A Novel Monolithic HBT-p-i-n-HEMT Integrated Circuit with HBT Active Feedback and p-i-n Diode Variable Gain Control

Kevin W. Kobayashi, *Member, IEEE,* Dwight C. Streit, *Senior Member, IEEE,* Donald K. Umemoto, *Member, IEEE,* and Aaron K. Oki, *Member, IEEE*

***Abstract*—We report the world's first functional MMIC circuit integrating HBT's, HEMT's, and vertical p-i-n diodes on a single III-V substrate. The 1–10 GHz variable gain amplifier monolithically integrates HEMT, HBT, and vertical p-i-n diode devices has been fabricated using selective MBE and a merged processing technology. The VGA offers low-noise figure, wideband gain performance, and good gain flatness over a wide gain control range. A noise figure below 4 dB was achieved using a HEMT transistor for the amplifier stage and a wide bandwidth of 10 GHz. A nominal gain of 10 dB was achieved by incorporating HBT active feedback techniques and 12 dB of gain control range was obtained using a vertical p-i-n diode as a varistor, all integrated into a compact 1.5 × 0.76 mm^2 MMIC. The capability of monolithically integrating HBT's, HEMT's, and p-i-n's in a merged process will stimulate the development of new monolithic circuit techniques for achieving optimal performance as well as provide a foundation for high performance mixed-mode multifunctional MMIC chips.**

I. Introduction

THE MONOLITHIC integration of HEMT and HBT technologies by selective molecular beam epitaxy (MBE) and a novel merged processing technology has lead to the world's first fully functional HEMT-HBT MMIC's [1], [2]. This previous work had demonstrated that both the 2 μm emitter width GaAs-AlGaAs HBT and 0.2 μm gate-length pseudomorphic InGaAs-GaAs HEMT device and circuit performance was equivalent to device and circuit performance produced using our conventional MBE single-technology processes. These revealing results suggest that optimum performance monolithic microwave integrated circuits (MMIC's) can be realized using the excellent linearity, power-added efficiency, and low $1/f$ flicker noise characteristics of HBT's and the state-of-the-art low-noise-figure capabilities offered by HEMT's.

Optimum MMIC performance and additional circuit functionality can be achieved from a merged HBT-p-i-n-HEMT process. New MMIC applications can result from this new technology. Optoelectronic applications such as a photo-receiver integrating p-i-n diode detection, low-noise HEMT transimpedance amplification, and high-speed (>5 Gbps) HBT clock-recovery and decision circuits to achieve >5 Gbps receiver chip performance are enabled by selective MBE techniques. Optimum performance Monolithic Transmit-Receive (T/R) MMIC's can also be obtained using HBT's for high Power Added Efficiency (PAE) power amplifiers, HEMT's for low-noise figure amplifiers (LNA's), and vertical GaAs p-i-n diode for low insertion-loss and high power handling switches. In addition, optimum performance mixed-mode digital receiver MMIC's can be realized by integrating HEMT LNA's, high linearity HBT vertical Schottky diode mixers, and high-speed (Gbps) HBT analog-to-digital converters. The number of MMIC applications will grow tremendously from this selective MBE merged processing capability.

Additional nuances in advanced circuit techniques will also result from the ability to combine analog, digital, and microwave design techniques. The HBT's can provide a host of analog-bipolar and digital design topologies and techniques that save area and power consumption, as well as offer precise self-biasing capability. The HEMT's can provide their inherently low-noise and high-frequency performance and high input impedance, which is advantageous for feedback designs. One novel MMIC demonstration embodied in this work that combines analog-bipolar and microwave design techniques is a variable gain amplifier. The amplifier achieves low-noise figure at maximum gain by using a low-noise HEMT transistor for the amplifying stage. Variable gain control is incorporated by using a p-i-n diode as a variable feedback resistor, which is electronically controlled. HBT active inductor feedback techniques are used to enhance bandwidth response as well as self-bias the HEMT transistor without degrading the noise performance of the VGA circuit. All these functions are incorporated into a very compact monolithic chip that requires little or no external components.

This mixed-technology VGA represents the world's first fully functional demonstration of an HBT-p-i-n-HEMT MMIC fabricated using selective MBE and a merged processing technology. Furthermore, this VGA illustrates the use of a mixture of design techniques to achieve optimal overall performance, which is made possible by this multi-technology integration capability.

The following sections will describe the monolithic integration technology, the design of a HEMT feedback amplifier implementing HBT active feedback, and the design of a HBT-p-i-n-HEMT variable gain amplifier MMIC that integrates HBT and HEMT transistors with a vertical p-i-n diode.

