Extraction of thermal time constant in HBTs using small signal measurements.

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Abstract

A novel method for finding the thermal time constant of HBTs is proposed. It utilizes small signal measurements in the frequency domain of the typical negative differential resistance found in the active region, i.e., normal bias conditions for the device. In this way, non-linearities in the thermal resistivity does not disturb the extraction and the device needs only to be characterized in one bias point.

Introduction

Different methods for finding the thermal time constant of two terminal devices have been proposed[1][2][3], but to the authors knowledge so far none has been suggested which operates in the frequency domain. Furthermore, conventional extraction procedures need to achieve a strong variation of power dissipation during the extraction. The device needs to be operated under two different bias conditions: at low power dissipation (cold state) and at high power dissipation (hot state). This means that essential parameters need to be known over a wide range compared to small signal operation. The suggested approach does not suffer from these shortcomings.

Theoretical background and description of method

The proposed method utilizes the variation of HBT current gain with temperature. In a first approximation, the thermally dependent part of the common emitter current gain (β) for an HBT can be expressed by an exponential term:

$$\beta_{HBT} = \beta_0 * e^{\frac{\Delta E_g}{k_B T}} \qquad (1)$$

where T is the junction temperature and ΔE_g is the bandgap energy difference between emitter and base, assuming this is located in the valence band (for an NPN-type transistor). This is true for a graded base GaAs HBT or for SiGe HBTs with strained base layers. Due to the thermal dependence in eq. 1, HBTs will exhibit a negative differential resistance in the (active, non-saturated) region of an IV-curve since the internal power dissipation will heat the device. This can be seen in Fig. 1 (a) as the negative slope at collector-emitter voltages above approximately 1 V. The device has then been simulated in a steady-state, i.e., each bias point has been held for a much longer time than the thermal time constant (τ_T) and the junction has thus reached a stable temperature.

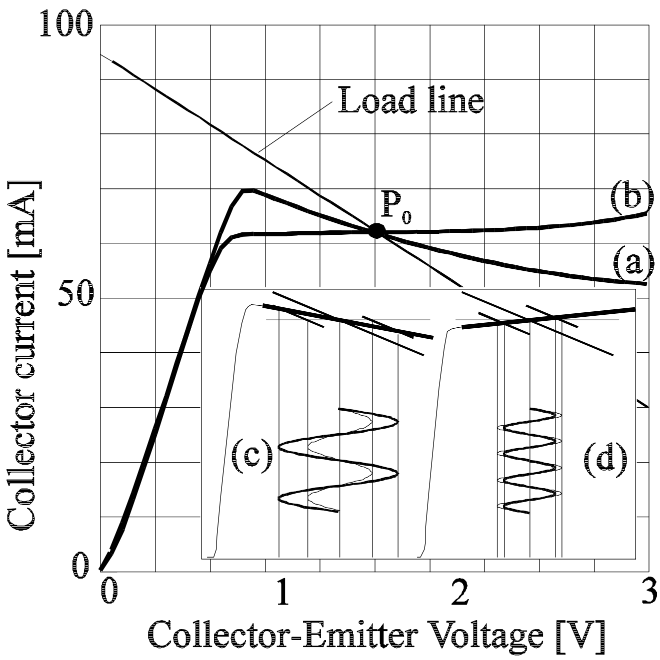

Fig. 1 Collector current versus collector-emitter voltage at a fixed base current. Employing thermal dependence (a), assuming a fixed junction temperature (b). A load line for a resistor in series with the collector is also shown. The inset shows schematically how the amplification of small signal input, v_{CC}, varies with frequency. Inset: (c) at low frequencies, the slope of the load line very closely resembles the slope of the IV-curve and thus creates an amplification of v_{CC}. (d) at high frequencies, the slope of the IV-curve has changed to become positive and v_{CC} is therefore attenuated. The thick curve is the small signal output, v_C, and the thin curve (equal in the two cases) is v_{CC}.

If the same sweep is done in a much shorter time ($<<\tau_T$), it means that the transient power dissipation within the device is not sufficient to alter the junction temperature and β will thus essentially remain constant which can be seen as a negligible or even a positive slope (caused by e.g. the Kirk-effect and Early-effect) in the IV-curve (see Fig. 1 (b)). By varying the bias point with a sine wave around a fixed power dissipation point (e.g. P_0 in Fig. 1), it is possible to find the transition between steady-state and transient mode and thus also the thermal time constant.

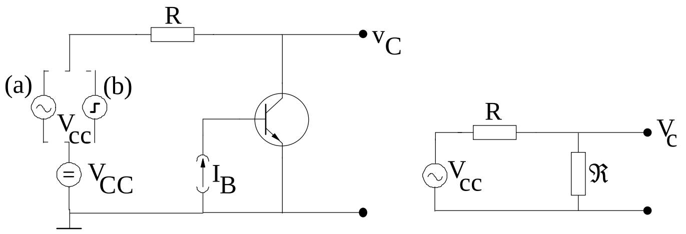

Fig. 2 Schematic of the measurement setup. On the left side the large signal setup with a constant base current (I_B) and a modulated collector voltage ($V_{CC}+v_{cc}$). In the frequency domain, v_{cc} is a sine wave (a). In the time domain (for later verification), v_{cc} is a voltage step (b). On the right side is a small signal equivalent where the transistor has been replaced by a frequency dependent resistor.

