

# Investigation of electron delay in the base on noise performance in InGaP heterojunction bipolar transistors

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The DC, RF and noise characteristics of InGaP/GaAs heterojunction bipolar transistors (HBTs) with different base layer widths and  $\delta$ -doped layer in the collector were investigated. Analysis of the RF and noise characteristics revealed that the high frequency noise of these HBTs is reduced due to cross-correlation of shot noise sources and Coulomb blockade from accumulated charge. The measured noise performance is in a good agreement with the HICUM L2 compact model [M. Schroter, IEICE Trans. Electron. **E88-C**, 1098 (2005)] when correlated shot noise sources with Fano factor for collector shot noise are included.

InGaAs	N	$>1 \times 10^{19}$	100 nm	
GaAs	N	$5 \times 10^{18}$	120 nm	
InGaP	n	$3 \times 10^{17}$	40 nm	
GaAs	p+	$N_A$	50, 70, 90 nm	
GaAs	n	$3 \times 10^{16}$	30 nm	
Spike	n	$2 \times 10^{18}$	5 nm	
InGaP	n	$3 \times 10^{16}$	10 nm	
GaAs	n	$3 \times 10^{16} / 7.5 \times 10^{15}$	155/400 nm	
GaAs	n	$5 \times 10^{18}$	1000 nm	

Doping and content profiles of the investigated InGaP HBTs.

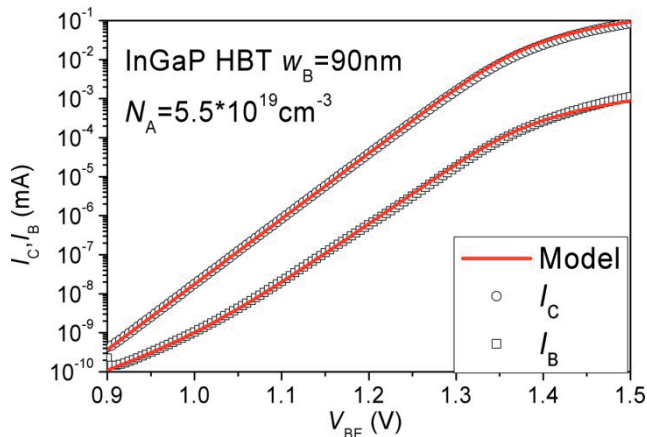
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**1 Introduction** Modern InGaP/GaAs heterojunction bipolar transistors (HBT) demonstrate excellent microwave and high-speed performance due to high carrier mobility and bandgap engineering. They have found a niche in wireless and optical electronics in spite of higher wafer fabrication costs and lower integration level compared to Si/SiGe technology [1, 2]. State of the art III–V HBTs have a cut-off frequency ( $f_T$ ) exceeding 600 GHz [3]. In a thin base ( $w_B < 90$  nm) HBT, the signal delay takes place mainly in the base and the base/collector (B/C) region where the electron transport is also quasi-ballistic [4, 5]. Thus  $f_T$  is expected to be higher for a thinner base width HBT. However, the base resistance ( $R_B$ ) increases as  $w_B$  shrinks resulting in compromised power gain and noise performance. Therefore a higher base doping is required to maintain low sheet resistance.

In III–V HBTs a space charge accumulated in the B/C region can introduce additional signal delay at high current densities [6], resulting in a decrease of  $f_T$  and degraded noise performance [7]. In a compound collector HBT (CCHBT) [8], an additional heavily  $\delta$ -doped layer in the collector region near to the base helps to get rid of the undesirable charge accumulation at high injection currents [9]. Therefore an improved noise performance in CCHBTs is expected.

It is well known that the minimal noise figure ( $NF_{\min}$ ) of HBTs is reduced due to the cross-correlation of base and collector current shot noise. The cross-correlation is described via a delay time approach. This might not be applicable to the thin base HBTs because of the quasi-ballistic electron transport.