Manuscript received June 27, 1994; revised September 15, 1994.
The authors are with TRW Electronic Systems and Technology Division, Redondo Beach, CA 90278 USA.
IEEE Log Number 9410319.

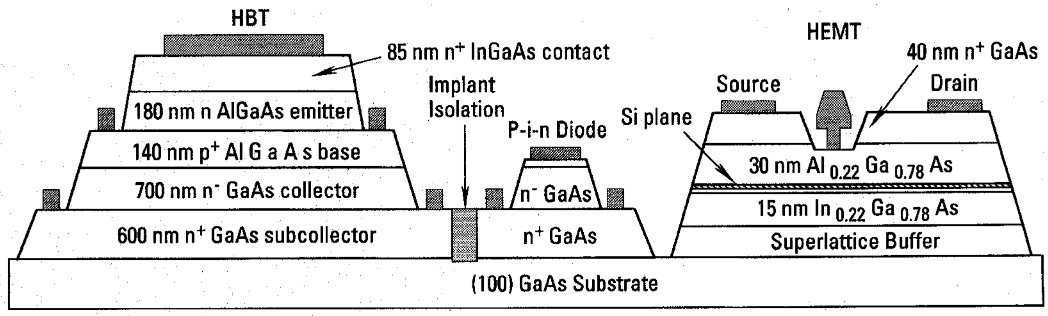


Fig. 1. Cross-section of the HBT, HEMT, and vertical p-i-n diode integrated circuit process technology.

II. HEMT-p-i-n-HBT Integrated Technology

The monolithic integration of HEMT's and HBT's by selective MBE has previously been reported in detail [1], [2]. The selective MBE techniques used here are based on silicon nitride definitions and patterning of a previously grown HBT epitaxial layer and are similar in concept to the techniques we have previously used to fabricate complementary *npn-pnp* HBT circuits [3]–[6]. The GaAs-AlGaAs HBT structure is grown first using our baseline process. This HBT MBE profile is optimized for TRW's high-linearity applications and has shown excellent reliability with a mean time to failure $>10^8$ hours at a junction temperature of 125°C, based on three-temperature life tests at a current density of $J_c \approx 6.7$ kA/cm^2 [7]. The HBT wafer is patterned with silicon nitride deposited by plasma-enhanced chemical vapor deposition. The silicon nitride and HBT layer are selectively etched to form HBT material islands. The patterned wafer is then cleaned and reintroduced into the MBE system for HEMT material growth. The pseudomorphic InGaAs-GaAs HEMT layer is grown using our normal HEMT growth procedures forming high quality epitaxial material in areas where the HBT material has been removed. A merged HEMT-HBT process technology was developed to allow a common process to be used for both the HEMT and HBT devices. The remainder of the process includes thin film resistors, airbridges within islands and between HEMT and HBT islands, wafer thinning, and backside vias. Fig. 1 shows a cross-section of the resulting HBT-p-i-n-HEMT integrated circuit technology.

This technology integrates 0.2 μm gate-length pseudomorphic InGaAs-GaAs HEMT's and 2 μm emitter-width self-aligned base ohmic metal GaAs-AlGaAs HBT's. The HEMT and HBT devices produced by selective MBE and fabricated using a merged HEMT-HBT process exhibit performance equivalent to devices fabricated using conventional MBE and our baseline single-technology processes [1], [2]. Using our baseline profiles with the selective MBE process, the 0.2-μm HEMT devices achieved $g_m = 600$ mS/mm, an $f_T = 80$ GHz, and a corresponding $f_{\max} = 150$ GHz. The 2-μm HBT devices achieved $\beta = 110$ at $J_c = 3.3$ kA/cm^2, an $f_T =$ 22 GHz, and an $f_{\max} = 50$ GHz. The vertical p-i-n diodes achieve >410 GHz cutoff frequencies calculated from the off-capacitance on-resistance R-C time constant. THz cutoff frequency vertical Schottky diodes may also be fabricated with only an additional mask layer and processing step. This merged processing technology can integrate the best circuit performance through optimal device technology selection.

III. HBT Active Feedback Techniques Integrated with HEMT Amplifiers

Active feedback techniques have previously been developed to economically implement regenerative feedback in amplifiers. Normally implemented as a spiral inductor in the parallel feedback loop in microwave circuits, positive feedback is used to regenerate the gain at the upper band edge of the gain response. Active feedback can be implemented with small 2 $\times$ 10-μm^2 area transistors instead of large spiral inductors that are 10–20 times greater in size. Thus by using HBT active techniques, positive feedback can be implemented with minimal impact on chip size. We have previously reported a novel active feedback technique which can increase the bandwidth of HBT amplifiers by 50% [8].

