250 nm InP DHBT Monolithic Amplifiers with 4.8 dB Gain at 324 GHz

Jonathan Hacker, Miguel Urteaga, Dino Mensa, Richard Pierson, Mike Jones, Zach Griffith, and Mark Rodwell.

***Abstract*–An indium-phosphide (InP) double-heterojunction bipolar transistor (DHBT) based common-base monolithic power amplifier has been fabricated and has a measured small signal gain of 4.8 dB at 324 GHz. This is the highest frequency DHBT MMIC amplifier reported to date. The submillimeter-wave power amplifier MMIC incorporates microstrip transmission lines on a 10-µm thick layer of BCB dielectric. The thick BCB layer provides mode-free low-loss millimeter-wave transmission lines without requiring a thin fragile InP substrate and through-wafer VIAs as with conventional microstrip placed directly on the semiconductor substrate. The single-stage power amplifier has a compact size of only 0.124 mm^2 and a simulated saturated output power of 7 milliWatts with a dc input power of 1.5 V at 14 mA. These results demonstrate the capability of 250nm InP DHBT technology to enable power amplifiers for submillimeter-wave applications.**

***Index Terms*—Submillimeter-wave, power amplifier, indium phosphide (InP) double-heterojunction bipolar transistor (DHBT).**

I. INTRODUCTION

SUBMILLIMETER-WAVE power amplifiers represent a critical component for many emerging systems applications including submillimeter-wave (140 to 340 GHz) active imagers and high-resolution all-weather remote sensing with favorable aperture sizes for mobile platforms [1]. They are also critical components for local oscillator generation in heterodyne submillimeter-wave receivers for astrophysics and earth remote sensing, and spacecraft radars for future planetary missions [2]. For such applications, 250nm InP DHBT devices are particularly promising because of their combination of high bandwidth (fmax = 550 GHz), and high breakdown voltage (Vcbo = 5V) that makes them ideally suited for output powers up to 10mW and higher [3,4]. To date, only InP HEMT devices have demonstrated gain above 220 GHz with a recent demonstration of a 3-stage MMIC with 16 dB gain at 340 GHz [5]. However, the low breakdown voltage of the HEMT devices imposes significant limitations on their application as power amplifiers at these frequencies.

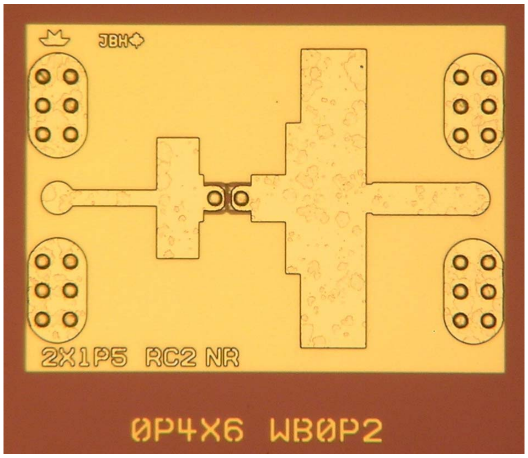

Fig. 1. A photomicrograph of a single-stage InP DHBT common base MMIC 324 GHz power amplifier with microstrip lines on thick 10µm BCB. The compact die measures 300 µm by 414 µm with a wafer thickness of 635 µm (thinning not required).

Only recently have 250nm InP DHBT devices reached sufficient maturity to permit the realization of submillimeter-wave MMIC amplifiers. We report here the first such amplifier MMIC, a single-stage 324 GHz microstrip MMIC with record gain (Fig. 1). The first pass success for this design is primarily due to a stable DHBT MMIC technology, high-quality InP epitaxial material, and accurate active and passive models, and a proven design approach.

II. DEVICE DESIGN AND CHARACTERIZATION

The DHBT structure is grown using molecular beam epitaxy on four-inch semi-insulating InP substrates (Fig. 2). The epitaxy utilizes a 30nm carbon-doped base layer and a 150nm N- InP collector region [3]. The emitter contact is patterned using electron-beam lithography and formed using an Au-based electroplating process [4]. A self-aligned emitter mesa etch is performed using a wet chemical process that undercuts the emitter contact by ~75nm on each side. In this work, results are reported for devices with emitter junction widths of 250nm.

