Avalanche Breakdown in GaInP/GaAs HBTs

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Abstract—Device destruction in gallium arsenide based multfiger heterojunction bipolar transistors (HBTs) mainly occurs due to thermal induced avalanche breakdown. Depending on the collector current density, different regions of avalanche breakdown in the collector are identified. A non-destructive pulsed measurement method of the collector base breakdown voltage at low and high current densities is developed. The measured breakdown voltages could be used to develop compact HBT simulation models.

Keywords — Avalanche breakdown, electrothermal effects, heterojunction bipolar transistors, power amplifier, reliability.

I. INTRODUCTION

The weak avalanche breakdown behavior is included in modern circuit simulation models for bipolar transistors [1, 2] to allow the circuit designer to predict the safe operating region of the transistor in power amplifier applications and to predict the transistors nonlinear distortion characteristics [3]. These models determine a collector base breakdown voltage \( V_{cbk} \) independent of collector current density \( j_c \). A model improvement has been done by Scott and Low [4] and Kloosterman [5]. Their [4] one dimensional model – based on pulsed measurements - determined a linear increase of \( V_{cbk} \) with \( j_c \) at low collector current density followed by a linear decrease of \( V_{cbk} \) with \( j_c \) at high current density. The critical current density for the transition between low and high current densities occurs at \( j_{ccrit} = N_c \cdot q \cdot v_{sat} \) (1), with \( N_c \) as averaged collector doping density, \( v_{sat} \) the electron saturation velocity in the collector and \( q \) the electron charge. This principal behavior could be explained as follows: At zero collector current density, the peak electric field occurs at the base-collector interface. Avalanche breakdown is initiated at this position when this electric field achieves a value of \( E_{max} \). In GaAs \( E_{max} = 3...4 \times 10^5 \) V/cm is the electric field at which impact ionization begins to be significant for avalanche breakdown [6]. As the current density in the collector increases, the negative space charge from the injected electrons decreases the effective doping density

\[ \text{N_{eff} = N_c - \frac{j_c}{q \cdot v_{sat}} (1)} \]

and lowers the maximum electrical field in the collector. Under this low current density operating conditions Reisch [7] predicted a linear increase of the breakdown voltage for constant doping profile in the collector:

\[ V_{cbk}(j_c) = V_{cbk}(0) + \frac{W_c^2}{2 \cdot \varepsilon \cdot v_{sat}^2} \cdot j_c \quad (2), \]

where \( W_c \) is the thickness and \( \varepsilon \) the permittivity of the collector region. At collector current densities higher than \( j_{ccrit} \), the maximum electrical field occurs at the collector-subcollector part of the base-collector space charge region under breakdown conditions as indicated in Fig. 1. A further increase of \( j_c \) lowers the breakdown voltage \( V_{cbk} \) considerably as the pulsed measurements on GaInP/GaAs HBTs in common emitter configuration show in Fig.2. Here a typical dc and pulsed output characteristic (collector current versus collector-base voltage with constant base current as parameter) of a single finger HBT with 2.5*10 μm² emitter area is shown. The critical current density \( j_{ccrit} = 1.6 \times 10^4 \) A/cm² predicted by eq. (1) fits to the measured data if the emitter area is used to calculate the collector current density. The paper is organized as follows: Section II investigates the breakdown mechanism under DC and pulsed operating conditions in single finger and multifinger HBT. Section III describes the investigated test structures and measurement results.

Figure 1. Schematic cross-section of mesa type HBT indicating areas of breakdown (not scaled).

II. BREAKDOWN MECHANISM

The HBT breakdown characteristics is determined by the collector doping profile \( N_c(x) \). In the case of zero collector current, the electrical field is determined by \( N_c(x) \) and the applied voltage. An increase in the applied collector-base Voltage \( V_{cb} \) increases the resulting electrical field up to \( E_{max} \) and breakdown occurs at \( V_{cb} = V_{cbk} \). The highest field appears at the base-collector interface as indicated in Fig.1. Under normal forward operating conditions of a nnp HBT an electron current flows into the collector space charge region which itself consists of positive fixed charges from the ionized dopants. As a result the total charge level in the collector decreases, which decreases the resulting electrical field. Thus breakdown should occur at higher voltages \( V_{cb} > V_{cbk} \). In this mesa type transistor, the calculated increase of \( V_{cbk} \) with \( j_c \) using (2) predicts a breakdown voltage increase of...
$\Delta V_{cbk} = 6.4 \, V$ up to the critical current density $j_{ccrit}$. In contrast to the simple one-dimensional model, the measurements in Fig. 2 show an increase of only $\Delta V_{cbk} = 0.5 \, V$. The reason for this discrepancy is the fact that there are always areas in the collector space charge region where no electron current flow is present. This region is located under the base contact layer and is indicated in Fig. 1 with breakdown region for $j_c < j_{ccrit}$. Due to this two dimensional effect, the breakdown will occur in the transistor region where no current flow is present - at approximately $V_{cbk}$. Therefore the breakdown voltage in compact bipolar models for mesa type transistors should be kept constant: $V_{cbk} = V_{cbk0}$ for $j_c < j_{ccrit}$.