HBT's are more convenient than HEMT's when incorporating active feedback because the HBT's are smaller, more easily self-biased, and consume less power. Selective MBE allows the integration of HBT active feedback techniques that have been previously developed to enhance the gain-bandwidth performance of a compact HEMT amplifier stage. Furthermore, the results shown below indicate that the HBT active feedback employed does not adversely affect the overall noise figure of the HEMT amplifier.

A HEMT amplifier employing three different types of feedback networks was studied in this work. The schematic of the HEMT amplifier integrated with each of the different feedback networks is shown in Fig. 2. Fig. 2(a)–(c) illustrates a resistive feedback network, a single HBT active feedback network, and a two HBT active feedback network employed with the same HEMT amplifier design, respectively. The simple resistive feedback was fabricated as a reference for comparison. The other two active HBT feedback topologies are based on previous active inductor work by S. Hara *et al.* [9]. The single transistor feedback topology is based on conventional bipolar techniques while the two-transistor topology has the added characteristic of providing a higher Q inductance and results in improved regenerative feedback. Both active HBT feedback topologies provide positive feedback, which is required to regenerate the gain at the upper band edge. The active HBT topologies can be realized with less than 25 mW of power consumption (4.3 mA–5 V). Fig. 3 shows a photograph of the HEMT amplifier and HBT active feedback of Fig. 2(c). The total size is 1.12 $\times$ 0.76 mm^2, and consumes a total of 138 mW through $\pm$5-V supplies. This layout illustrates the monolithic integration of the HBT active feedback with a HEMT amplifier.

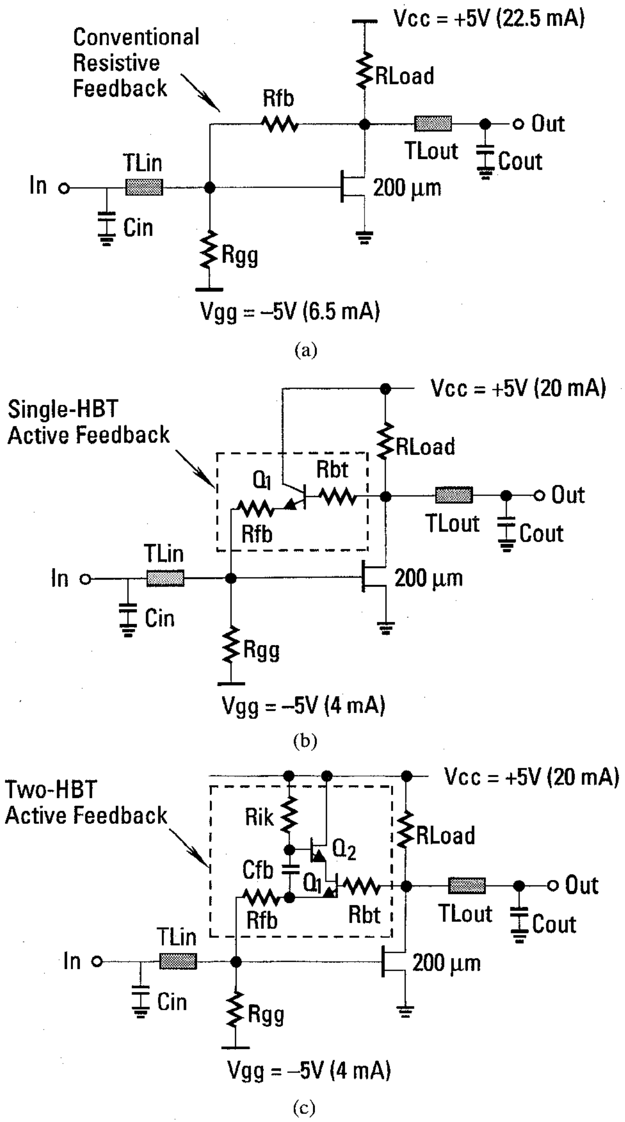


Fig. 2. (a) Conventional resistive feedback. (b) Single HBT active feedback. (c) Two-HBT active feedback topologies integrated with a HEMT amplifier.

