THz InP Bipolar Transistors- Circuit Integration and Applications

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***Abstract* — Highly-scaled Indium Phosphide (InP) transistor technologies have bandwidths extending into the terahertz (THz) frequency regime (0.3-3 THz). The high transistor bandwidth can be exploited to both extend circuit operation to THz frequencies and improve system performance at millimeter wave and sub-millimeter wave frequencies. InP heterojunction bipolar transistor (HBT) technologies offer wide bandwidths, high RF power handling and the capability to realize high levels of integration. We review integrated circuit (IC) results from Teledyne's InP HBT technologies that span frequencies from 60 GHz to >600 GHz focusing on performance benefits and applications.**

***Index Terms* — InP HBT, terahertz, millimeter wave, sub-millimeter wave, power amplifiers.**

I. INTRODUCTION

THz transistor bandwidths are achieved in the InP material system by combining the advantageous material properties of InGaAs and InP (high electron mobilities in both quantum-well channels and p-doped bases, large heterojunction offsets for carrier confinement, and high achievable doping levels for low Ohmic contact resistivities) with scaled transistor design and sophisticated fabrication techniques. Both field-effect high electron mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs) have been demonstrated with maximum frequencies of oscillation (f_{max}) exceeding 1 THz [1] [2]. Integrated circuit technologies have been matured to permit the demonstration of THz monolithic integrated circuits (TMICs) at increasing frequencies with increasing levels of complexity. The first demonstration of solid-state amplification at >1 THz was reported from a 25 nm InP HEMT technology [3]. Fully integrated single-chip transmitter and receiver ICs have been demonstrated at 600 GHz in an InP HBT technology [4].

At millimeter wave (mmWave) and sub-millimeter wave (sub-mmWave) frequencies, transistor bandwidths that far exceed the targeted operating frequency enable improvements in IC dynamic range and can lower prime power dissipation. Reduced noise figure, increased power added efficiency and larger fractional bandwidths can be obtained by incorporating THz bandwidth transistors.

In this paper, we review integrated circuits demonstrated in Teledyne's THz bandwidth InP HBT IC technologies. Results include: THz integrated circuits operating to > 600 GHz, sub-mmWave power amplifiers with record output powers at G-band (140-220 GHz) and ultra-low power W-band transceiver components.

II. THZ INP HBT IC TECHNOLOGIES

HBT bandwidths are increased through transistor scaling [5]; whereby the devices vertical and lateral dimensions are reduced with concurrent reductions in Ohmic contact resistivities and an increase in peak operating current density (normalized to junction area). At Teledyne, our InP HBT technology has been successively scaled from 500 nm through 130 nm technology nodes [6-8], where the technology node refers to the emitter junction width. The technologies share a common base-emitter process flow that utilizes an electroplated emitter contact with dielectric sidewall spacers. These features permit the formation of a high-yield self-aligned base contact in close proximity to the emitter. Details of the HBT process flow have been reported elsewhere [4].

THz frequency integrated circuit operation has been demonstrated in both the 250 nm and 130 nm technology nodes. The 250 nm technology demonstrates typical peak transistor figures-of-merit f_t/f_{max} of 400 GHz/700 GHz. The transistors have a common-emitter breakdown voltage BV_{CEO} =4.5 V and support high output power densities. The technology has been used extensively in mmWave and sub-mmWave power amplifier designs. RF power densities of > 2 W/mm normalized to emitter *length* have been demonstrated at W-band in this technology [9].

The 130 nm technology has RF figures-of-merit f_t/f_{max} of 520 GHz/1.15 THz, when biased for peak f_{max}. The HBTs exhibit a common-emitter breakdown voltage BV_{CEO} = 3.5 V and can support collector current densitites J_C > 30mA/μm^2, normalized to the emitter junction area. Fig. 1 shows representative common-emitter IV curves for a 130 nm HBT and measured extrapolated values of f_t and f_{max} versus bias.

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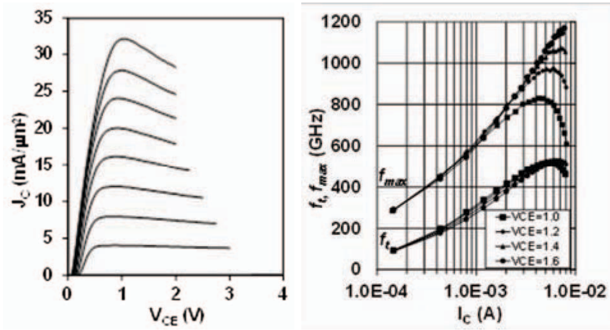

Fig. 1. (left) Common-emitter IV characteristics of 130 nm InP HBT (right) extrapolated RF figures-of-merit f_t and f_{max} versus bias for 0.13 x 2μm^2 HBT.

