Investigation of Shot Noise Reduction in InGaP HBTs with different Base Thickness

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Abstract. DC, AC characteristics and Noise parameters of InGaP/GaAs HBTs with base thicknesses of w_B/nm=90, 70, 50 as well as CCHBTs with w_B=90 nm, were measured and modeled using advanced compact model HICUM. Very good agreement of HICUM versus measured data was observed for AC and DC data. Significant base thickness reduction only slightly increases peak transit frequency f_T /GHz =(45 (90nm), 54 (50nm)) due to reduced base transit time. High speed performance is mainly controlled by nonequilibrium electrons which form minority carrier jam in B/C SCR and thus additional delay. Significant increase of f_T /GHz =60 (90nm) was observed for CCHBTs, which feature lower collector internal resistance and smaller delay in B/C SCR. Therefore measured NF_{min} of different w_B HBTs did not exhibit expected difference, in contrast to CCHBTs, which demonstrated significantly lower NF_{min}. Our analytical noise model clarified that strong shot noise reduction in $A_{III}B_V$ is stemming not only from correlated currents, but also from Coulomb blockade by nonequilibrium electrons.

INTRODUCTION

The physical mechanism for shot noise in p-n junctions is based on thermal fluctuations of minority carriers, which produces a disturbance in the minority carrier distribution, resulting in diffusion current fluctuations [1],[2]. Bipolar transistors, having two p-n junctions, exhibit base and collector current shot noise, which are correlated. The cross-correlation noise of base and collector current is defined by $S_{CB} = 2qI_C(j\omega(\tau_B/3))$, where τ_B is the delay time in the base due to minority carrier drift-diffusion [1]. Thus for HBT noise performance the base transit time is of great importance. The diffusion coefficient of electrons for GaAs is $D_e \cong 200(cm^3/s)$. Therefore, following $\tau_B = w_B^2/(2D_e \cdot \vartheta) + w_B/v_T$ [3], where w_B is base layer thickness, ϑ is a factor, that depends on the built in electric field, and $v_T = \sqrt{((2k_BT))/\pi \cdot m_e^x}$ is the drift velocity with m_e^x as effective mass, the evaluated base transit time is $\tau_B \cong 200fs$ for 90 nm base HBT, if only diffusion processes considered. If τ_B is the major cause for the E/C delay, then this implies f_T>750 GHz for an ideal transistor, it is not the case in reality. Actually, in $A_{III}B_V$ HBTs electrons are injected across a conduction band barrier, which reduces the base transit time. Drift diffusion simulations, accounting for bandgap discontinuity, show that τ_B reduction due to injection across the barrier is significant only for very narrow base ($w_B = 30nm$) HBTs [4]. Velocity saturation in $A_{III}B_V$ HBTs increases τ_B, but not very significantly, (14% for $w_B = 50nm$ and only 8% for $w_B = 100nm$ [5]). In the total E/C delay $\tau_{EC} = \tau_E + \tau_B + \tau_C + \tau_{CC}$, where τ_E is

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emitter charging time, collector transit time $\tau_C = w_{BC}/(2v_S)$ plays an important role. v_S is saturation velocity, and $\tau_{CC} = (R_E + R_C + \eta \cdot k \cdot T/(q \cdot I_C))C_{jC}$ is collector charging time, where C_{jC} is B/C junction capacitance. Electrons in $A_{III}B_V$ HBTs can gain enough energy from electric field and suffer Γ-L intervalley transfer. Higher effective mass and thus reduced mobility and drift velocity in L valley gives rise to τ_C [6],[7]. Since cross-correlation of base and collector shot noise in noise model [1] is described via transit time, experimental high frequency noise investigation of different base thickness and collector composition in $A_{III}B_V$ HBTs can reveal current transfer peculiarities and their impact on DC, scattering and noise parameters. In this work we have investigated an impact of base thickness and collector composition in InGaP HBTs on DC, f_T and noise parameters.

