An InP HEMT W-Band Amplifier with Monolithically Integrated HBT Bias Regulation

K. W. Kobayashi, *Member, IEEE*, H. Wang, *Senior Member, IEEE*, R. Lai, L. T. Tran, T. R. Block, P. H. Liu, J. Cowles, *Member, IEEE*, Y. C. Chen, T.-W. Huang, A. K. Oki, *Member, IEEE*, H. C. Yen, and D. C. Streit, *Senior Member, IEEE*

***Abstract*—This paper presents the results of the first W-band InP-based high electron mobility transistor-heterojunction bipolar transistor (HEMT-HBT) monolithic microwave integrated circuit (MMIC). The InP-based HBT and HEMT devices are monolithically integrated using selective molecular beam epitaxy (MBE). The amplifier demonstrates the highest frequency performance MMIC so far obtained with this technology. A single-stage HBT op-amp current regulator is integrated with a single-stage HEMT amplifier in order to regulate and self-bias the HEMT device over process, temperature, and age variations. The HBT regulates the HEMT dc bias to within 3% of the bias current while consuming only a small fraction of the total dc power. The HEMT W-band amplifier achieves a radio frequency (RF) gain of 8.25 and 5.9 dB at 77 and 94 GHz, respectively. A minimum noise figure of 4.2 dB was also recorded at 93.5 GHz. The RF performance achieved from the HEMT amplifier using the InP-based HEMT-HBT integrated technology is comparable to that of InP-based single-technology HEMT performance.**

***Index Terms*— HBT, HEMT, monolithic integration, selective epitaxy.**

I. Introduction

While the application of monolithic microwave integrated circuits (MMIC's) has generally resulted in a reduction in size, weight, and cost of the integrated microwave assembly by consolidating several circuit functions on a single semiconductor chip, there is a limit to the number of circuit functions which *can* be integrated with a single-device IC technology and still maintain optimum performance. For example, the low-noise and high-frequency properties of HEMT's make them ideal for low-noise and millimeter-wave amplifiers, but are typically not desirable for voltage-controlled oscillators (VCO's) nor analog-digital circuit functions due to their high $1/f$ noise corner frequencies and significantly varying dc threshold voltage characteristics. On the other hand, the high linearity and low $1/f$ noise corner frequency characteristics of HBT's make them ideal for high-efficiency linear power amplifiers as well as low-phase noise VCO applications, while their excellent dc current gain (β) and threshold characteristics make them well suited for analog and digital applications as well. However, the HBT's will fall short of providing state-of-the-art low-noise-figure amplifiers at microwave and millimeter-wave frequencies above 10 GHz where low-noise HEMT devices are better suited. By monolithically integrating both HEMT's and HBT's on the same chip using an enabling technique called selective molecular beam epitaxy (MBE), the best device technology and circuit combinations can be realized, resulting in optimum circuit performance which is comparable to, or better than, equivalent hybrid implementations. GaAs-based HEMT-HBT integration using selective MBE has previously been reported [1] with numerous MMIC demonstrations [2]–[9]. InP-based HEMT-HBT integration has recently demonstrated excellent dc and RF device performance which is equivalent to conventionally processed devices [10], [11]. In this letter, we describe an InP-based HEMT-HBT MMIC result which demonstrates the highest frequency performance so far obtained with any HEMT-HBT integrated technology.

One major application of HEMT-HBT monolithic integration is bias regulation for the HEMT MMIC. This need stems from the widely varying nature of the dc threshold voltage of HEMT devices. HEMT MMIC's therefore typically require off-chip silicon bipolar regulators in order to maintain RF performance over process, temperature, and aging. Bipolar technologies such as HBT's are more suitable for regulator circuits because of their uniform dc threshold and beta characteristics, high dc transconductance, and low dc power consumption. These properties are required for the low dc power and high gain op-amp bias regulator design.