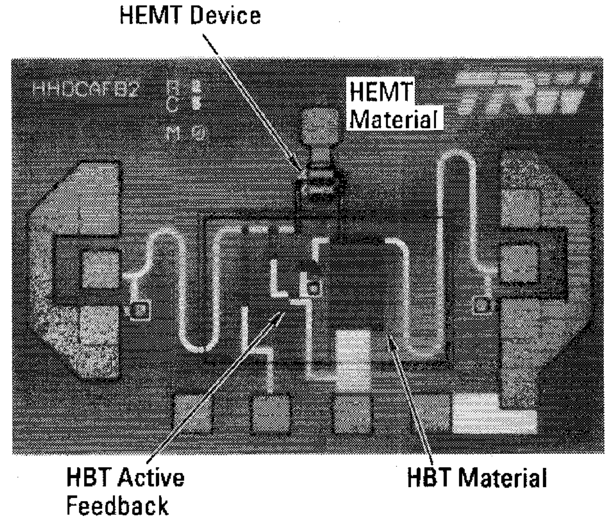


Fig. 3. Photograph of the HEMT amplifier integrated with the two-HBT active feedback topology. Chip size is 1.12×0.76 mm^2.

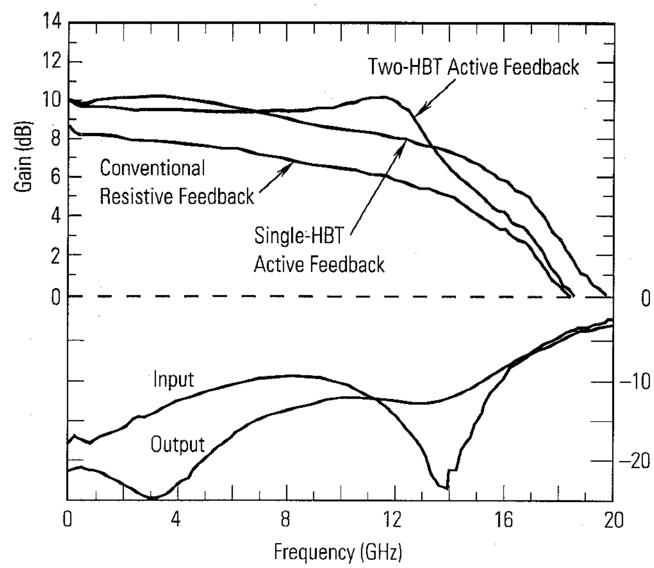


Fig. 4. Broadband gain performance for each of the three feedback designs and typical return-loss response.

Broad band gain performance was measured for each of the three feedback configurations and are shown in Fig. 4. The resistive feedback obtains a gain of 8.6 dB and a 3-dB bandwidth of 12.7 GHz. The Gain-Bandwidth-Product (GBP) is 34.1 GHz. The single HBT active feedback implementation obtained a gain of 9.7 dB and a bandwidth of 14.8 GHz. The GBP is 45.2 GHz which is a 32% improvement over the resistive feedback. The two-HBT transistor active feedback implementation achieved 9.75 dB gain, a 14 GHz bandwidth, and a GBP of 43 GHz. Fig. 4 shows that this two-HBT active feedback network achieved a slight gain peaking of 0.5 dB at 12 GHz. This circuit achieves a much flatter gain response over much of the band.

The input and output return-loss performance of the single HBT active feedback design is also given in Fig. 4. The input return-loss is better than 10 dB across the band, while the output return-loss is better than 12.5 dB, respectively. The other two designs have similar return-loss performance.

Noise figure performance was also measured for the three feedback implementations. Fig. 5 shows a wideband plot of the noise figure for the various feedback designs. The resistive feedback had a noise figure between 3 and 3.5 dB up to 14 GHz. The single HBT active feedback had a noise figure that ranged from 2.5–2.9 dB up to 14 GHz. This is actually lower than the noise figure of the purely resistive feedback design, which suggests that the active HBT does not adversely affect the noise figure performance. The reason for the lower noise figure might be explained by having a higher frequency dependent feedback impedance presented by the active HBT. The two-HBT active feedback design, however, achieved poorer noise figure above 10 GHz. For frequencies above 10 GHz the noise figure ramps up to around 5 dB. This increase in noise figure could be explained by the fact that this design is employing enough positive feedback to peak the gain at 12 GHz. The additional positive feedback may be regenerating noise as well as gain at the upper band edge.

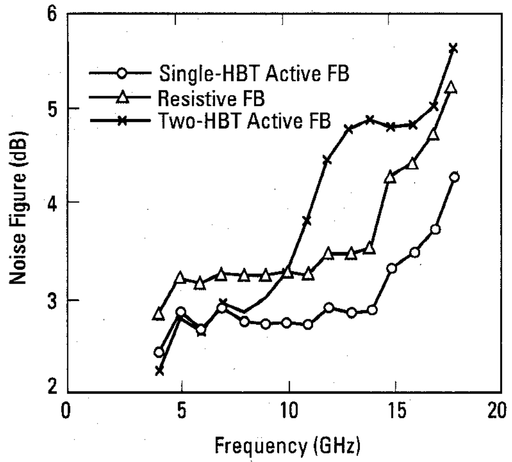


Fig. 5. Broadband noise figure performance for each of the three feedback designs.