The undercut of the emitter contact is utilized to form a self-

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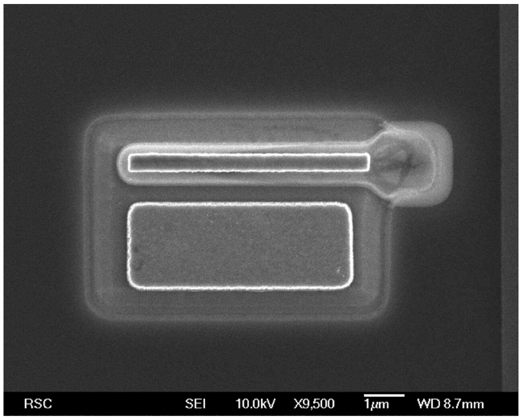
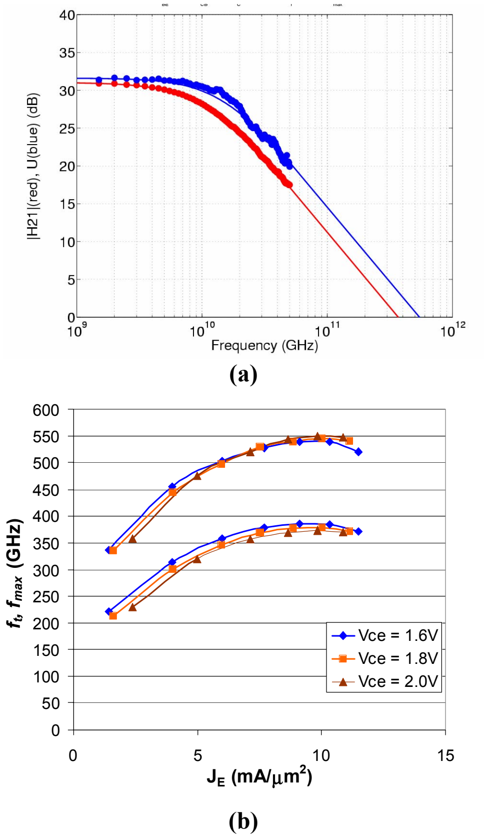


Fig. 2. SEM of 0.25 μm HBT device footprint.

aligned base contact by e-beam evaporation. Excellent base contact resistances (< 20 Ohm-μm^2) allow for the formation of a narrow base-collector junction width without sacrificing device performance. First-level interconnects are formed using electroplated gold.

The 250nm InP DHBT has measured dc beta of 20 at a Vce of 2V. For a 0.25 x 5 μm device, on-wafer s-parameter measurements show a cutoff frequency, f_t, of 373 GHz and a maximum oscillation frequency, f_{max}, of 550 GHz (Fig. 3).



(a)

(b)

Fig. 3. (a) Measured unilateral power gain and h_{21} for 0.25x5 μm^2 HBT used to extrapolate an f_{max} of 550 GHz and an f_t of 373 GHz, respectively. (b) f_{max} and f_t, versus emitter current (J_E) density at varying collector emitter voltages (V_{CE})

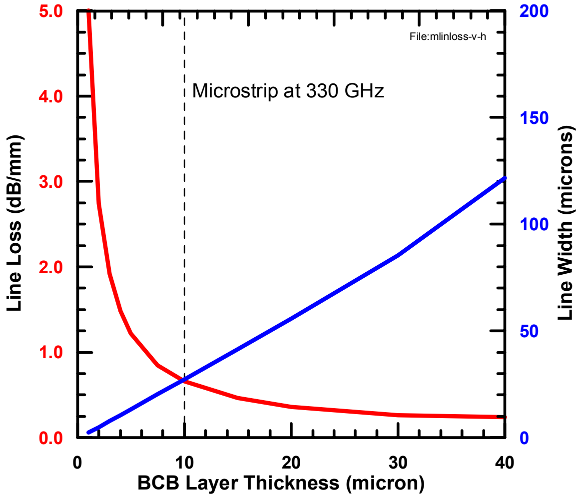


Fig. 4. Modeled insertion loss and line width of 50Ω microstrip as a function of BCB dielectric layer thicknesses at 330 GHz. A good compromise between low insertion loss and compact line width is at 10μm thickness per BCB layer.