In typical HEMT MMIC applications, the size of the off-chip regulators can consume over 25 times the area of the actual HEMT MMIC [12]. Moreover, much of the module cost will be due to the assembly of several discrete wirebonds, resistors, and capacitors which are integrated with the silicon regulator and HEMT MMIC chips. At W-band, monolithic bias regulation is even more desirable because of the restrictions on the size of the integrated microwave assembly (IMA), which must be small in order to prevent cavity moding effects which can degrade the RF performance at these extremely high frequencies. By monolithically integrating HBT bias regulation on the HEMT MMIC, the size and assembly cost can be reduced, and the RF cavity moding effects minimized. Although HBT regulated HEMT LNA MMIC's have already been demonstrated with GaAs-based selective MBE [5], [13], this letter presents the first report of an InP-based W-band HEMT amplifier MMIC which monolithically integrates HBT bias regulation.

Manuscript received February 18, 1997. This work was supported by the U.S. Air Force Wright Laboratory, Wright-Patterson AFB, OH 45433-7522 USA under Contract F33615-94-C-1560.

The authors are with TRW Electronics Systems and Technology Division, Redondo Beach, CA 90278 USA.

Publisher Item Identifier S 1051-8207(97)05421-4.

II. InP HEMT-HBT W-Band Amplifier Performance

Fig. 1 shows a schematic of the InP-based HEMT W-band amplifier integrated with an InP-based HBT current regulator. The W-band amplifier design and results using the single-technology InP-based HEMT process has previously been reported in [14]. This work employs the same design, except that an InP HBT current regulator has been monolithically integrated using selective MBE in order to provide bias regulation. The W-band amplifier design employs a four-finger 40-μm gate width InP-based pseudomorphic HEMT with a 0.1-μm electron beam lithography (EBL) T-gate which typically achieves an f_T of 160 GHz, an $f_{\max}$ of 290 GHz, and a device minimum noise figure of 1.7 dB at 94 GHz. The monolithically integrated HBT current regulator is based on an InAlAs–InGaAs–InP HBT technology which has been previously described in recent literature [15]. These HBT's achieve peak f_T's and $f_{\max}$'s of 60 and 100 GHz, respectively, with dc current gains $(\beta) > 20$ at a current density of 40 kA/cm^2. The bias regulator consists of an HBT op-amp design which provides 36 dB of gain and is used to actively regulate the I_{ds} bias current of the HEMT device. For the same dc supply voltages, the op-amp will improve the bias regulation performance over a resistive self-bias approach by approximately the gain of the op-amp [12]. The HBT op-amp operates off of $+3.5$- and -2-V voltage supplies and consumes 0.8 mA of current. The op-amp is used to construct a positive current source on the drain of the HEMT device through a sensing resistor R_{dd}. The regulator sets up a nominal HEMT I_{ds} bias current of 8 mA and a corresponding V_{ds} bias of 0.9 V. The total dc power of the MMIC is 33.1 mW. The HBT regulator consumes as little as 13% of the total dc power of the HEMT-HBT MMIC while providing better than 3% bias regulation over HEMT process threshold variations. This is a four-times reduction in regulator dc power compared to a monolithic HEMT regulator approach which consumes a little over 50% of the total dc power of a single-stage HEMT MMIC [12]. The 13% dc power consumed by the HBT approach can easily be reduced to under 4% using a more aggressive op-amp design, however, a conservative design was employed to ensure first-pass success.

Fig. 2 shows a microphotograph of the HBT bias regulated HEMT W-band MMIC. The chip is 1.4×2.0 mm^2 in area. The compact HBT regulator consumes only one-fourth of the total chip area. This monolithic MMIC employment results in a significant reduction in size of the IMA when compared to the off-chip hybrid regulator implementation.