Transistors are integrated in a multi-level backend-of-line wiring environment that utilizes electroplated Au-based metallization and a spin-on benzocyclobutene (BCB, ε_r= 2.7) interlayer dielectric (ILD). A 3- or 4-level wiring stack with 2 μm ILD thicknesses is typically used for digital and mixed-signal ICs. A modified process with a thicker (>5μm) top-most dielectric has also been developed to provide low-loss microstrip for mm-wave and THz circuit applications.

Circuit designs typically use top-side thin-film transmission line wiring, and we have found that this type of wiring can be well-modeled with electromagnetic simulation to frequencies > 600 GHz. For IC packaging, wafer thinning and through-substrate vias (TSVs) are still required for control of substrate modes. Wafers are thinned to 50 μm or 75 μm with TSVs and backside metallization.

Integrated circuit design is supported by large-signal HBT models that utilize the Keysight III-V HBT model [10]. This model can accurately capture HBT bandwidth variation versus bias arising from non-equilibrium transport effects in the collector; such effects are difficult to model with standard Si BJT models. We have generally seen good agreement with simulated results for both small-signal and large-signal measurements on fabricated MMICs up to frequencies approaching the transistor cutoff frequencies.

III. THz Integrated Circuits

At the 250 nm technology node, InP HBT-based ICs have been demonstrated operating above 300 GHz. Results include fundamental oscillators operating to 570 GHz [11] and power amplifiers at 300 GHz with 20 mW saturated output power [12]. The 130 nm technology has demonstrated fundamental signal generation and amplification at >600 GHz [13] [14].

Custom waveguide circuit blocks are bulky and expensive and waveguide-to-chip transitions are lossy. For these reasons, single-chip transceivers solutions are desirable at THz frequencies. With dense multi-level wiring and compact device footprints HBT IC technologies permit highly integrated THz transceiver components in small-from factors; the realization of arrays at λ/2 element spacings can be envisioned. Fig. 2 shows shows a chip photograph and measured IF output spectrum of a 580 GHz receiver circuit. The circuit includes an integrated 195 GHz phase-locked loop (PLL) for the LO source, an LO buffer amplifier, a 3rd-order sub-harmonic down-converting mixer and a differential common-base input amplifier similar to that reported in [14]. The PLL circuit topology is similar to that reported in [15]. The circuit utilizes 105- 130 nm HBTs and consumes ~700 mW of DC power. For the shown measurement, the RF input frequency was 576 GHz and the PLL output frequency was set to f_{LO} = 193 GHz. On-wafer Noise Figure testing was performed using the Y-factor method with a Hot and Cold source. For this measurement, a horn antenna was used to couple the input to the receiver through an on-wafer probe. The loss of the probe was deembedded from the measurements based on measured S-parameters. A receiver NF of 18.4 dB was measured. Integrated transmitter circuits with a similar circuit topology have been described elsewhere [4].

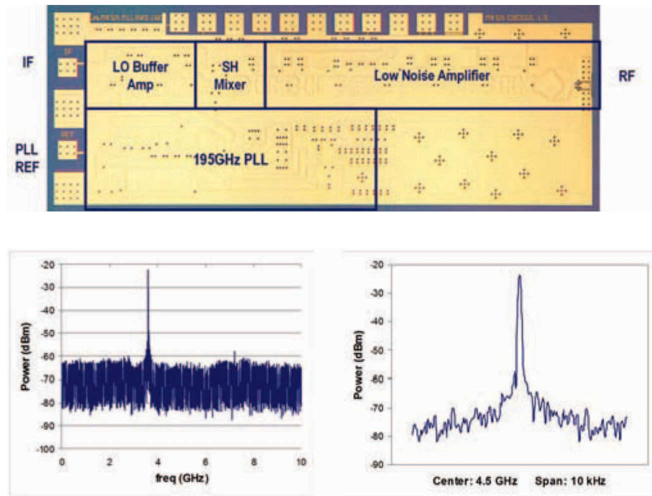

Fig. 2. Chip photograph of integrated 580 GHz receiver circuit and on-wafer measurement of IF output spectrum of 580 GHz receiver circuit with PLL LO source. f_{RF} = 576 GHz, f_{LO} = 193 GHz. Chip dimensions: 1.95x0.7 mm^2

Fig. 3 shows an image of a 600 GHz amplifier circuit in a waveguide package and measured S-parameters of a packaged amplifier. E-plane waveguide probes (chip-to-waveguide transitions) are integrated on the die. A backside etch singulation process has been developed to form non-rectangular die. Narrow InP extensions support