EXPERIMENTAL, RESULTS AND DISCUSSION

DC, AC and Noise parameters were measured on a set of InGaP/GaAs HBTs with the base thicknesses and concentrations of (w_B /nm, N_A /cm^{-3})=(90, 5.5e19), (90, 4.5e19), (70, 5e19), (50, 5.5e19), (50, 5.5e19). High-frequency test transistors with various configurations were realized on a test chip along with adequate de-embedding structures. Composite collector (CCHBTs) with w_B=90 nm were measured as well. Transistors presented in this paper have a CBE contact configuration (i.e. 1 emitter, 1 base and 1 collector) with emitter window areas (W*L) of A_{E0} / μm^2=2.2*2.2, 2.2*4.4, 2.2*8.8, 2.2*22, 2.2*44 and were fabricated at Skyworks Solutions. Noise and *s*-parameters were measured with ATN NP5 noise system and HP8510C VNA, using Suss Microtech semiautomatic RF-probestation and "Probebench" software in a 2-26 GHz frequency range. Careful de-embedding of pad parasitics was performed using a 2-step method and, for the noise parameters, employing correlation matrix technique. DC, S- and noise parameters were simulated using advanced compact model HICUM in Agilent ADS2004A and Aplac 8.0 simulator. Noise parameters were also simulated employing our recently derived analytical model (An) [8], [9].

Measured and simulated $J_C(V_{CE})$ and $J_C(V_{BE})$ are in a good agreement for all measured devices. Despite higher but less scattered NF_{min} data, HBTs with larger emitter area A_{E0} =2.2*8.8 [μm^2] have been chosen for the analysis. $J_C(V_{CE})$ of HBT with w_B=90 nm is presented in Fig.1a. HICUM, accounting for selfheating and other physical effects, yields good fit. HBTs with w_B=50 nm, exhibited higher current gain, as it is seen from Fig.1b. Output current density of w_B=50 nm HBT for a given fixed I_B was higher (J_C=0.9 mA/μm^2 @ I_B=80 μA). Composite collector HBTs with w_B=90 nm at I_B=80 μA returned slightly higher J_C=0.46 mA/μm^2 in comparison to conventional w_B=90 nm HBT. Note, that HICUM is in agreement with forward Gummel plot for all devices as well. Base thickness reduction from 90 nm down to 50 nm increases f_T by 18% only (Fig.2a). Simulation of $\tau_B = w_B^2/(2D_e \cdot \vartheta) + w_B/v_T$ shows, that such w_B decrease, even with included velocity saturation term, implies ~70% of f_T change [10]. This means that τ_B itself is not a limiting factor of high frequency behavior for $A_{III}B_V$. Collector transit time $\tau_C = w_{BC}/(2v_S)$ due to saturated drift velocity and impact of Γ-L transfer becomes important. It is obvious from the rapid increase to f_T=59 GHz in CCHBTs, for which collector is designed to avoid the electron jam. HICUM analysis indicates that peak f_T increase towards higher J_C is due to

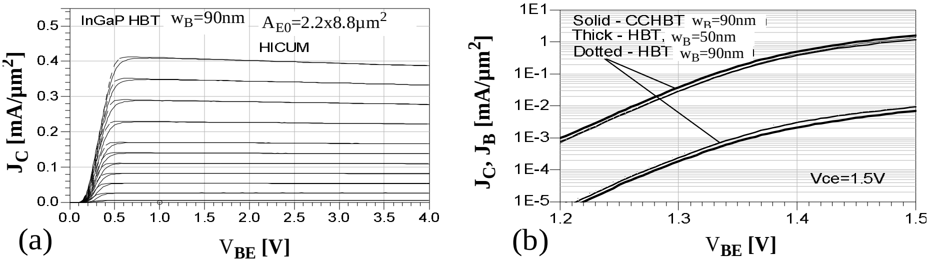

FIGURE 1. (a) $J_C(V_{CE})$ for 90 nm HBT, solid line is measured fixed I_B /μA=1, 5, 10, 20-80, dotted line is HICUM, (b) Measured J_C, $J_B(V_{BE})$ for w_B/ nm=90, 50 and CCHBT w_B= 90 nm.