The measured gain and noise figure of the HEMT-HBT MMIC is given in Figs. 3 and 4. Fig. 3 illustrates the broad-band amplifier gain and return-loss response. A peak gain of 8.75 dB is measured at 77 GHz while a gain of 5.9 dB is recorded at 94 GHz. This performance is quite comparable with the single-technology InP-based HEMT measured amplifier response [14] which obtained a gain of 8 dB at 77 GHz and a gain of 5 dB at 94 GHz. In fact, the amplifier gain response is about 1-dB higher for the InP-based HEMT-HBT selective MBE results of this work. Fig. 4 gives the noise figure of the W-band amplifier. The noise figure varies from 4.15 to

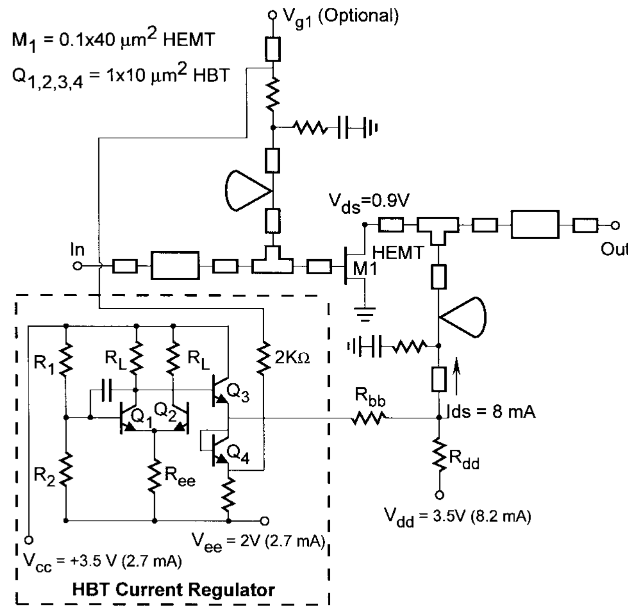

Fig. 1. Schematic of the InP HEMT W-band amplifier with integrated InP HBT current regulator.

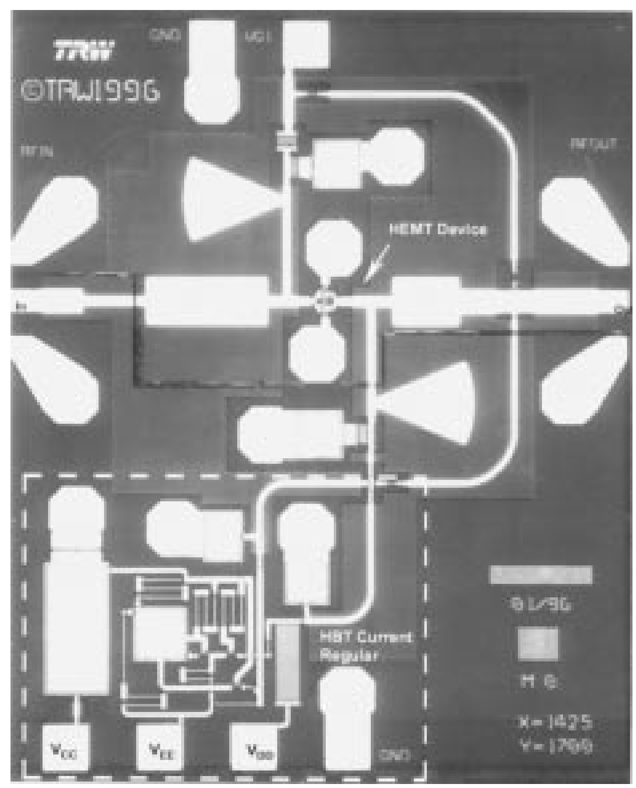

Fig. 2. Microphotograph of the InP HBT bias regulated InP HEMT W-band MMIC. The chip is 1.4×2.0 mm^2 in area.