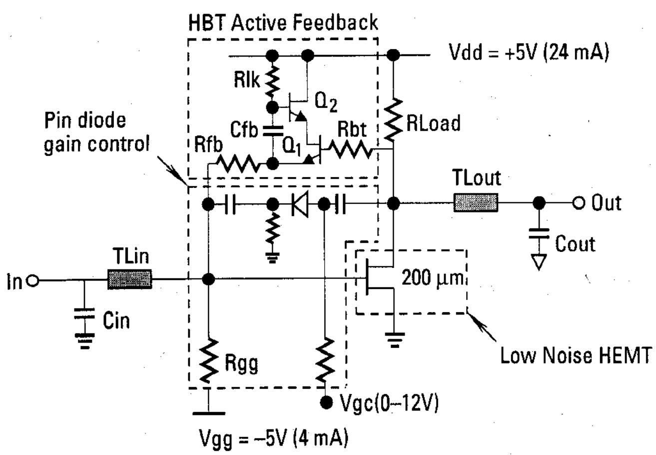


Fig. 6. Schematic of the HBT-p-i-n-HEMT selective-technology variable gain amplifier.

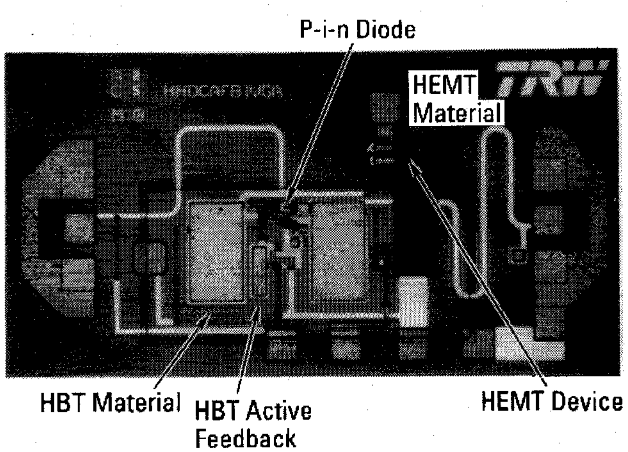


Fig. 7. Photograph of the HBT-p-i-n-HEMT variable gain amplifier.

Both HBT active feedback topologies achieved improved gain-bandwidth performance with little impact on dc power and overall MMIC size. In addition, we have shown that the single HBT active feedback design had no degradation in noise performance, in fact it could be designed to achieve both improved gain-bandwidth and noise figure.

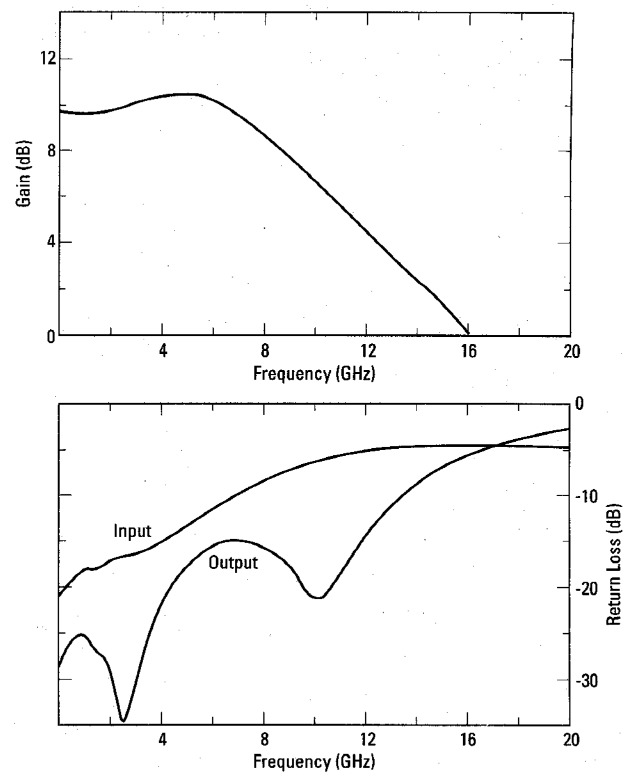


Fig. 8. Gain and return-loss response of the VGA at maximum gain setting.