In the discussion below, signals will be defined in the following way: upper-case letters for signal type (i.e., V or I) denote time-independent magnitude and lower-case letters denote time dependence. Upper-case index denote complete part of signal and lower-case letters denote the modulating part. As an example, the complete signal v_C is then defined as $V_C+V_c\sin(\omega t)$ where V_C is the DC-part and $V_c\sin(\omega t)=v_c$ is the AC modulating part.

The circuit used for the measurements described above can be seen in Fig. 2. A DC voltage source (V_{CC}) is connected via a resistor (R) to the collector of the transistor and a constant current source (I_B) is connected to the base. By choosing appropriate values for I_B and V_{CC}, a bias point in the active region is found (e.g. P_0 in Fig. 1, the load line is the one of R). Around this point, the collector-emitter voltage is varied by modulating V_{CC} with a signal v_{cc}. Since this is a small signal operation, it suffices to study the small signal equivalent circuit, see Fig. 2, where the transistor has been substituted with a frequency dependent differential resistance ($\Re(f)$). Using ordinary voltage division the magnitude of v_c, V_c, is found as:

$$V_c = V_{cc} * \frac{\Re(f)}{R+\Re(f)} \qquad (2)$$

Since $\Re(f)$ can be negative, V_c can be greater than V_{cc}. At low frequencies this is the case and a schematic describing this process can be seen in Fig. 1(c). When modulating with higher frequencies, the signal changes in shorter times than τ_T and the junction temperature stays essentially constant. There is thus no longer a thermally induced negative differential resistance and the electronically induced positive differential resistance prevails, instead attenuating the signal, see schematic in Fig. 1 (d). Plotting V_c versus frequency in a Bode diagram, see Fig. 3, allows extraction of τ_T from the higher characteristic frequency by finding its 3 dB-point, assuming the device has no other time constants in the same order of magnitude as the one of τ_T.

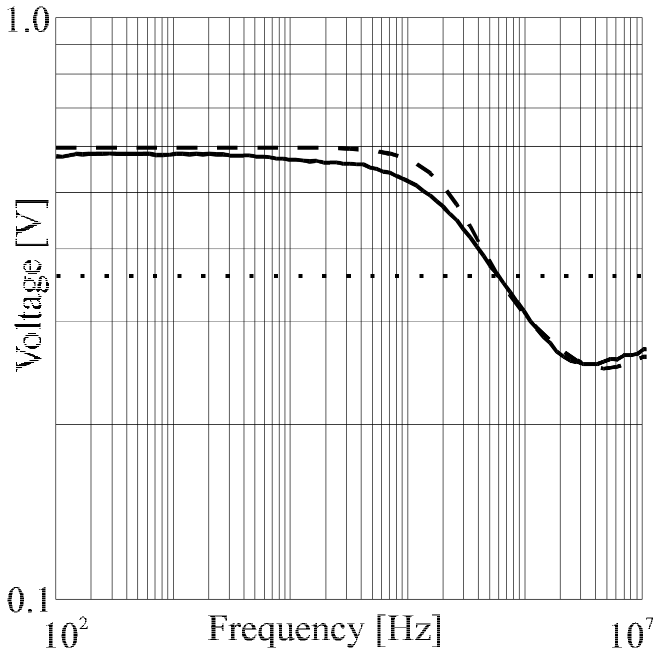

Fig. 3 Bode diagram of measured (full line) and calculated (dashed line) output signal magnitude, V_C, versus frequency. Low frequencies denote the steady state mode and high frequencies denote the transient mode. The dotted straight line corresponds to amplitude of fed small signal amplitude (V_{cc} in Fig. 2).

To achieve higher accuracy, an electrothermal model of the device can be used. Such a model has been developed and shown to accurately model SiGe HBTs from DC upto millimetre-wave frequencies [4]. It uses a modified Ebers-Moll model where the different physical processes occuring in the device are as closesly as possible modelled with lumped elements. Electron and hole injection are here treated separately using different diodes which gives an efficient way of modelling the temperature dependence of β.

To model junction heating from internal power dissipation, an RC-network has been used in the model [4] where current and voltage drop has been related to internal power dissipation and device heating respectively. A thermal resistance (R_T) relates to the steady-state part and a thermal capacitance (C_T) relates to the transient part of the device heating. Together, these two parts define τ_T. The thermal resistance can be found either by direct extraction [5] or by fitting to a measured IV-curve. Using the electrothermal model in a setup like in Fig. 2, it is possible to fit C_T to the measured curve and from this calculate τ_T. The Harmonic Balance simulation method was chosen in order to have the same signal levels as in the measurement and thus facilitate the fitting procedure.

Measurements and verification

To verify the validity of this method, Si/SiGe HBTs with area of 1x20 μm^2 and 5x20 μm^2 were measured with the setup described above and C_T was extracted. A measured and simulated curve of V_c versus frequency for a device with an area of 5x20 μm^2 can be seen in Fig. 3. Due to parasitic reactances between the base and collector pads, the attenuation at higher frequencies was affected, but this has been accurately modeled and accounted for.

A measurement in the time domain of the 5x20 μm^2 device was performed using a setup like in Fig. 2. The device was fed a constant base current. A large-signal voltage step increased the power dissipation of the device and the large signal output, v_C, was then measured. From this resulting signal, a temperature dependent collector current was calculated. Using simulations with the extracted thermal capacitance, we find excellent agreement with the experiment in the temporal response.

Conclusion

A method to find the thermal time constant utilising small signal measurements in the frequency domain has been presented. Using an electrothermal model of an HBT, the method has been verified.

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