Solid-State Amplifiers for Terahertz Electronics

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***Abstract* — With the f_{MAX} of current generation InP transistors pushing above 1-THz and new transistor scaling in progress, the operational frequency of solid-state amplifiers is being pushed towards THz frequencies. In this paper we present out latest work towards demonstrating THz frequency amplifiers, including measured gain and noise performance of a 0.48 THz low noise amplifier using scaled InP transistors. Initial performance of next generation transistors is also presented, along with infrastructure necessary to package and operate solid-state amplifiers at THz frequencies.**

***Index Terms* — MMIC, Low Noise Amplifier, Terahertz, Indium Phosphide, HEMT, HBT, Integrated Circuit**

I. Introduction

In the last few years, transistor technologies have improved to the point that solid-state amplifiers operating above 300-GHz ($\lambda 0 < 1.0$-mm) have become viable for the first time. Although no hard rule exists for the practical operating limit of a hard for a given transistor f_{MAX}, a good practical rule of thumb is to choose a transistor with an f_{MAX} 50-100% higher than the target operating frequency of the circuit. In the past few years, our group has developed both InP HEMT and HBT technologies with an $f_{MAX} > 1$ THz [1] and 0.62 [2], [3] respectively. This implies that the current upper limit for amplifiers lies between 0.5-0.67 THz with the current generation of HEMT transistors and between 0.3-0.4 THz for HBT transistors. With a recent amplifier demonstration at 0.48 THz [4] and ongoing transistor scaling developments in progress on the DARPA Terahertz Electronics Program [5], we expect significant advances in the practical operating frequencies of solid-state amplifiers in the near future.

A variety of applications exist at these frequencies, with present scientific needs for low noise amplification and local oscillator chains for radiometry, atmospheric sensing, and spectroscopy. Solid state power amplifiers operating at these frequencies would also have immediate impact in lowering the DC power consumption of local oscillator multiplier chains. Moreover, if moderate volume manufacturing of integrated circuit THz amplifiers can be demonstrated with reasonable yields, immediate impacts on emerging THz applications would be realized. These systems would leverage the short wavelength and bandwidth at THz frequencies; and include THz radar, imaging, and communications. Replacing or augmenting current diode based systems could realize significant improvements in system dynamic range and DC power consumption.

In this paper, we provide an overview of our current transistor performance and roadmap for future scaling being performed at Northrop Grumman. We also provide an overview of our recent integrated circuit work making use of our most recent generation of transistor.

II. THz Transistor Development

The most fundamental tool which has been used to increase the operating frequency of electron device integrated circuits has been the progressive improvement in transistor f_T and f_{MAX}. Our group has placed a significant amount of effort on developing high speed InP HEMT and HBT transistors for the purpose of improving the performance of critical aerospace and defense applications. A table of current performance is shown in Table 1, as well as projected performance of next generation technologies which are now beginning development.

	InP HEMT		InP HBT	
Technology	Current	Next Gen	Current	Next Gen
Feature Size	50 nm gate	30 nm gate	250 nm emitter	150 nm emitter
f_T	0.55 THz	0.69 THz (projected)	0.53 THz	0.64 THz (projected)
f_{MAX}	>1 THz	> 1.2 THz (projected)	> 0.63 THz	> 1.2 THz (projected)
Highest IC	0.48 THz	-	0.32 THz	-

Table 1. Summary of Northrop Grumman high frequency transistor current and next generation performance.

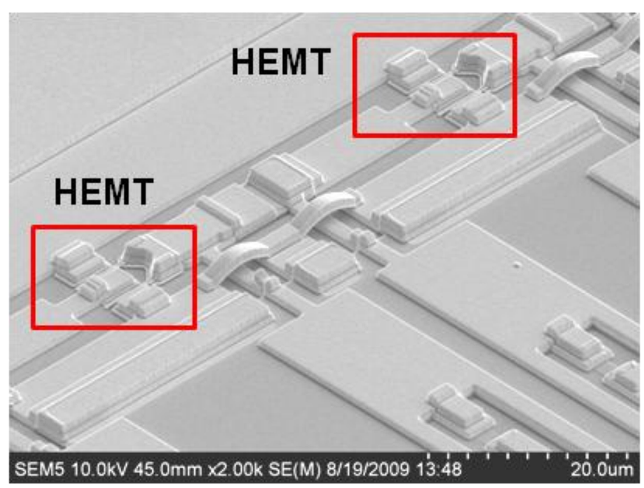


Fig. 1 SEM showing detail from a prototype 670 GHz integrated circuit utilizing 10 um transistors**.**