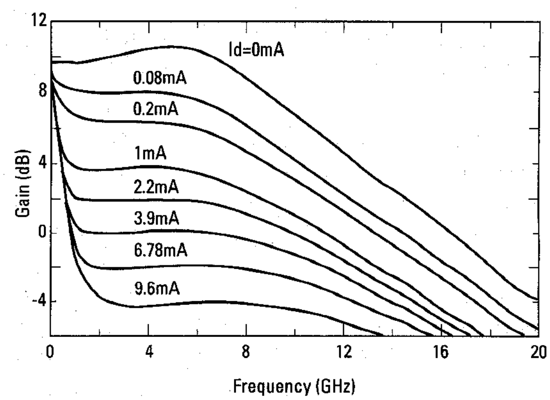


Fig. 9. Broadband variable gain response at various p-i-n diode bias currents (gain settings).

IV. HEMT-p-i-n-HBT Variable Gain Amplifier

A HEMT variable gain amplifier MMIC integrating HEMT's, HBT's, and vertical p-i-n diodes was designed using the selective MBE merged processing technology. The active feedback techniques described above were implemented to obtain broadband gain flatness over gain control. Fig. 6 shows a schematic of the multi-technology variable gain amplifier. By incorporating a p-i-n diode in the paralleled feedback path, electronic variable gain control is obtained using the p-i-n as a varistor. In addition, the two-HBT active feedback topology is also implemented to increase the gain flatness and bandwidth performance over gain control. A similar variable gain amplifier using these techniques was demonstrated in InAlAs-InGaAs HBT technology [10]. The VGA consists of a $0.2 \times 200\ \mu m^2$ HEMT device biased at 20 mA. A vertical

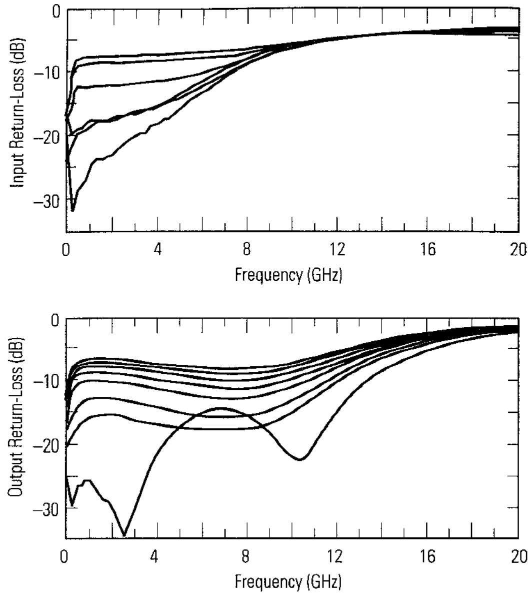


Fig. 10. Input and output return-loss over p-i-n diode gain control.

p-i-n diode in the parallel feedback is used as a variable resistance to control the amount of feedback. An HBT active feedback comprised of transistors Q_1, Q_2, capacitor C_{fb}, and resistors, R_{lk}, R_{fb}, R_{bt} is implemented in order to regenerate the gain at the upper band. The HBT active feedback is used to improve the gain flatness response, especially over the gain control range. The HBT active feedback consumes less than 4.4 mA. Additional series transmission lines and shunt capacitors are used to improve the matching of the input and output at the upper band frequencies. Fig. 7 shows a photograph of the HBT-p-i-n-HEMT VGA. The circuit is realized in a compact 1.5 × 0.76 mm^2 area.

Fig. 8 shows the wideband small-signal response of the VGA at maximum gain setting. The amplifier achieves a nominal gain of 10 dB with a 3-dB bandwidth of 10 GHz. The input return-loss is better than 10 dB up to 7 GHz and degrades to 6.3 dB at 10 GHz. The output return-loss is 14 dB or better up to 12 GHz. Fig. 9 shows the gain response for various p-i-n diode bias currents. The 3-dB bandwidth is maintained to within 1 GHz across the gain control range. Additional bandwidth compensation could be implemented at each gain setting by changing the bias of the HBT active feedback [10]. Fig. 10 shows the corresponding input and output return-loss over gain control. The input and output return-losses degrade to a worst case of between 6 and 7 dB.

Broadband noise figure performance was measured at each of the gain settings and is shown in Fig. 11. At maximum gain the noise figure is ≈4 dB. This is 1–1.5 dB higher than the HEMT amplifier integrated with the single HBT active feedback discussed above. The additional noise figure may have resulted from additional noise contribution from the p-i-n diode feedback path. Overall, the noise figure is flat over the entire bandwidth and degrades with decreasing gain. Fig. 12 further illustrates this point, showing that the noise figure is insensitive to gain control at the higher gain settings, NF: Gain ≈1:3. At lower gain settings the noise figure sensitivity