5.1 dB across the 92–96-GHz band. This is substantially poorer than the recorded 2.3-dB noise figure obtained for the single-technology passivated InP-based HEMT results in [14], even though the gain was actually better. We emphasize here that these results reflect only a small sample size of the first InP-based HEMT-HBT wafers ever produced with this technology and represents a general proof of concept as

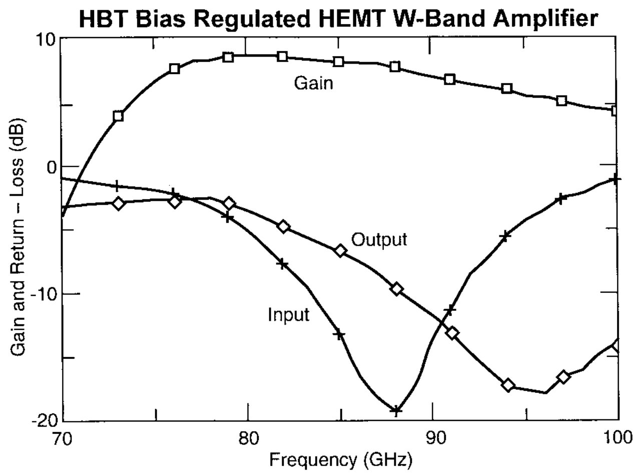

Fig. 3. Measured broadband amplifier gain and return-loss response.

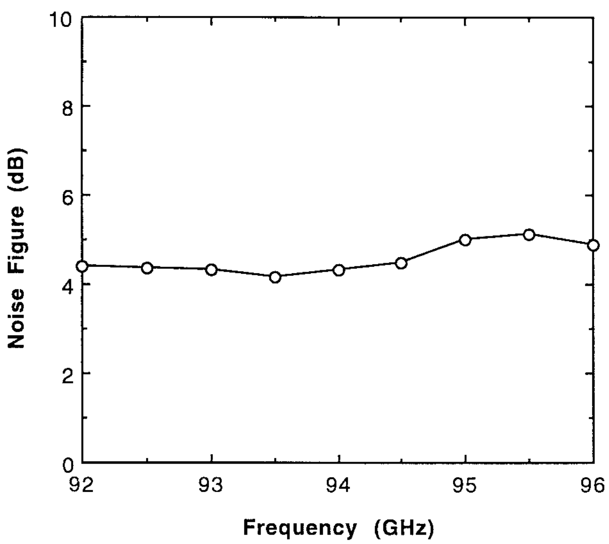

Fig. 4. Measured W-band amplifier noise figure.

well as a first-pass success. More characterization and further process optimization will reveal the true performance capability of this revolutionary InP-based HEMT-HBT integrated IC technology.

III. Conclusion

We presented the first MMIC performance results of an InP-based HEMT-HBT integrated MMIC which is the highest MMIC frequency performance demonstrated for any HEMT-HBT monolithically integrated device technology. The RF performance achieved from the InP-based HEMT-HBT amplifier MMIC is comparable to previously reported InP-based single-device-technology HEMT performance. In addition, it was demonstrated that HEMT-HBT selective MBE integration technology can provide an elegant solution to fundamental circuit needs, such as the monolithic HBT bias regulation of HEMT MMIC's and can significantly reduce the IMA implementation cost while improving overall performance.

Acknowledgment

The authors would like to acknowledge the support of K. W. Chang for design discussions; T. Naeole, R. Di, and R. Zamora, for wafer processing; C. Osaka for EBL; D. Tran, Y. Y. Tu, and N. Nguyen for backside processing; S. Esparza and Art Schiaroli for RF testing; and S. Makishi for layout.

References

[1] D. C. Streit, D. K. Umemoto, K. W. Kobayashi, and A. K. Oki, "Monolithic HEMT-HBT integration by selective MBE," *IEEE Trans. Electron Devices*, vol. 42, pp. 618–623, Apr. 1995.

[2] K. W. Kobayashi, A. K. Oki, D. K. Umemoto, T. R. Block, and D. C. Streit, "A monolithic integrated HEMT-HBT S-band receiver," in *IEEE GaAs IC Symp. Dig.*, Orlando, FL, 1996.