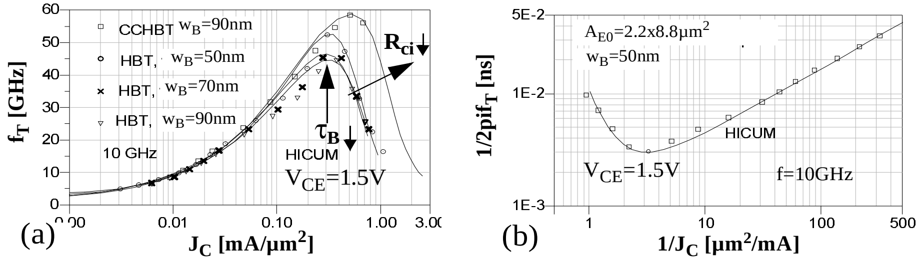

FIGURE 2. (a) Measured (symbols), HICUM (lines) $f_T(J_C)$, (b) $1/2\pi\ f_T(1/J_C)$ for w_B=50 nm.

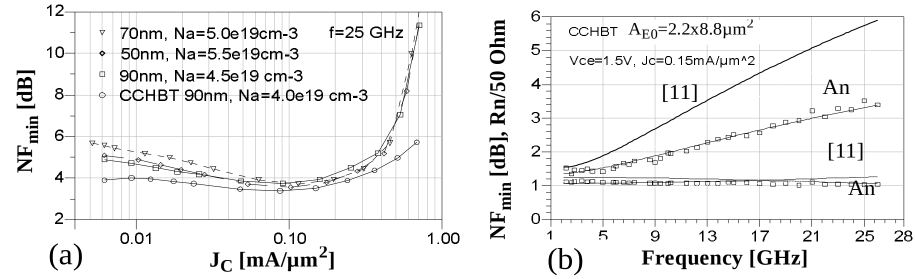

FIGURE 3. (a) Measured NF_{min} (J_C,w_B), (b) measured and simulated NF_{min} with An [8], [9] and with [11].

lower internal collector resistance R_{Ci}. Taking into account that the base resistance increase for w_B=50 nm HBT is negligible [12], the combination of reduced base thickness with composite collector technology should improve device speed and noise performance. The total delay time τ_f can be extracted from the dependence $\tau_f = (1/(2\pi f_T)) - C_{B\upsilon}/g_m$ [13], where $C_{B\upsilon}$ is sum of capacitances at the base node, $g_m = I_C/(m_C \cdot V_T)$ and m_C is non ideality factor, Fig.2b. Actually τ_f is very close to the sum of all EC delay times τ_{EC}. Since τ_E is negligible and $\tau_{CC} \cong 50fs$ is rather small in comparison to τ_B and τ_C, for noise simulations as a delay time we can use

$\tau_f/3$. The comparison of $NF_{min}(J_C)$ (Fig.3a) shows that base thickness reduction only slightly influence noise properties at 25 GHz, while CCHBTs even with w_B=90 nm exhibit an improved $NF_{min}(J_C,f)$. Using HICUM analysis all HBT circuit parameters, including bias dependent, were obtained and used for NF_{min} simulation with analytical noise model [8],[9]. Simulated $NF_{min}(f)$ for CCHBT with An approach (Fig.3b) shows that base and collector cross-correlation with a delay parameter $\tau_f/3$ fairly well fits measurement. High reduction of NF_{min} is observed in a wide J_C. Extracted correlation coefficient at high frequency exceeds "1" indicating an additional noise reduction mechanism, arising in BC SCR. Accumulated charge blocks electron transfer through the base so reducing collector shot noise [14]. Analytical model fairly well accounts for this effect with the additional delay time τ_C.

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