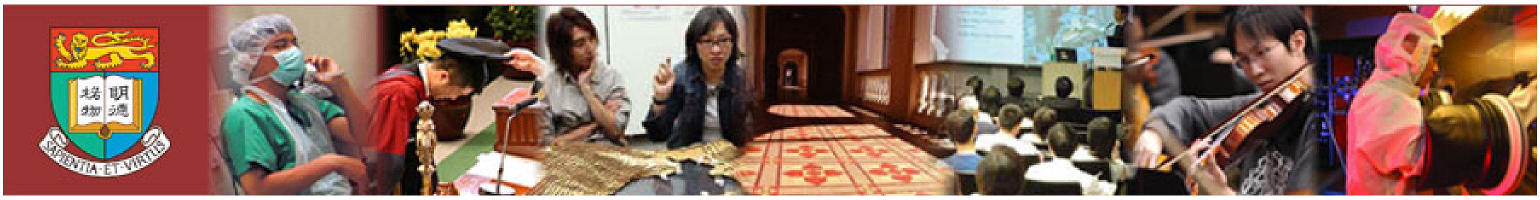


Title	**High efficiency, low offset voltage InGaP/GaAs power heterostructure-emitter bipolar transistors with advanced thermal management**
Author(s)	**Yan, BP; Yang, ES; Yang, YF; Wang, XQ; Hsu, CC**
Citation	**Ieee Transactions On Electron Devices, 2003, v. 50 n. 10, p. 2154-2158**
Issued Date	**2003**
URL	**http://hdl.handle.net/10722/42982**
Rights	**©2003 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.**

High Efficiency, Low Offset Voltage InGaP/GaAs Power Heterostructure–Emitter Bipolar Transistors With Advanced Thermal Management

Bei-Ping Yan, Edward S. Yang, *Fellow, IEEE*, Yue-Fei Yang, *Member, IEEE*, Xiao-Qin Wang, and Chung-Chi Hsu

***Abstract*—High efficiency, low offset voltage InGaP/GaAs power heterostructure-emitter bipolar transistors (HEBTs) have been demonstrated. The large signal performance of the HEBTs is characterized. Output power of 0.25 W with power added efficiency (PAE) of 63.5% at 1.9 GHz has been achieved from a 26-finger HEBT with total emitter area of 873.6 μm^2. Output power of 1.0 W with PAE of 63% has been obtained from the composition of four above-mentioned power cells at the optimum conditions of impedance matching. The thermal performance of HEBT is presented and the results show better thermal management than conventional HBT. The experimental results demonstrate good power performance and capability of HEBTs.**

***Index Terms*—Current gain, HEBT, InGaP/GaAs HBT, power performance, temperature dependence.**

I. Introduction

Heterojunction bipolar transistors (HBTs) based on III-V compound semiconductors have been widely used as power amplifiers of mobile handsets because of their remarkable microwave power capabilities and efficiencies. Various publications and communications over the last decade on the topic have shown major improvements in terms of performances and reliability [1], [2]. Today, new ideas and concepts to improve the microwave power characteristics, thermal management, and long term reliability, are very important to make the HBT family to be a major player of the mobile market. As one of the trends to be explored, the heterostructure–emitter bipolar transistor (HEBT) has been of particular interest [3]–[6]. In comparison with conventional HBTs, HEBTs can effectively eliminate the emitter potential spike and offers a low offset voltage [4], [5]. In addition, the heterostructure–emitter can also accommodate the base dopant outdiffusion, which increases device lifetime [6]. Recent theoretical and experimental results show that the current gain of HEBT can be much less dependent on the junction temperature and it can be a better candidate than the HBT for power devices [7]. So far, however, there have been few reports on power performances of HEBTs [8], especially in thermal performance and thermal stability. In this work, we report microwave large-signal results measured from two InGaP/GaAs HEBTs. One consists of 26 2.8×12 μm^2 emitter fingers which constitute a power cell. The other is composed of four above-mentioned power cells. They are all fabricated in the common-emitter configuration. An output power level of 0.25 W, with power added efficiency (PAE) of 63.5% at 1.9 GHz, has been obtained from the 26-finger HEBT with a total emitter area of 873.6 μm^2, and output power of 1.0 W with PAE of 63% has been achieved from the composition of the four above-mentioned power cells at the optimum conditions of impedance matching. The thermal performance of the HEBT is also presented and the results show that the HEBTs possess more advanced thermal management than conventional HBT. The experimental results demonstrate good power performance and capability of the HEBTs in wireless communication applications.