Our current generation of InP HEMT uses a sub-50nm process. We have demonstrated InP HEMT devices with greater than 0.55 THz f_T and over 1.0 THz f_{MAX}. These devices have successfully powered integrated circuit amplifiers to 0.48 THz in frequency. To push this window further in frequency, we are currently developing a new gate process using 100kV EBL. This should provide improved gate scalability required for higher frequency operation. Other enhancements are also being made to improve transistor performance, including designing the epitaxial profile for better electron transport properties and improving ohmic contact to lower access resistance and yield higher transconductance. Additionally, we are designing the gate recess to maintain a good aspect ratio, and a layout footprint for reduced parasitics at short wavelengths when the transistor is interfaced with electrically compact circuitry in an integrated circuit.

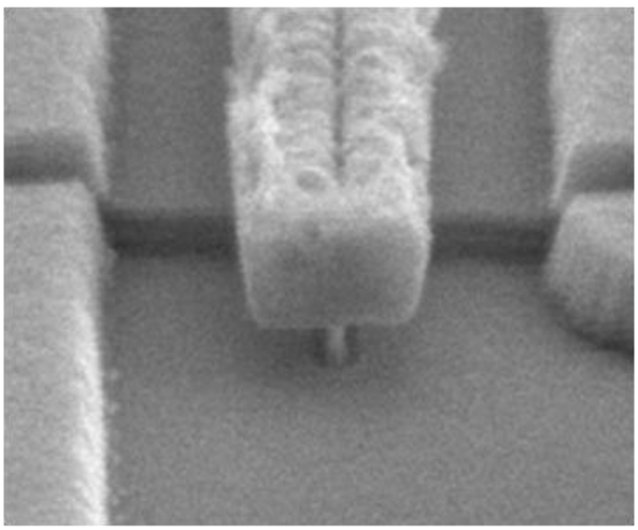


Fig. 2 SEM of ~30 nm InP HEMT T-gate.

The advanced InP HBT technology has been developed for device and interconnects scalability with an emphasis on improved manufacturability and yield [2], [3]. This technology utilizes an aggressively scaled triple-mesa HBT with emitter widths as narrow as 0.25µm. Self-aligned base metal and base mesa layouts are designed to produce minimum intrinsic and extrinsic base-collector capacitance (C_{BC}) while maintaining low base resistance values. The HBT epitaxial profiles are scaled for this generation of HBT and the MBE-grown epi profiles can be tailored to the needs of the specific circuit applications. The advanced InP HBT technology includes the multi-level interconnect with up to four plated Au metal layers and low-k benzocyclobutene (BCB) as the interlayer dielectric between metallization [2].

An advanced InP HBT with 0.25□4-µm^2 emitter area, 220Å compositionally-graded base layer and 1200Å thick is InP collector layer demonstrates a breakdown voltage (BV_{CEO}) over 4 Volts and the peak current gain (□) is 30. S-parameter measurements obtained using an HP8510XF, on-wafer TRL calibration, and no de-embedding show a peak f_T = 530 GHz with simultaneous f_{max} in excess of 650 GHz at V_{CB} = 0.4 V and collector current density (J_C) of 13 mA/□m^2. A MAG/MSG Gain of 15.5 dB is measured at 100 GHz.

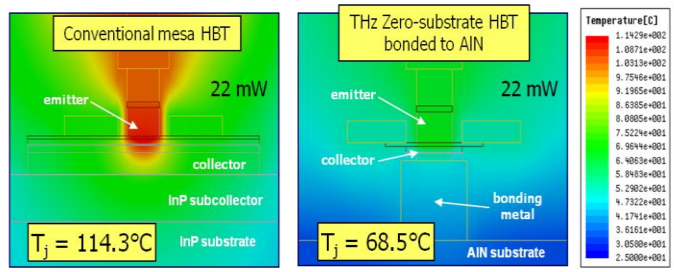


Fig. 3 Isolated HBT cross-section temperature of substrate removal HBT vs. conventional mesa HBT.