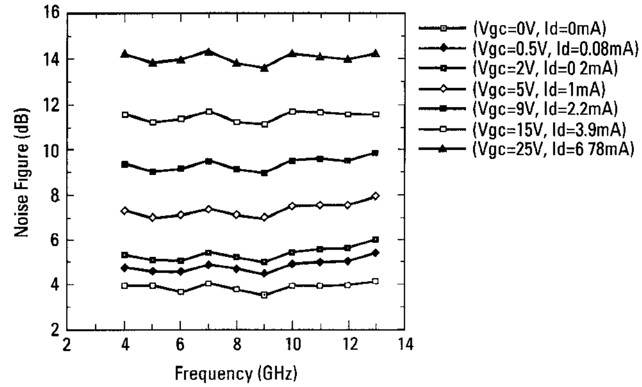


Fig. 11. Broadband noise figure performance at various gain settings.

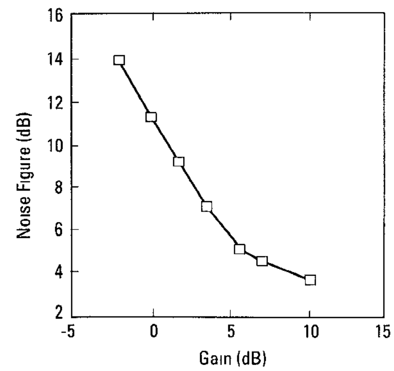


Fig. 12. Noise figure plotted versus gain at a frequency of 6 GHz.

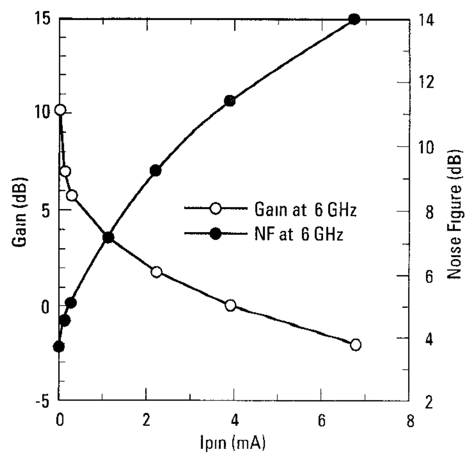


Fig. 13. Gain and noise figure performance at 6 GHz versus p-i-n diode bias current.

increases, NF: Gain ≈1:1. Finally, Fig. 13 shows both gain and noise figure performance at 6 GHz over the various p-i-n diode bias currents. This figure indicates a total gain control of 12 dB and a corresponding noise figure range of ≈10 dB.

V. Conclusion

A variable gain amplifier that monolithically integrates HEMT, HBT, and vertical p-i-n-diode devices has been fabricated using Selective MBE regrowth techniques and a merged processing technology. This is the world's first fully functional MMIC circuit integrating HBT's, HEMT's, and vertical p-in diodes. The VGA offers the low-noise figure of a HEMT, wideband gain performance using active feedback, and wide gain control range using a vertical p-i-n diode as a feedback varistor. The high performance multi-functional mixed technology MMIC consumed only 138 mW of dc power and was realized in a compact 1.5×0.75 mm^2 area. In addition, the novel integration of HBT-analog active feedback with a HEMT amplifier was successfully demonstrated showing as much as a 32% improvement in gain-bandwidth product and a 0.5 dB improvement in noise figure. The capability of monolithically integrating HBT's, HEMT's, and p-i-n's in a merged process will provide a foundation for high performance mixed-mode multi-functional MMIC chips and stimulate the development of novel circuits integrating analog-digital-bipolar and microwave design techniques.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Po-Hsin and Anika Freudenthal for EBL, Tom Block and An-Chich Han for MBE, Tim Naeole and Sue Thomas for device processing, and the members of TRW's RF Products Center for their assistance.

REFERENCES

[1] D. C. Streit, D. K. Umemoto, K. W. Kobayashi, and A. K. Oki, "Monolithic HEMT-HBT integration by selective MBE," in *IEEE GaAs IC Symp. Dig.*, Philadelphia, PA, Oct. 1994.

[2] D. C. Streit, D. K. Umemoto, J. R. Velebir, K. W. Kobayashi, and A. K. Oki, "35 GHz HEMT amplifiers fabricated using integrated HEMT-HBT material grown by selective MBE" *IEEE Microwave and Guided Wave Lett.*, vol. 4, no. 11, Nov. 1994.

[3] ——, "Selective molecular beam epitaxy for integrated *npn/pnp* heterojunction bipolar transistors," *J. Vac. Sci. Tech.*, vol. B10, pp. 1020–1022, 1992.