At higher current densities $j_c > j_{ccrit}$, the net charge in the collector changes its sign (base pushout occurs [8]). Under these conditions the highest electrical field appears at the subcollector side of the space charge region. Further increase of the collector current density at constant collector base voltage increases the resulting field at this location and thus reduces $V_{cbk}$. Fig. 2 shows a measured output characteristic which confirms the above description. In addition dc measurements are included in Fig. 2 to show that the breakdown voltage under pulsed conditions is always greater than the breakdown voltage at dc for $j_c > j_{ccrit}$. In contrast to the published compact models for avalanche breakdown, [1],[2],[4], the dependence of the measured breakdown voltages on the collector current density for breakdown $V_{cbk}$ is strongly nonlinear as shown in Fig. 3. A simulation of the dependence of $V_{cbk}$ on $j_{break}$ is included using the equations for the calculation of the collector field and the resulting avalanche current from [5]. As model parameters $W_i=1 \, \mu m$, $N_i=10^{18} \, / \, cm^2$, $\alpha_i=1.899*10^7 \, 1/m \cdot V$, and $\beta_i=5.75*10^7 \, V/m$ are used. Here $\alpha_i$ and $\beta_i$ are the parameters to calculate the ionization coefficient of electrons in the GaAs collector layer. Their values are determined empirically by Bulman[9]. In this 1-d simulation it is also possible to calculate the electrical field in the reverse biased base-collector junction. In the results are plotted at 4 different operating points which are indicated in Fig. 2. At the operating points A and B ($j_c > j_{ccrit}$) base pushout occurs and the effective basewidth is increased by the injection width $W_i(A)=0.8 \, \mu m$ and $W_i(B)=0.65 \, \mu m$. In this situation the maximum electrical field $E_{max}$ occurs at the collector-subcollector interface. At operating point B $E_{max}$ is high enough to initiate the breakdown of the transistor. At the operating points C and D ($j_c < j_{ccrit}$) $E_{max}$ is located at the base-collector interface. At D the collector is not fully depleted while at C a nearly constant electrical field profile is achieved.

The models [1],[2],[4],[5] do not include thermal effects. In GaAs based HBTs the collector current collapse can occur in multifinger transistors [10] resulting in a current flow only through a single finger. This collapse increases $j_c$ and therefore reduces the avalanche breakdown voltage $V_{cbk}$ if the resulting current density after the thermal collapse is greater than $j_{ccrit}$. In this situation, the breakdown voltage of a multifinger transistor is lower than in a single finger device and equals the base collector voltage for the onset of the collector current collapse. Therefore avalanche breakdown is caused by a thermally triggered increase of the collector current density $j_c > j_{break}$.
The thermal collapse itself is not necessarily accompanied with a destruction of the device. Thus if the current collapse occurs at low electric field in the collector, the collapse phenomenon could be observed in the transistors DC output characteristics as increased negative output conductance (e.g. DC measurement in Fig. 7). To analyze this complicated interactions, pulsed and DC measurement techniques to determine the HBTs output characteristics are developed.

III. MEASUREMENT RESULTS

The devices under test where supplied by United Monolithic Semiconductors (UMS) from their HB20D GaInP/GaAs HBT process. Capacitance voltage measurements of the base-collector junction allowed to extract the constant collector doping with \( N_c=1 \times 10^{19} \) cm\(^{-3}\) and the collector thickness with 1 \( \mu \)m. Therefore the onset of base pushout occurs at \( j_{\text{cw}} = 1.6 \times 10^7 \) A/cm\(^2\) assuming \( v_{\text{sat}}=1 \times 10^7 \) cm/s. At this current density a change of breakdown voltage with current density is expected. As test structures we used single finger transistors with emitter area between 6 \( \mu \)m\(^2\) up to 200 \( \mu \)m\(^2\) and one multifinger transistor with four emitter fingers and a total emitter area of 100 \( \mu \)m\(^2\).

The common emitter measurements of the HBTs are performed under pulsed conditions where the base current is pulsed and the collector voltage is held constant. The complete measurement equipment is computer controlled over the GPIB bus. The pulsed measurements are performed with a pulse width of 300 ns and a duty cycle of 0.4 % to avoid thermally induced current collapse phenomena. Fig. 5 shows the on wafer measurements of the pulsed current waveforms using tungsten probe tips where the pulse base current is supplied with a resistor of 3.3 k\( \Omega \) in series to the base contact. The collector voltage is supplied by a DC power supply for currents up to 2A and voltages up to 20 V. Additionally a broadband (10 kHz – 18 GHz) bias tee is used to prevent low frequency oscillations. The collector current \( I_c \) is measured as voltage drop on a 10 \( \Omega \) series resistor with a digital oscilloscope. The triggering of the oscilloscope is performed on the falling edge of the pulse. Therefore the shown timebase during the pulse is negative. Steady state is achieved after approximately -200 ns. After this time delay reliable current measurements are possible.