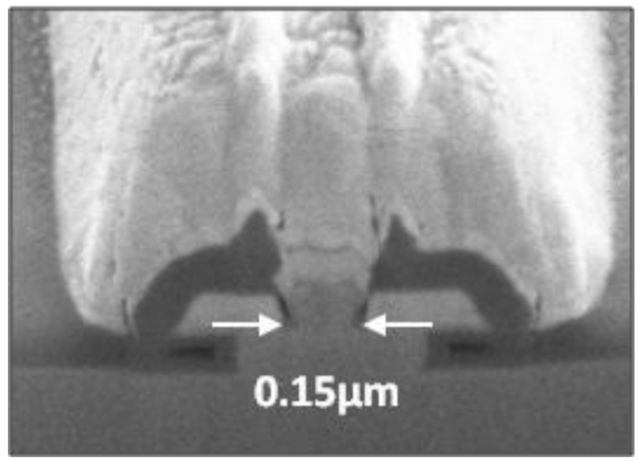


Fig. 4 Cross-section image of a next-generation InP HBT with 0.15µm width emitter

Our target next-generation InP HBT technology further increases device and epitaxial scaling to improve device f_{max} values over 1THz. Electron beam lithography (EBL) will be used to pattern emitter widths as narrow as 0.15 µm, and the base and collector epitaxial thicknesses are being reduced to improve transit time. Improvements to the base doping and composition will allow for reduction in base thickness without penalty to the base resistance. Improvements will be made to the emitter and base contact preparation and chemistry to minimize contact resistance. Paired with low emitter resistance, higher current density operation is a key objective in designing HBTs with high f_T. Our target operating current densities is ~30 mA/µm^2. However, higher current density operation leads to heating of the HBT. To surmount this, we are developing a substrate transfer process to transfer the transistor from the native InP substrate to a higher thermal conductivity AlN wafer. Thermal simulations of this approach show a 40% reduction in device temperature when compared to a conventional mesa structure HBT with similar device dimensions, shown in Fig. 3. Preliminary work has begun on realizing this advanced structure. Shown in **Fig. 4** is the transistor cross-section of a mechanical sample before substrate transfer.

III. HEMT SMMW Integrated Circuits

A variety of low noise amplifiers [6], [7], power amplifiers and oscillators [9] have now been demonstrated operating in the range of 300-350 GHz using InP HEMT and MHEMT technology. Very recently, a packaged solid state amplifier has recently demonstrated greater than 11 dB gain at 480 GHz using this technology. Little data has been published in the open literature on noise performance at these frequencies. Shown in **Fig. 5** and **Fig. 6** are associated gain and noise figure for a packaged 300 GHz amplifier module. Peak gain of ~ 15 dB is achieved for the 3 stage amplifier at ~ 300 GHz. Note that this is in a waveguide package, and includes waveguide and transition losses, which are estimated to be on the order of 1-1.5 dB, which gives a minimum noise figure at the MMIC of ~7.2-7.7 dB. For reference, the first reported noise figure at 270 GHz measured on-wafer was reported to be 7.5 dB [10], [11]. Also note that the minimum noise figure is not measured at the maximum gain frequency. In fact, the noise figure is approximately 1 dB worse where peak gain is measured, even though measured gain is approximately 3 dB higher. Moreover, minimum noise figure is not achieved at peak gain bias. From this we conclude that the noise match at the input of the amplifier is not ideal. We believe that future design iterations will further improve the noise figure at these frequencies, as well as additional iterations of the amplifier package.

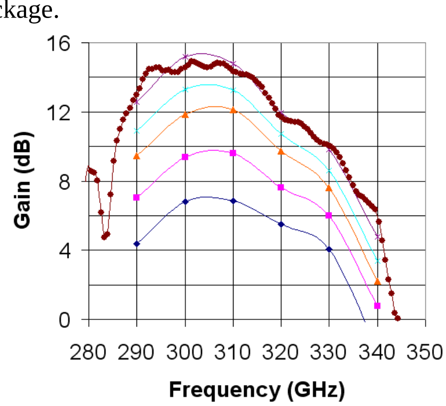


Fig. 5 Measured gain vs. bias for 300 GHz amplifier module

Very recently, a packaged amplifier operating at 0.48 THz has been demonstrated [4]. We have performed initial noise measurements using the Y-Parameter method on the amplifier. The packaged amplifier showed measured noise figure of 11.7 dB with an associated gain of 11.4 dB. Note that in this case, minimum noise is obtained at peak gain for the amplifier, indicating that gain is limiting the amplifier noise performance.

