InP HBT Digital ICs and MMICs in the 140-220 GHz band

Mark Rodwell, Z. Griffith, V. Paidi, N. Parthasarathy, C. Sheldon, U. Singisetti
ECE Department, University of California, Santa Barbara, 93106, USA,

M. Urteaga, R. Pierson, P. Rowell, B. Brar
Rockwell Scientific Company, Thousand Oaks, CA 91360, USA

Abstract

Well-balanced InP HBTs now have ~450 GHz cutoff frequencies and ~4 V breakdown. With such devices, 150 GHz digital circuits (static dividers) and 175 GHz amplifiers have been demonstrated. We discuss device requirements (scaling laws and scaling limits) for realizing transistors and both digital and analog/RF circuits at sub-mm-wave frequencies; the most critical limitations are metal/semiconductor contact resistivities and dissipated power densities. Given present contact performance and thermal design, 200 GHz digital technologies and 300 GHz power amplifiers are now feasible and will soon be realized.

Sub-mm-Wave Transistors: Present & Future

Radios, imaging systems, and radars today employ transistor circuits only at low mm-wave frequencies, with higher frequencies served by Schottky diodes, vacuum electron devices, and gas lasers. Travelling-wave vacuum devices offer much higher output power than transistors, lasers offer a much wider frequency range, and both lasers and bolometers offer lower noise. Despite these disadvantages, transistors offer key attributes which motivate us to extend their operation to sub-mm-wave frequencies. Transistors are very small, are efficient power amplifiers, and can be very reliable. Unlike diodes, THz tubes and lasers, transistors serve many functions, including amplifiers, oscillators, mixers, harmonic multipliers, switches, and logic gates. With transistors, one can compactly construct a wealth of important communications circuits, including PLLs and frequency synthesizers, monolithic frequency multiplier chains, QAM (de)modulators, superheterodyne receivers, and monolithic phased arrays.

Today (Figure 1) InP transistors, both HEMTs and HBTs, obtain balanced ($f_\tau \approx f_{\max}$) cutoff frequencies slightly below 500 GHz. HEMTs and HBTs are complementary: HEMTs exhibit much lower noise for receivers while HBTs provide faster digital circuits and have higher breakdown hence serve better in power amplifiers and in ADCs and DACs. Breakdown is such that a 450-GHz - f_τ HBT can produce a 4-V signal (Figure 1)

Transistor bandwidth is increased by scaling (Table 1). A γ :1 increase in HBT bandwidth is accomplished by a γ :1 reduction in the collector and a $\gamma^{1/2}$:1 reduction in the base layer thicknesses, a $\sim\gamma^2$:1 reduction in the emitter and collector junction widths, a $\sim\gamma^2$:1 increase in the current density, and a $\sim\gamma^2$:1 reduction in the emitter contact resistivity. Base contact resistivity scaling requirements depend upon the collector-base junction geometry. Table 1 shows illustrative HBT designs for 150 GHz through 300 GHz digital clock rates.

Contact resistivities and thermal resistance are the key limits to further improvements in high frequency transistors. A 125-nm scaling generation (Table 1) HBT suitable for ~300 GHz digital clock rate and ~600 GHz power amplifiers ($f_{signal} / f_{\max}$ ~2/3) requires ~5 $\Omega - \mu$m^2 contact resistivities and must operate at ~40 mW/μm^2 power density, requiring < 3-4 K - μm^2 / mW thermal resistance. Advanced fabrication processes (pedestal implants, emitter regrowth) ease these requirements.