Further details on the DHBT structure and performance used in this MMIC have been reported elsewhere [3].

III. THICK BCB TRANSMISSION LINE CIRCUITS

In order to fabricate mode-free 330 GHz low-loss microstrip transmission lines with a wide range of realizable characteristic impedances for the amplifier matching networks, we have developed an InP DHBT MMIC power amplifier process based upon a single layer of 10μm thick benzocyclobutane (BCB) [6,7] on top of a ground plane deposited on the topside of the wafer. The thick BCB layer provides low-loss submillimeter-wave transmission lines with smaller dimensions compared to conventional microstrip placed directly on the thinned semiconductor substrate with a backside ground plane. Additionally, the use of BCB as the microstrip substrate isolates the rf signals of the circuit from the InP carrier substrate, permitting the use of a thicker and, hence, more robust MMIC substrate while eliminating the need for backside processing of through-wafer VIAs.

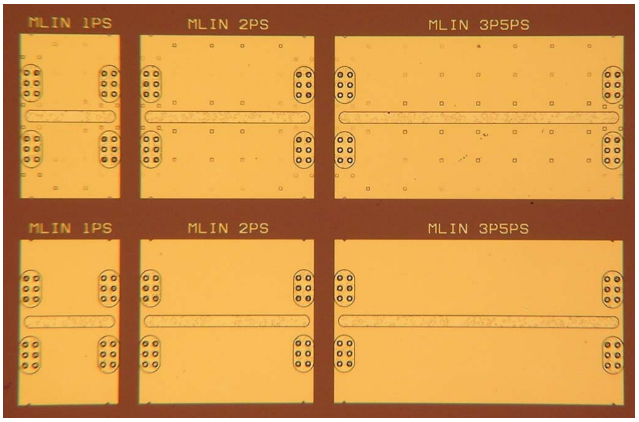


Fig. 5. Microphotograph of thick BCB stripline test structures showing 1, 2, and 3.5ps 50ohm lines for characterization up to 330 GHz.

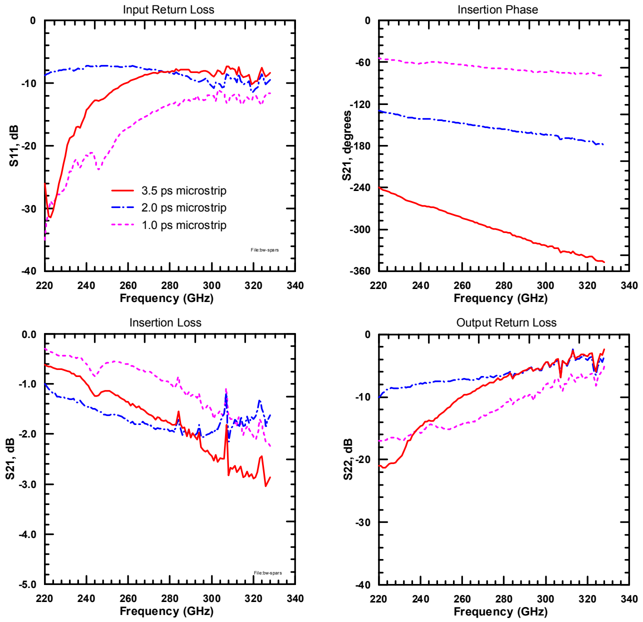


Fig. 6. Measured insertion phase (s21, deg), insertion loss (s21, dB) and input (s11) and output (s22) return loss of three BCB microstrip test lines of length 1 ps, 2ps, and 3.5ps. The lines exhibit low loss with excellent impedance control to 328 GHz.