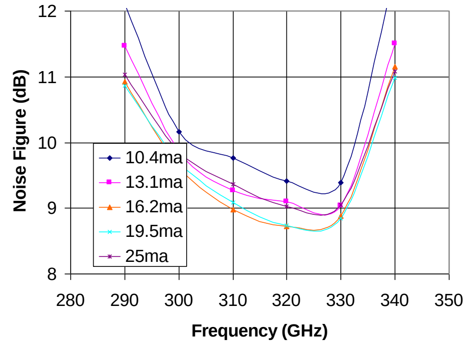


Fig. 6. Measured noise figure for 300 GHz amplifier module**.**

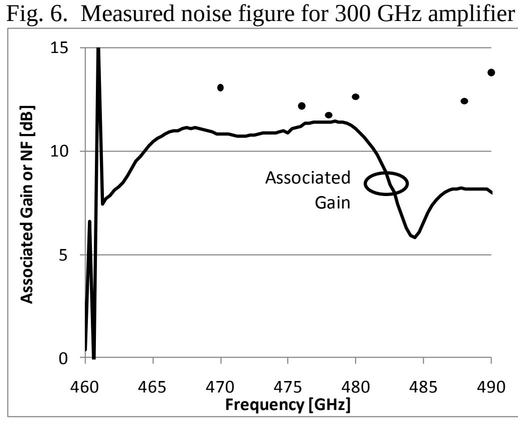
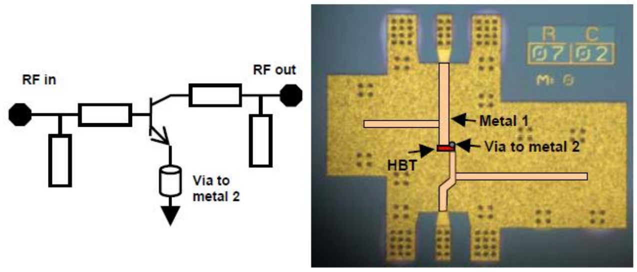


Fig. 7. Measured noise performance of 0.48 THz LNA.

IV. HBT SMMW Integrated Circuits

HBT based integrated circuits have previously been reported operating at G-Band [12]. The first sub-millimeter wave integrated circuit using HBT's was an oscillator capable of being injection locked [13]. More recently, a single-stage amplifier operating at 324 GHz was presented [14] using 250 nm InP DHBTs and realized in thin film microstrip.

To further our own development of InP HBT based integrated circuits, we have also demonstrated single stage amplifiers. The primary purpose of doing this is to validate transistor performance "at frequency", and as a tool for optimizing and validating the transistor model. The circuit shown in Fig. 8 is the result. From our experience in [13], the inductance of ground access is critical. For this reason, the circuit is realized in "inverted microstrip". We use metallization at the top of the BCB as ground. RF routing and components are in Metal 1 below the BCB, as shown in Fig. 8. Measured vs. modeled agreement is excellent.



(a) (b)

Fig. 8 Schematic (a) and microphotograph (b) of 255-GHz amplifier.

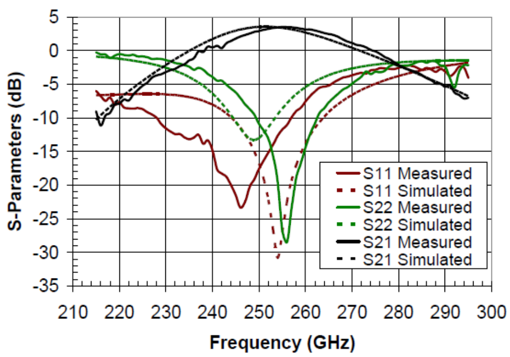


Fig. 9 Measured and modeled S-Parameters of single stage amplifier.

V. Conclusion

In this paper, we have discussed current efforts in InP HEMT and HBT scaling. Additionally, we have provided new data on integrated circuit performance to 480 GHz. We expect that circuit performance operating frequencies will continue to increase as transistor performance continues to increase, and additional processing advances are made.

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References

[1] R. Lai, X.B. Mei, W.R. Deal, W. Yoshida, Y.M. Kim, P.H. Liu, J. Lee, J. Uyeda, V. Radisic, M. Lange, T. Gaier, L. Samoska, A. Fung, "sub 50 nm InP HEMT device with Fmax greater than 1 THz," *IEEE 2007 IEDM Conf. Dig.*, pp. 609-611, Dec. 2007.

[2] C. Monier, D. Scott, M. D'Amore, B. Chan, L. Dang, A. Cavus, E. Kaneshiro, P. Nam, K. Sato, N. Cohen, S. Lin, K. Luo, J. Wang, B. Oyama, A. Gutierrez, "High-Speed InP HBT technology for advanced mixed-signal and digital applications", *IEEE IEDM Digest*, pp. 671-674 (2007).