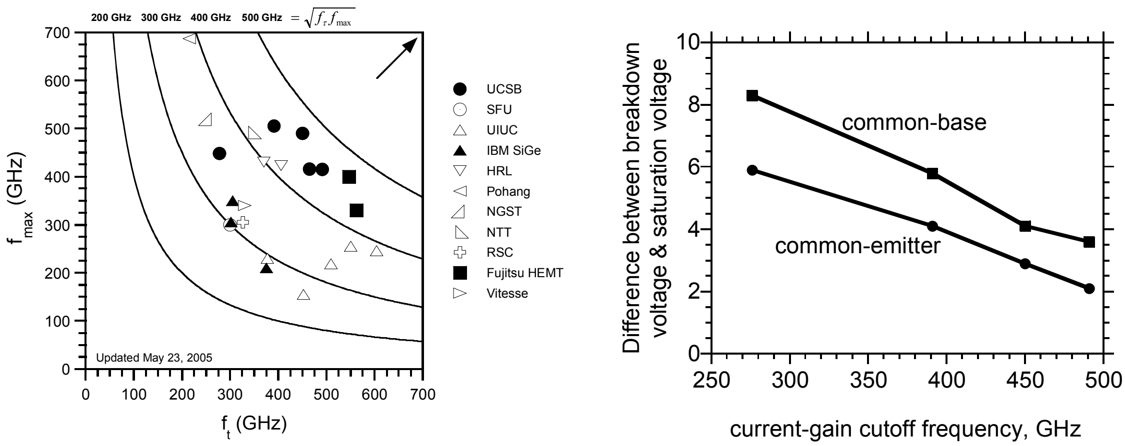
Results

Present results with 500-nm scaling generation HBTs include 450 GHz f_τ and 490 GHz $f_{\max}$, and 150 GHz digital benchmark circuits (static frequency dividers). 172 GHz medium-power amplifiers have been realized with 300-GHz-$f_{\max}$ HBTs; we are now designing 300 GHz amplifiers using our present 490 GHz $f_{\max}$ HBTs.

[1] Z. Griffith *et al*, "Transistor and Circuit Design for 100-200 GHz ICs", IEEE Journal Of Solid-State Circuits, Vol. 40, No. 10, October 2005.
[2] Z. Griffith *et al*, “Ultra high frequency static dividers > 150 GHz in a narrow mesa InGaAs/InP DHBT technology”, IEEE Bipolar/BiCMOS Circuits and Technology Meeting, Montreal, Canada, September 13-14, 2004, pp. 176-179.
[3] Vamsi K. Paidi *et al*, "G-band (140-220-GHz) and W-band (75-110-GHz) InP DHBT Power Amplifiers", IEEE Transactions on Microwave Theory and Techniques, vol. 53, no. 2, February 2005.
[4]M.J.W. Rodwell *et al*, “Submicron Scaling of HBTs” IEEE Trans. on Electron Devices, Vol. 48, pp. 2606-2624, November 2001.

Parameter	scaling law	Gen. 2	Gen. 3	Gen. 4
MS-DFF speed	γ^1	158 GHz	230 GHz	330 GHz
Emitter Width	$1/\gamma^2$	500 nm	250 nm	125 nm
Resistivity	$1/\gamma^2$	15 Ω-μm^2	7.5 Ω-μm^2	5 Ω-μm^2
Base Thickness	$1/\gamma^{1/2}$	300Å	250 Å	212 Å
Doping	γ^0	7 10^{19}/cm^2	7 10^{19}/cm^2	7 10^{19}/cm^2
Sheet resistance	$\gamma^{1/2}$	500 Ω	600 Ω	707 Ω
Contact ρ	$1/\gamma^{1/2}$	20 Ω-μm^2	10 Ω-μm^2	5 Ω-μm^2
Collector Width	$1/\gamma^2$	1.1 μm	0.54 μm	0.27 μm
Thickness	$1/\gamma$	1500 Å	1060 Å	750 Å
Current Density	γ^2	5 mA/μm^2	10 mA/μm^2	20 mA/μm^2
$A_{collector}/A_{emitter}$	γ^0	2.8	2.8	2.8
f_τ	γ^1	371 GHz	517 GHz	720 GHz
$f_{\max}$	γ^1	483 GHz	724 GHz	1.06 THz
I_E / L_E	γ^0	2.4 mA/μm	2.4 mA/μm	2.4 mA/μm
τ_f	$1/\gamma$	340 fs	250 fs	170 fs
C_{cb} / I_c	$1/\gamma$	440 fs/V	310 fs/V	220 fs/V
$C_{cb}\Delta V_{\text{logic}} / I_c$	$1/\gamma$	130 fs	94 fs	66 fs
$R_{bb} /(\Delta V_{\text{logic}} / I_c)$	γ^0	0.66	0.51	0.41
$C_{je}(\Delta V_{\text{logic}} / I_C)$	$1/\gamma^{3/2}$	350 fs	250 fs	180 fs
$R_{ex} /(\Delta V_{\text{logic}} / I_c)$	γ^0	0.24	0.24	0.24

Table 1: Device scaling laws, and illustrative HBT designs for 150 GHz through 300 GHz digital clock rates.



a) b)

Figure 1: InP DHBT Technology. (a) Recent results (b) DHBT maximum voltage swing as a function of device f_τ .