The low dielectric constant BCB allows for more compact impedance matching and power-combining networks, reducing IC area [8] and facilitating low-parasitic connections to the small active devices. Because the primary skin losses $\alpha_{skin} \propto \varepsilon_r^{1/2} / T$ increase as the substrates is thinned, reduced die area indirectly results in increased line losses. However, selecting a low ε_r substrate such as BCB (ε_r=2.5) can reduce the attenuation compared to a typical semiconductor substrate that has an ε_r of ~11–13.

Thin substrates offer higher wiring density but thick substrates offer less transmission-line attenuation as shown in Fig. 4. Therefore, we have selected a 10µm BCB substrate thickness as a good compromise between line width IC density and line attenuation. The 10 µm BCB thickness also allows lines with impedances as high as 110 Ω to be realized using the thinnest line width possible of 5 µm for the microstrip conductor.

To characterize the thick BCB microstrip rf wiring process, a set of 50Ω microstrip test structures of varying length were fabricated (Fig. 5). Measured performance of the lines up to 328 GHz (the limit of our vector network analyzer test set) is shown in Fig. 6, including launch losses associated with the on-wafer probe pads that were not deembedded. The measured data shows low loss and good agreement with model predictions for Z_0. The measured loss (pads deembedded) is 0.88 dB/mm. From this data, the BCB dielectric constant and loss tangent were found to be 2.54 and 0.005 respectively at 300 GHz.

IV. AMPLIFIER DESIGN AND FABRICATION

The single-stage common-base 324 GHz power amplifier was designed by combining two single-finger common base subcells each with a single InP DHBT 0.25 x 6 µm emitter finger to produce 3µm^2 of total device area. A Gummel-Poon nonlinear large-signal model was used for the design and was based primarily upon analytical device parameter computations. The devices are dc biased at a nominal collector voltage of 1.5 V and 6.7 mA/µm^2 of collector current. RF power densities of 2.3 mW/µm^2 are typically simulated from these devices at 330 GHz.

The common-base configuration was selected because the breakdown voltage of the common base (CB) output device is significantly higher than that in the common emitter (CE) connection (since BVCBo is greater than BVCEo). CE HBT amplifier designs typically pay a significant penalty on power, efficiency, and bandwidth to assure thermal runaway does not occur.

The two single-finger common-base devices used in the amplifier are interconnected with microstrip matching networks on thick BCB as described earlier. A full-wave 2.5D electromagnetic solver was used to model layout induced effects. Several iterations of design and EM simulation were needed to obtain good simulated amplifier performance. The single stage amplifier was biased through the input and output pads using the internal bias tees of the GGB WR-3 probes used in the on-wafer test setup. For some designs, a thin film nichrome resistor layer was included directly under the microstrip ground plane as EM simulations showed it could be effective at dampening radiation from the ground plane at

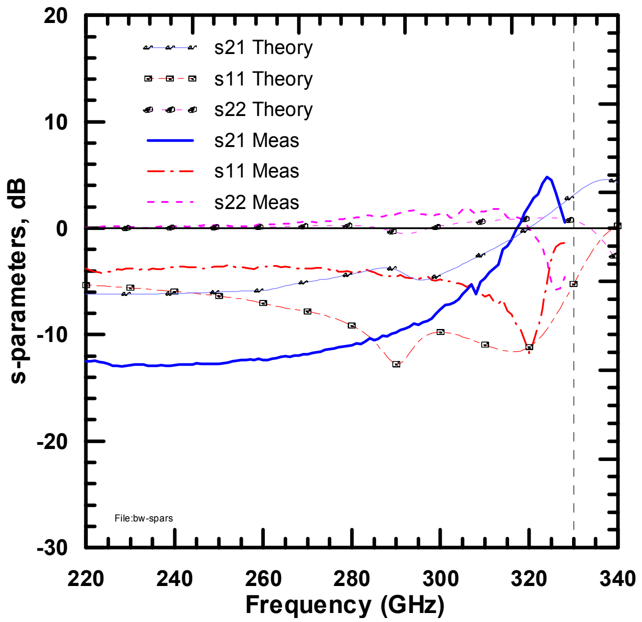


Fig. 7. Measured insertion gain (s21) and input (s11) and output (s22) return loss of the InP HBT PA compared with the theoretical prediction from circuit model. The peak measrued PA gain is 4.8 dB at 324 GHz.