The transistors active collector area could not be easily obtained due to a two dimensional current flow in the collector and possible underetching of the thick collector layer. Therefore the measured currents are always related to the active emitter area to calculate the collector current density. The breakdown voltage \( V_{\text{cb}} \) is then extracted from the type of non-destructive measurements shown in Fig. 2. There, one characteristic is measured applying a constant base current pulse and increase the applied collector-base voltage \( V_{\text{cb}} \) in 100 mV steps. To detect the onset of avalanche breakdown the history of the measurement is used to allow the measurement of the next operating point. \( V_{\text{cb}} \) is increased until \( I_c \) changes more than 1 % during this 100 mV voltage step. This 1 % current increase criterion is used to estimate the breakdown voltage \( V_{\text{cb}} \) in a non-destructive way. Therefore the whole output characteristics is measured using only one device. Measurements shown by [4] used one device for each curve. Therefore 19 transistors would be necessary to achieve the results shown in Fig. 2. If we use e.g. 2 % current increase with a \( V_{\text{cb}} \) voltage step of 100 mV as stop criterion for the voltage sweep, a destruction of the transistor occurs.

An explanation that the 1 % criterion is sufficient to detect the breakdown voltage is given as follows: The collector current in the linear operating region of bipolar transistors at constant base current is determined by three effects: Base width modulation (Early effect), temperature dependent common emitter current gain and avalanche multiplication. The destination of all three effects at DC operating conditions is not possible. The collector current increase at the onset of considerable avalanche multiplication shown in the pulsed measurements of Fig. 2 and Fig. 7 is caused by avalanche multiplication because the Early effect could be neglected in our HBTs: The Early effect is suppressed due to the high base doping accompanied with low emitter and collector doping resulting in a collector current increase of only 0.05 % if we assume an early voltage > 200V. Additionally the current gain of these transistors has a negative temperature coefficient resulting in negative output conductance under DC operating conditions.

Fig. 6 shows the results of the determined breakdown Voltage \( V_{\text{cb}} \) from pulsed measurements as a function of the collector current density \( j_c \) for three different sized single finger devices. The measured current density versus breakdown voltage characteristic is scalable with the determined emitter area. For a collector current density smaller 1.6\( \times 10^7 \) A/cm\(^2\),
$V_{cb}$ is nearly constant at approximately 15 V. For $j_c > 1.6 \times 10^4 \, \text{A/cm}^2$ the characteristics is given as a nonlinear function of $j_c$.

The straight line included in Fig. 6 gives the save operating regime of the device and sets the maximum emitter current density for class A power amplification to achieve maximum output power: The operating point for maximum output power should therefore be at $V_{ce} \approx 8 \, \text{V}$ with $j_c = 0.35 \times 10^5 \, \text{A/cm}^2$, which translates in a maximum power density of approximately $1.4 \times 10^3 \, \text{W/cm}^2$ with the assumption of 50 % power added efficiency. This means: to achieve an RF output power of $1.4 \, \text{W}$, a transistor with an emitter area of $1000 \, \mu\text{m}^2$ has to be used without consideration of self heating effects which worsens the situation.

A comparison of DC with pulsed measurements is done in Fig. 7 on a four finger transistor with a total emitter area of $100 \, \mu\text{m}^2$. The DC measurements could not be extended to the same level of $V_{cb}$ as shown in the pulsed measurements. The reason for the destruction is the increased junction temperature caused by self-heating. resulting in a current collapse due to the negative temperature coefficient of the current gain [10]. The collapse occurs in a way that at a certain temperature difference between the hottest and the coldest finger, the colder finger is switched off while the hotter finger has increased current density. This process repeats until only one finger carries the whole collector current at four times the current density in our four finger device. If the current density at a certain $V_{cb}$ exceeds the value shown in Fig. 6, catastrophic destruction through avalanche breakdown occurs. This is shown in a strong increase of $I_c$ in the DC measurement of Fig. 7.

**IV. CONCLUSION**

The nonlinear dependence of the avalanche breakdown voltage under different collector current densities is measured in a non-destructive way under pulsed and DC operating conditions. Two regions of operation could be distinguished: At $j_c > j_{crit}$ the breakdown occurs in the part of the collector space charge region where no current flow is present. Therefore nearly no change of $V_{cb}$ with $j_c$ is observed. At $j_c < j_{crit}$ a strong nonlinear decrease of $V_{cb}$ with $j_c$ is measured. The behavior can be used to predict the maximum available power density under class A power operation. The difference between the DC and the pulsed breakdown voltages $V_{cb}$ is explained by a thermally triggered avalanche breakdown caused by a current collapse in multifinger HBTs which increases $j_c$ at the hottest finger. The measurements presented could be used to built a new compact electro-thermal HBT transistor model for circuit simulation which includes a weak avalanche breakdown voltage dependence as shown in Fig. 4. This will give circuit designers the possibility to simulate the save operating region of multifinger power transistors under DC and pulsed operation.

**REFERENCES**