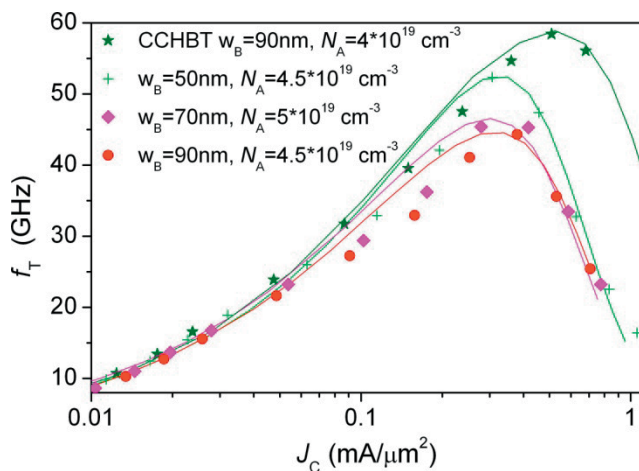
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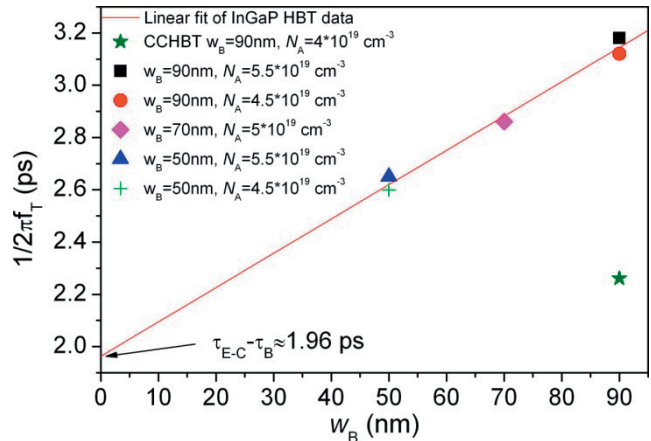
**Figure 1** (online colour at: [www.pss-rapid.com](http://www.pss-rapid.com)) Forward Gummel plot for InGaP/GaAs HBTs, symbols: measured data, line: HICUM,  $V_{BC} = 0$ .

This Letter demonstrates that the cross-correlation of the shot noise sources in thin base HBTs in terms of noise delay time [7] does not adequately describe the noise performance of InGaP-based HBTs. Investigation of different base width devices reveals the impact of carrier delay in the base on RF and noise behaviour. In addition, investigating similar HBTs with a compound collector enables the impact of accumulated collector charge on noise and RF behaviour to be determined.

**2 Devices and measurement setup** The investigated InGaP/GaAs HBTs have different base doping levels  $N_A$  ( $4.5\text{--}5.5 \times 10^{19} \text{ cm}^{-3}$ ) and base widths  $w_B = 50 \text{ nm}$ ,  $70 \text{ nm}$ ,  $90 \text{ nm}$  and are compared with an InGaP CCHBT ( $N_A = 4 \times 10^{19} \text{ cm}^{-3}$ ,  $w_B = 90 \text{ nm}$ ) (Fig. in abstract). Noise and  $s$ -parameters were measured in the 2–26 GHz frequency range with a Maury ATS tuner system, Agilent



**Figure 2** (online colour at: [www.pss-rapid.com](http://www.pss-rapid.com)) Cut-off frequencies  $f_T$  vs. collector current densities for InGaP HBT with different base widths and for CCHBT. Symbols are measured data, lines are HICUM.



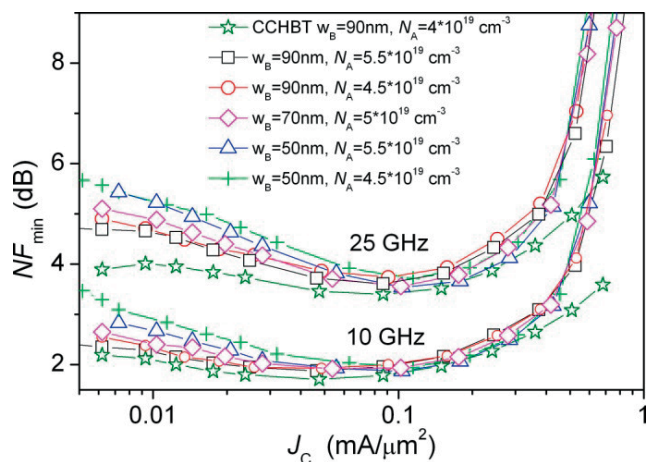
**Figure 3** (online colour at: [www.pss-rapid.com](http://www.pss-rapid.com)) Extrapolated emitter–collector transit time  $\tau_{E-C}$  vs. base width for the investigated InGaP HBTs at  $V_{CE} = 1.5 \text{ V}$ .

PSA E4448A, PNA 8364B and Sues Microtech probe-station PM8.

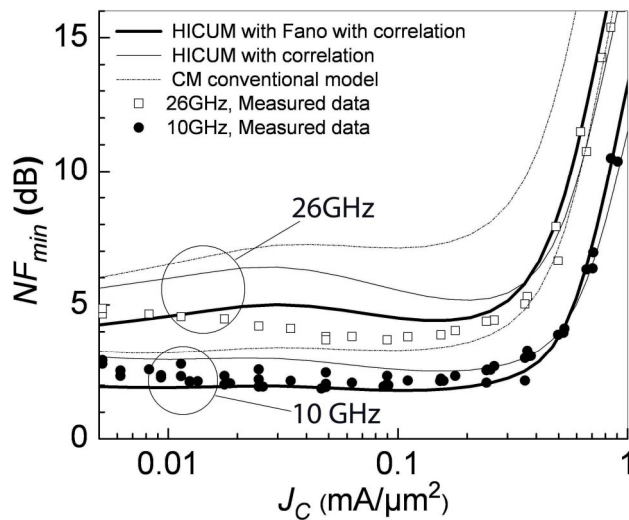
**3 Results and discussion** The compact model (CM) HICUM/L2v2.23 [10] (HICUM = high-current model) was used for the verification of DC (Fig. 1) and RF standard characteristics (Fig. 2). The frequency performance of InGaP CCHBTs was better than that of conventional InGaP HBT with the same base layer thickness (cf. Fig. 2). For conventional InGaP HBTs, the cut-off frequency slightly increases with the base width decrease (Fig. 2, circles, diamonds, and crosses).