[4] D. K. Umemoto, J. R. Velebir, K. W. Kobayashi, A. K. Oki, and D. C. Streit, "Integrated *npn/pnp* GaAs/AlGaAs HBT's grown by selective MBE," *Electron. Lett.*, vol. 27, pp. 1517–1518, 1991.

[5] K. W. Kobayashi, D. K. Umemoto, J. R. Velebir, A. K. Oki, and D. C. Streit, "Complementary HBT push-pull amplifier by selective MBE," *IEEE Microwave and Guided Wave Lett.*, vol. 2, pp. 149–150, 1992.

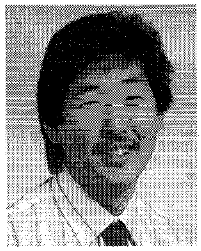
[6] ——, "Integrated complementary HBT microwave push-pull and Darlington amplifiers with p-n-p active loads," *IEEE J. Solid-State Circuits*, vol. 28, pp. 1011–1017, 1993.

[7] D. C. Streit, A. K. Oki, D. K. Umemoto, J. R. Velebir, K. S. Stolt, F. M. Yamada, Y. Saito, M. E. Hafizi, S. Bui, and L. T. Tran, "High-reliability GaAs-AlGaAs HBT's by MBE with Be based doping and InGaAs emitter contacts," *IEEE Electron Dev. Lett.*, vol. 12, pp. 471–473, 1991.

[8] K. W. Kobayashi, L. T. Tran, J. R. Velebir, A. K. Oki, and D. C. Streit, "A novel active feedback design using InAlAs/InGaAs heterojunction bipolar transistors," *IEEE Microwave and Guided Wave Lett.*, vol. 4, no. 5, pp. 146–148, May 1994.

[9] S. Hara, T. Tokumitsu, and M. Aikawa, "Lossless broadband monolithic microwave active inductors," in *IEEE MTT-S Dig.*, Long Beach, CA, 1989, pp. 955–958.

[10] K. W. Kobayashi, A. K. Oki, D. K. Umemoto, S. Claxton, and D. C. Streit, "Monolithic GaAs HBT p-i-n diode variable gain amplifiers, attenuators and switches," *IEEE Trans. Microwave Theory Tech.*, vol. 41, no. 12, pp. 2295–2302, Dec. 1993.



Kevin W. Kobayashi (M'93) was born in San Diego, CA, in 1963. He received the B.S.E.E. from the University of California at San Diego in 1986 and the M.S.E.E. degree from the University of Southern California in 1991.

Since 1986 he has been working at TRW's Advanced Microelectronics Laboratory in Redondo Beach, CA, where he has been involved in the development of HBT, HEMT, and MESFET technology. His primary focus is the design of HBT and HEMT MMIC's for insertion into TRW systems. He has authored/co-authored 60 technical papers and has received six patents on novel circuit techniques.

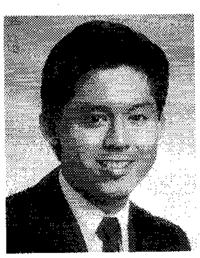
Dwight C. Streit (S'81–M'86–SM'92) received the Ph.D. degree in electrical engineering from the University of California, Los Angeles, in 1986.

He is currently Assistant Manager of the Microelectronics Product and Technology Development Department and Manager of the Advanced Materials Section in TRW's RF Products Center. He is also principal investigator for two research and development projects related to III–V materials and monolithic microwave HEMT-HBT integrated circuits. His primary research interest is the relationship between material characteristics and device performance, and his work has dealt with both HEMT and HBT material development and device design. He has authored or co-authored over 150 technical papers and has over a dozen patents awarded or pending related to semiconductor material and devices.

Dr. Streit is a TRW Technical Fellow. He is a three-time recipient of the TRW Chairman's Award for Innovation, and is a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi.

Donald K. Umemoto (M'88) received the B.S. degrees in biology and electrical engineering in 1979 and 1986, respectively, and the M.S. degree in electrical engineering in 1988, all from the University of Hawaii at Manoa.

He joined TRW, Inc., Redondo Beach, CA, in 1988 as a member of the technical staff of the HBT Technology Section in the GaAs IC Department. He is currently the Section Head of the Photolithography/Wet Etch Section of TRW's GaAs Flexible Manufacturing Process Laboratory.



Aaron K. Oki (M'85) was born in Honolulu, HI. He received the B.S. degree in electrical engineering in 1983 from the University of Hawaii, Manoa, and the M.S. degree in electrical engineering and computer science in 1985 from the University of California, Berkeley.

Since joining TRW as a member of technical staff in 1985, he has been working on production and advanced development of HBT technology. In 1990 he became the principle investigator for HBT IR&D and Section Head of the HBT products section.