some frequencies. SiN MIM capacitors were available but not used in the single-stage amplifier. Future multi-stage designs will use them for the bias network and interstage dc blocks. The resulting amplifier has a compact 300 µm by 414 µm die size.

V. AMPLIFIER CHARACTERIZATION

Performance of the single-stage common-base amplifier was measured on-wafer with GGB Picoprobe WR-3 rf probes with a 50 um probe pitch. The setup consists of an Oleson Microwave Laboratory WR-3 frequency extender test set with an Agilent 8510c network analyzer. The measured *s*-parameters are shown in Fig. 7 where they are compared with simulated results. The agreement between theory and measurement is acceptable, with an observed 6 GHz shift downwards in frequency of the measured gain bandwidth. We believe the discrepancy is due to limitations in the first-pass device model that was extracted using data measured below 110 GHz. Over the band from 323 to 326 GHz, the measured gain is 4.8 ± 1 dB. The measured amplifier is not unconditionally stable with K < 1 from 281 to 318 GHz, although no oscillations were observed during measurement. Large signal measurements are not available at the time of publication. Simulated data is shown in Fig. 8. The simulated saturated amplifier output power is 7 mW (8.4 dBm) at 330 GHz, with coincident dc power added efficiency (PAE) of 14.5% for a dc bias of 1.5V and 14 mA.

VI. CONCLUSION

We report on a 250nm InP DHBT based common-base MMIC power amplifier with a record measured small signal gain of 4.8 dB at 324 GHz. This is the highest frequency DHBT MMIC amplifier reported to date. The InP DHBT MMIC process is well suited for submillimeter-wave power amplifier MMICs due to its high bandwidth (fmax = 550 GHz) and high breakdown voltage (BVCBo = 5V) and integrated 10 µm thick layer of BCB dielectric for rf wiring. The thick BCB layer provides low-loss mode-free submillimeter-wave transmission lines with much smaller dimensions compared to conventional microstrip placed directly on the semiconductor substrate. These results demonstrate the capability of 250nm InP DHBT technology to enable power amplifiers for submillimeter-wave applications.

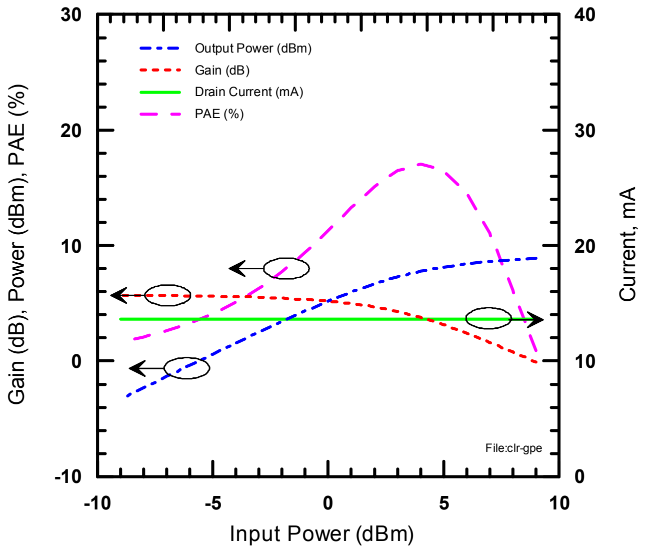


Fig. 8. Plot of simulated large signal output power, gain and power added efficiency at 330 GHz versus input power at a dc bias of 1.5 volts and 14 mA of collector current. A saturated output power of 7 mW is simulated. Measured data was not available at the time of publication.

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