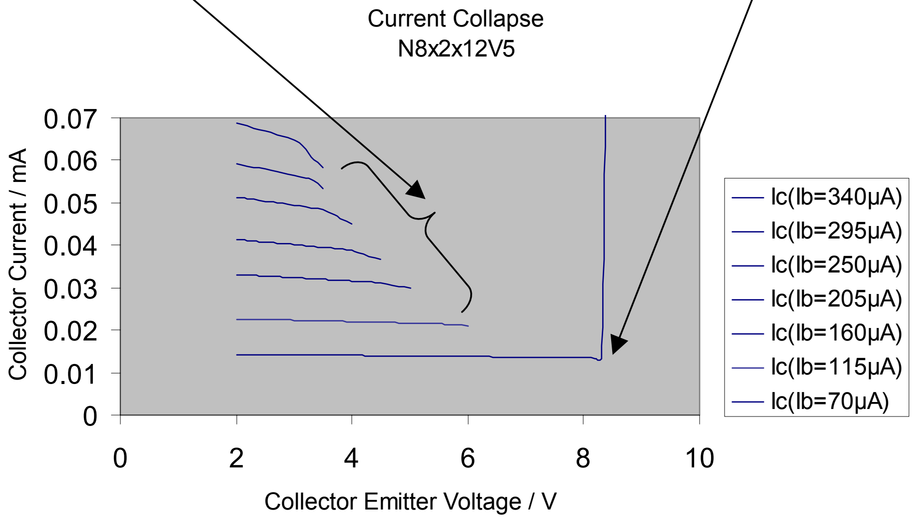
current collapse without destruction

current collapse with destruction

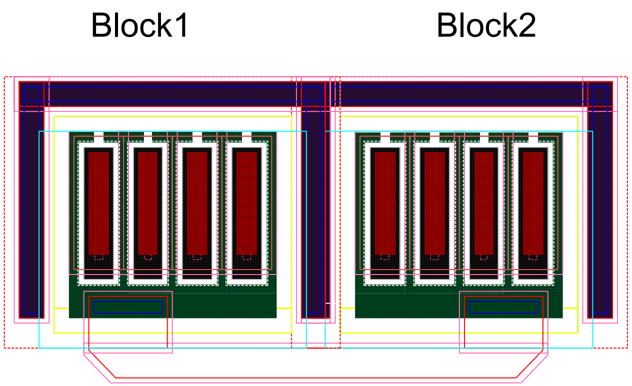
Blockwise Current Collapse with and without avalanche breakdown

reversible Collapse without destruction
(E<Emax)

irreversible Collapse with destruction
(E > Emax)



Layout of 8 Finger Transistor



Determination and simulation of M

$$M(V_{cb}) = \frac{I_c(x = W_c)}{I_c(x = 0)} \approx \frac{I_c(V_{cb})}{I_c(V_{cb} = 0V)}$$

problems	*solutions*
measurement of M	
Early effect	correction : $\Delta I_c = \frac{I_c}{V_A} \cdot \Delta V_{cb}$ V_A : Early voltage
temperature effects (current concentration and collapse)	pulsed measurements or correction
simulation of M	
high current effect ($j_c > j_{ccrit}$)	calculation of the injection width is necessary
two-dimensional effects	current spreading factor
analytical formulas	fitting of ionization coefficients
low current effects (expected increase of V_{cbk} is not observed)	keep V_{cbk} constant for $j_c < j_{ccrit}$

Conclusions

- identification of different breakdown regions
- development of non destructive breakdown voltage characterization methods in common emitter and common base configuration
- simulation of the electrical field in the collector and the avalanche multiplication factor as a function of collector current density
- determination of the maximum linear power density under pulsed and DC operating conditions
- explanation of "early" device destruction in multifinger HBT