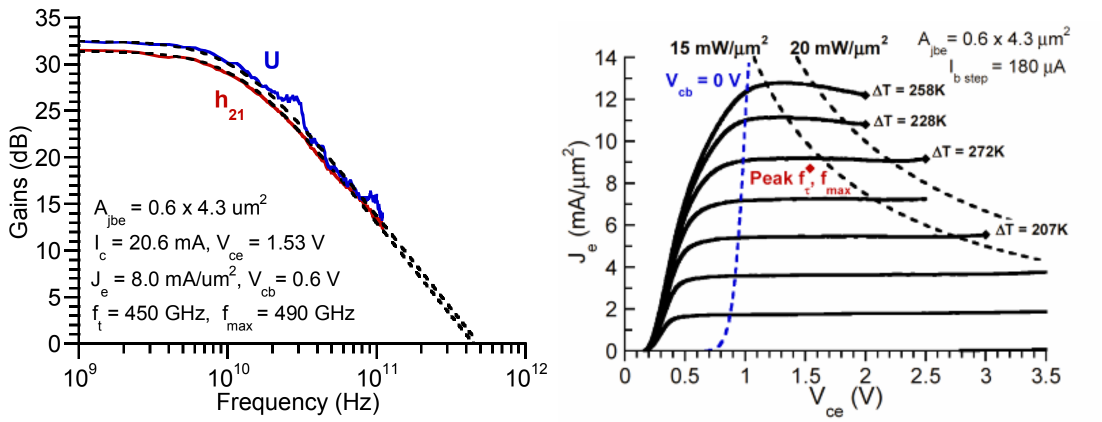


Figure 2: DC and RF characteristics of and InP DHBT 120 nm collector thickness.-common-emitter breakdown is 3.9 V.

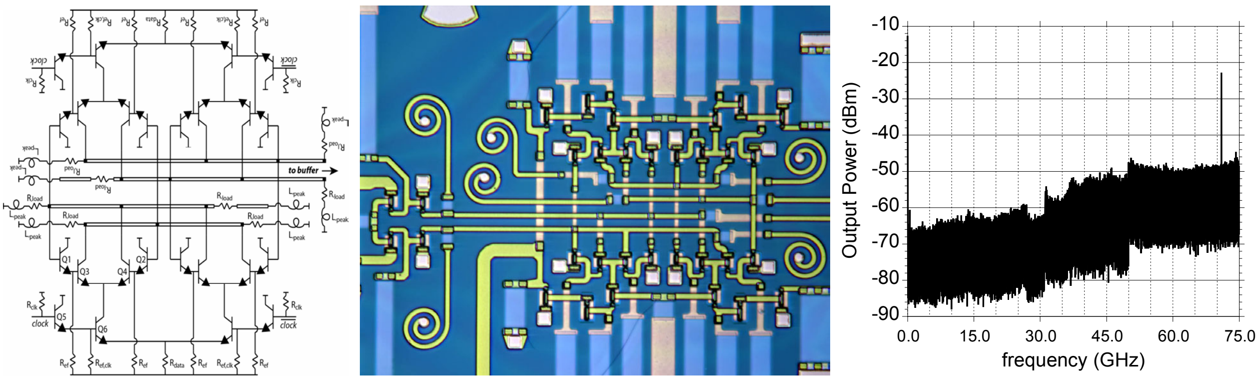


Figure 3: Static frequency divider schematic diagram, IC photograph and output spectrum at 142 GHz input.

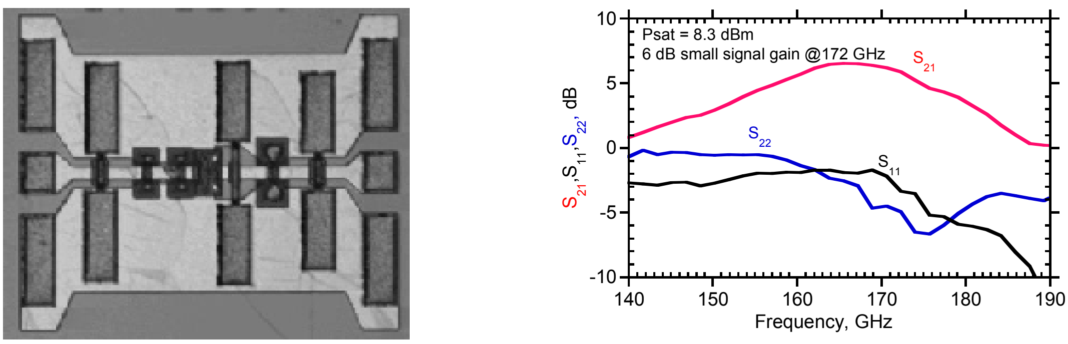


Figure 4: Common-base DHBT medium-power amplifier at 172 GHz