[3] B. Chan, B. Oyama, C. Monier, A. Gutierrez-Aitken, "An ultra-wideband 7-bit 5-Gsps ADC implemented in submicron InP HBT technology", *IEEE Journal of Solid-State Circuits* V43 (10), pp. 2187-2193 (2008).

[4] W.R. Deal, X.B. Mei, V. Radisic, K. Leong, S. Sarkozy, B. Gorospe, J. Lee, P.H. Liu, W. Yoshida, J. Zhou, M. Lange, J. Uyeda, R. Lai, "Demonstration of a 0.48 THz amplifier module using InP HEMT transistors", *submitted to the IEEE MWCL.*

[5] http://www.darpa.mil/mto/programs/thz/index.html

[6] W.R. Deal, X.B. Mei, V. Radisic, W. Yoshida, P.H. Liu, J. Uyeda, Barsky, T. Gaier, A. Fung, R. Lai, "Demonstration of a S-MMIC LNA with 16-dB gain at 340-GHz," *IEEE 2007 CSIC Conf. Dig.*, pp. 1-4, Oct. 2007.

[7] A. Tessman, A. Leuther, H. Massler, W. Bronner, M. Schlechtweg, and G. Weimann, "Metamorphic H-band low-noise amplifier MMICs," in *2007 IEEE MTT-S International Microwave Symposium Digest*, June 2007, pp. 353-356.

[8] V. Radisic, W.R. Deal, K.M.K.H. Leong, X. B. Mei, W. Yoshida, P.-H. Liu, J. Uyeda, A. Fung, L. Samoska, T. Gaier, R. Lai, "A 10 mW submillimeter wave solid state power amplifier module," submitted to *IEEE Trans. Microwave Theory Tech.*

[9] V. Radisic, X.B. Mei, W.R. Deal, W. Yoshida, P.H. Liu, J. Uyeda, M. Barsky, L. Samoska, A. Fung, T. Gaier and R. Lai, "Demonstration of Sub-Millimeter Wave Fundamental Oscillators Using 35-nm InP HEMT Technology", *IEEE Microwave and Wireless Components Letters*, vol. 17, no. 13, pp. 223-5, March 2007.

[10] W.R. Deal, X.B. Mei, V. Radisic, W. Yoshida, P.H. Liu, J. Uyeda, M. Barsky, T. Gaier, A. Fung, L. Samoska, R. Lai, "Demonstration of a 270-GHz MMIC Amplifier using 35-nm InP HEMT Technology", IEEE Microwave and Components Letters, May, 2007.

[11] T. Gaier, L. Samoska, A. Fung, W.R. Deal, V. Radisic, X.B. Mei, W. Yoshida, P.H. Liu, J. Uyeda, M, Barsky, R. Lai, "Measurement of a 270 GHz low noise amplifier with 7.5 dB noise figure," *IEEE Microwave and Components Letters*, vol. 17, no. 7, pp. 546-548, July 2007.

[12] M. Urteaga, D. Scott, S. Krishnan, Y. Wei, M. Dahlstrom, Z. Griffith, N. Parthasarathy, and M. Rodwell, "G-band (140-220-GHz) InP-based HBT amplifiers," *IEEE Journal of Solid-State Circuits*, vol. 38, no. 9, Sept. 2003, pp. 1451-6.

[13] V. Radisic, D. Sawdai, D. Scott, W. R. Deal, L. Dang, D. Li, J. Chen, A. Fung, L. Samoska, T. Gaier, R. Lai, "Demonstration of a 311-GHz fundamental oscillator using InP HBT technology," *IEEE Trans. on Micr. Theory and Techn.*, vol. 55, no. 11, 2007, pp. 2329-2335.

[14] J. Hacker, M. Urteaga, D. Mensa, R. Pierson, M. Jones, Z. Griffith, M. Rodwell, "250 nm InP DHBT monolithic amplifiers with 4.8 dB gain at 324 GHz, IEEE 2008 MTT-S IMS Digest, June 2008, pp. 403-406.

[15] V. Radisic, D. Sawdai, D. Scott, W.R. Deal, L. Dang, D. Li, A. Cavus, A. Fung, L. Samoska, R. To, T. Gaier, R. Lai, "Demonstration of 184 and 255-GHz amplifiers using InP HBT technology," IEEE MWCL, vol. 18, no. 4, , April 2008 pp. 281 – 283.