The electron emitter–collector transit time  $\tau_{E-C}$  is determined from

$$\tau_{E-C} = \frac{1}{2\pi f_T} \quad (1)$$



**Figure 4** (online colour at: [www.pss-rapid.com](http://www.pss-rapid.com)) Minimum noise figure  $NF_{min}$  vs. collector current density  $J_C$  for the investigated InGaP HBTs.



**Figure 5**  $NF_{\min}$  vs.  $J_C$  for an InGaP HBT with  $w_B = 90$  nm, symbols: measured data, lines: HICUM,  $\gamma = 0.34$ .

The dependence of  $\tau_{E-C}$  on the base width and doping is shown in Fig. 3 and a weak increase with base doping is observed (circle and square). Ignoring the base doping contribution, a linear extrapolation yields  $\tau_{E-C} - \tau_B$  where  $\tau_B$  is base transit time. Assuming the base is the only variable (emitter and collector doping and thicknesses are the same), the values of  $\tau_B$  can be estimated:  $\tau_B \sim 1.1$  ps for HBTs with  $w_B = 90$  nm and  $\tau_B \sim 0.6$  ps for HBTs with  $w_B = 50$  nm.

The measured data in Fig. 3 confirm the theoretically expected linear dependence of the measured emitter–collector transit time on the base width (Fig. 3) for quasi-ballistic electron transport. The electrons injected into the base through the E/B heterojunction acquire additional kinetic energy due to the conduction band offset.

However, in the B/C space charge region the electrons acquire additional energy to be able to be transferred from the  $\Gamma$  valley to the L or X valleys where the effective mass is higher and the drift velocity is lower. This inter-valley transfer is in part responsible for the electron jam. The space charge of the jammed electrons introduces additional signal delay. If a  $\delta$ -doped layer is used (CCHBT) a significant decrease of the emitter–collector transit time by  $\sim 0.9$  ps is obtained (Fig. 3, star). The accumulated charge effectively recombines at the  $\delta$ -doped layer in the B/C region.

A surprisingly small dependence of  $NF_{\min}$  versus  $w_B$  was obtained according to Fig. 4. At lower  $J_C < 0.1$  mA/ $\mu\text{m}^2$ , the difference of  $NF_{\min}$  is due to different base resistances, but curves for different  $w_B$  and  $N_A$  converge as  $J_C$  increases. The HBT with  $w_B = 50$  nm shows only a slight improvement in  $f_T$  and  $NF_{\min}$  while the short base supports higher current gain which usually implies a lower  $NF_{\min}$ . If  $\tau_B$  were the main contributor to  $\tau_{E-C}$ , the  $NF_{\min}$  would have

been strongly dependent on  $w_B$ . The experimental results show that the base transit time is not the main cause for the noise performance in III–V HBTs.

The InGaP CCHBT demonstrates a lower  $NF_{\min}$  compared to the conventional HBT of similar base width. The charges accumulated in the B/C and collector regions establish an additional delay and reduce  $NF_{\min}$ . The composite collector improves  $f_T$  and  $NF_{\min}$  because of the partial washout of the jammed electrons.

We assume that Coulomb shot noise blockade by the accumulated charge in the collector region is a significant factor for reduction of collector current shot noise [11]. The dotted curve in Fig. 5 illustrates the effect of the Fano factor ( $\gamma$ ) that enters the expression for the spectral density of collector current noise power,

$$S_{I_c} = 2 \cdot q \cdot I_c \cdot \gamma, \quad (2)$$

where  $q$  is an elementary charge,  $I_c$  is the collector current. HICUM with implemented correlated noise model [12] and with introduced Fano factor ( $\gamma = 0.34$ ) shows very good agreement with experimental data (Fig. 5).

**4 Conclusions** The HICUM/L2v2.23 model with implemented cross-correlation together with an introduced Fano factor yields very good agreement with measured noise data in a large frequency and bias range. Coulomb blockade of shot noise is assumed to be among the main factors reducing and shaping  $NF_{\min}$  in InGaP HBTs.

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