[3] K. W. Kobayashi, D. K. Umemoto, T. R. Block, A. K. Oki, and D. C. Streit, "A monolithicly integrated HEMT-HBT 1–6 GHz low noise-high linearity variable gain amplifier by selective MBE," *IEEE J. Solid-State Circuits*, vol. 31, pp. 714–718, May 1996.

[4] K. W. Kobayashi, D. C. Streit, A. K. Oki, D. K. Umemoto, and T. R. Block, "A novel monolithic HEMT LNA integrating HBT-tunable active-feedback linearization by selective MBE," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2384–2391, Dec. 1996.

[5] K. W. Kobayashi, D. K. Umemoto, T. R. Block, A. K. Oki, and D. C. Streit, "A wideband HEMT cascode low-noise amplifier with HBT bias regulation," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 457–459, Dec. 1995.

[6] K. W. Kobayashi, A. K. Oki, L. B. Sjogren, D. K. Umemoto, T. R. Block, and D. C. Streit, "A monolithic HEMT passive switch with integrated HBT standard logic compatible driver for phased array applications," *IEEE Microwave Guided Wave Lett.*, vol. 6, pp. 55–57, Jan. 1996.

[7] K. W. Kobayashi, D. K. Umemoto, T. R. Block, A. K. Oki, and D. C. Streit, "A novel monolithic LNA integrating a common-source HEMT with an HBT Darlington amplifier," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 442–444, Dec. 1995.

[8] K. W. Kobayashi, D. C. Streit, D. K. Umemoto, T. R. Block, and A. K. Oki, "A monolithic HEMT-HBT direct-coupled amplifier with active input matching," *IEEE Microwave Guided Wave Lett.*, vol. 6, pp. 55–57, Jan. 1996.

[9] K. W. Kobayashi, D. C. Streit, D. K. Umemoto, and A. K. Oki, "A novel monolithic HBT-p-i-n-HEMT integrated circuit with HBT feedback and p-i-n diode variable gain control," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1004–1009, May 1995.

[10] D. C. Streit, T. R. Block, A.-C. Han, M. Wojtowicz, D. K. Umemoto, K. Kobayashi, A. K. Oki, P.-H. Liu, R. Lai, and G. Ng, "GaAs and InP selective molecular-beam epitaxy," *J. Vac. Sci. Technol.*, vol. B-13, no. 2, pp. 771–773, Mar./Apr. 1995.

[11] L. Tran, J. Cowles, R. Lai, T. Block, P. Liu, A. Oki, and D. Streit, "Monolithic integration of InP HBT and HEMT by selective molecular beam epitaxy," in *Proc. 8th Int. Conf. on Indium Phosphide and Related Materials Dig.*, Schwäbisch, Gmünd, Germany, Apr. 21, 1996, pp. 76–78.

[12] K. W. Kobayashi, R. Esfandiari, B. L. Nelson, K. Minot, W. Jones, R. Lai, M. Bendenbender, K. L. Tan, and J. Berenz, "Monolithic regulated self-biased HEMT MMIC's," *IEEE Trans. Microwave Theory Tech.*, pp. 2610–2616, Dec. 1994.

[13] D. C. Streit, K. W. Kobayashi, A. K. Oki, and D. K. Umemoto, "A monolithic HBT-regulated HEMT LNA by selective MBE," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 124–126, Apr. 1995.

[14] H. Wang, G. I. Ng, R. Lai, Y. Hwang, D. C. W. Lo, R. Dia, A. Freudenthal, and T. Block, "Fully passivated W-band InAlAs/InGaAs/InP monolithic low noise amplifiers," *Proc. Inst. Elec. Eng., Microw. Antennas Propag.*, vol. 143, pp. 361–366, Oct. 1996.

[15] K. W. Kobayashi, L. T. Tran, J. C. Cowles, T. R. Block, A. K. Oki, and D. C. Streit, "Extending the bandwidth performance of heterojunction bipolar transistor-based distributed amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 739–748, May 1996.