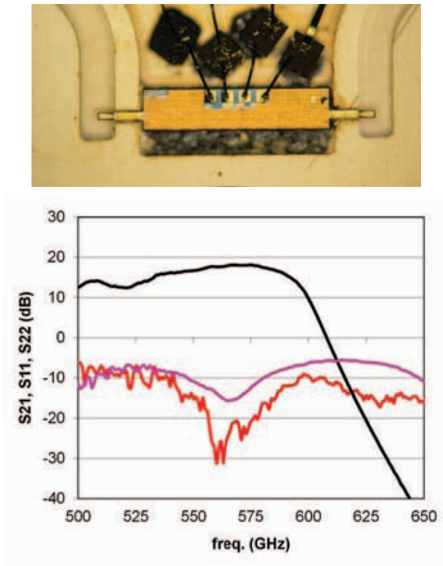

Fig. 3. Photograph of 600 GHz amplifier in waveguide block package and measured S-parameters of a packaged amplifier (S21-black, S11-red, S22-blue).

the antenna in the extensions entering the waveguide channel but the substrate is removed directly beneath the antenna to reduce loss. Further results from packaged amplifier and transceiver components will be described at the conference.

IV. Sub mmWave Power Amplifiers

InP HBTs are the leading power amplifier technology at frequencies between 100 and 300 GHz. At these frequencies, reported GaN HEMT power amplifier technologies demonstrate insufficient gain, and the higher breakdown voltage of InP DHBTs offers power density advantages over InGaAs-channel HEMTs. A record output power of 248 mW at 200 GHz has been demonstrated from a 16-way combined cascode amplifier fabricated in the 250 nm HBT technology [16]. H-band InP power amplifiers have exceptional large signal bandwidths. An 8-way combined amplifier based on the same circuit topology demonstrates 20 dB gain from 194-265 GHz with greater than 50 mW of output power over the same frequency range [16]. Peak power-added efficiency for the 8-way combined PA is greater than 5%.

High power solid-state power amplifier modules have been demonstrated combining multiple power amplifier MMICs with 710mW output power at 230GHz [17], and 823mW at 216GHz [18]. These results represent a 3-4x improvement in available output power from solid state sources operating in this frequency range. Access to higher available source power enables improvements in THz signal generation with multiplier sources. In [19], a

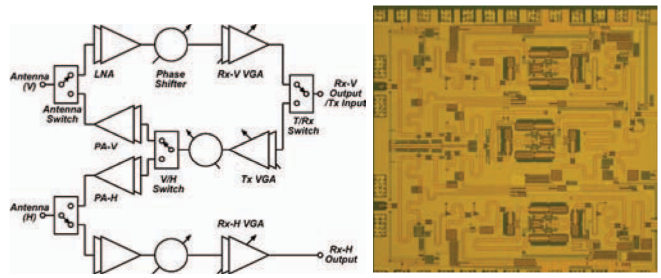

Fig. 4. Block diagram and chip photograph of ultra-low power 94 GHz transceiver front-end [21]. Chip dimensions: 1.77x1.55 mm^2.

packaged 4-way combined amplifier covering the entire WR04 waveguide band was used to demonstrate a 325-500 GHz doubler source with 0.5-1.0 mW output power, a 500-750 GHz tripler source with 0.2-0.6 mW output power, and through subsequent tripling a 1.6-2.2 THz source with 0.1-2.3 µW output power.

V. mmWave Circuit Demonstrations

A mmWave frequencies through W-band (110 GHz), THz transistors can significantly improve system performance. High efficiency broad band amplifiers have been demonstrated with up to 40% power added efficiency at 81 GHz [9] using 250 nm HBTs. In [20], high dynamic range W-band frequency conversion ICs were demonstrated in the 130 nm HBT technology. These ICs were designed for a broadly tunable 1-22 GHz dual-conversion receiver. Both up-conversion and down-conversion ICs were demonstrated with 22 dBm IIP3 while covering most of the W-band (75-110 GHz) frequency range.

THz transistors offer the potential for significant system impact in improving beamformer front-end circuits for large-element mmWave phased-arrays. Compared to existing SiGe or CMOS technologies, THz bandwidth InP transistors can offer superior RF performance at equivalent DC power consumption or equivalent performance at greatly reduced DC power consumption. In [21], an ultra-low power 94 GHz transceiver frontend was presented (Fig.4). In dual-polarization receive mode with a 1.0 V supply, the transceiver consumes only 26 mW of DC power and demonstrates 22 dB peak gain with < 8.9 dB noise figure. In transmit with a 1.5 V supply, the transceiver consumes 40 mW of DC power, demonstrates 22 dB peak gain and achieves 5 dBm output power. Low power operation is critical in targeted arrays with >10,000 elements, where large power dissipation puts strains on prime power requirements and heatsinking of the array.

In [21], control of channel amplitude and phase was achieved with analog control voltages. 3D heterogeneous integration of InP transistor with Si CMOS, like that reported in [22], offers a path for implementing digital control electronics while maintaining λ/2 element spacing.

VII. Conclusion

We have described Teledyne Scientific's THz InP IC technologies and their application in MMICs ranging from mmWave to THz frequencies. Sophisticated MMIC design across these frequencies is aided by the high achievable integration levels, accurate transistor models and well-established design flows

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