Manuscript received April 29, 2003; revised June 26, 2003. This work was supported by grants from the Research Grants Council of Hong Kong Special Administrative Region, China (Projects HKU 7057/98E and HKU7069/02E). The review of this paper was arranged by Editor M. A. Shibib.

B.-P. Yan, E. S. Yang, X.-Q. Wang and C.-C. Hsu are with the Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong (e-mail: bpyan@eee.hku.hk).

Y.-F. Yang is with the Global Communication Semiconductors, Inc., Torrance, CA 90505 USA.

Digital Object Identifier 10.1109/TED.2003.816551

II. Device Fabrication

InGaP/GaAs HEBTs were grown by MOCVD on a GaAs substrate. The device structure consists of a 600 nm n$^+$-GaAs subcollector $(\mathrm{n} = 4 \times 10^{18}\ \mathrm{cm}^{-3})$, a 700 nm n$^-$-GaAs collector $(\mathrm{n} = 1 \times 10^{16}\ \mathrm{cm}^{-3})$, a 100 nm p$^+$-GaAs base $(\mathrm{p} = 4 \times 10^{19}\ \mathrm{cm}^{-3})$, a 10 nm n-GaAs setback layer $(\mathrm{n} = 3 \times 10^{17}\ \mathrm{cm}^{-3})$, a 40 nm $\mathrm{n-In_XGa_{1-X}P}$ confinement layer (x = 0.5, $\mathrm{n} = 3 \times 10^{17}\ \mathrm{cm}^{-3}$), and a 150 nm n$^+$-GaAs emitter cap layer $(\mathrm{n} = 4 \times 10^{18}\ \mathrm{cm}^{-3})$, a 50 nm $\mathrm{n^+ - In_XGa_{1-X}As}$ graded layer (x from 0 to 0.6, $\mathrm{n} = 1 \times 10^{19}\ \mathrm{cm}^{-3}$), and a 50 nm $\mathrm{n^+ - In_XGa_{1-X}As}$ contact layer ($x = 0.6$, $\mathrm{n} = 1 \times 10^{19}\ \mathrm{cm}^{-3}$). The HEBTs were fabricated using a non self-aligned process. Standard photolithography and chemical wet selective etching were used in the device processing. The InGaP layer was etched using a solution of dilute HCl and the InGaAs and GaAs layers were etched with H_3PO_4: H_2O_2: H_2O. Emitter and base metal are Ti/Pt/Au and collector metal is AuGe/Ni/Au. A thin depleted InGaP ledge with a length of 0.8 μm was used as a passivation layer for the extrinsic base surface to reduce the surface recombination current. To reduce thermal resistance, the substrates were thinned to 100 μm and a gold plated heat sink structure was used.

III. Results and Discussion

Fig. 1 shows typical common-emitter current–voltage (I–V) characteristics of a 26-finger power HEBT. Notice that the current gain increases with the collector current. The current gain is more than 30 at high collector current but only about 10 at

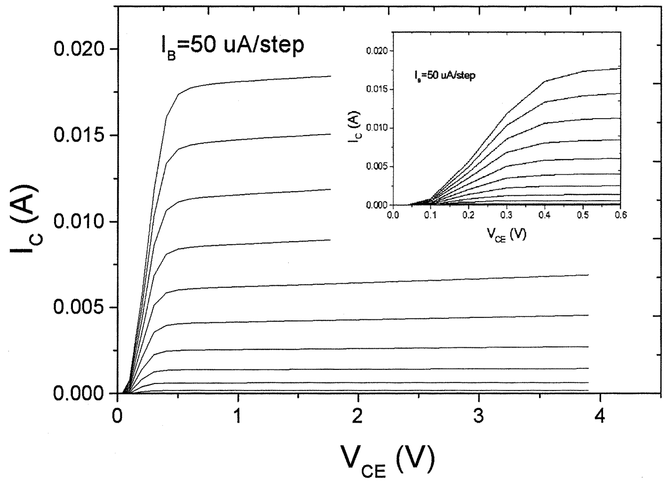


Fig. 1. I–V characteristics of 26-finger power HEBT with an emitter size of $2.8 \times 12 \times 26$ μm^2.

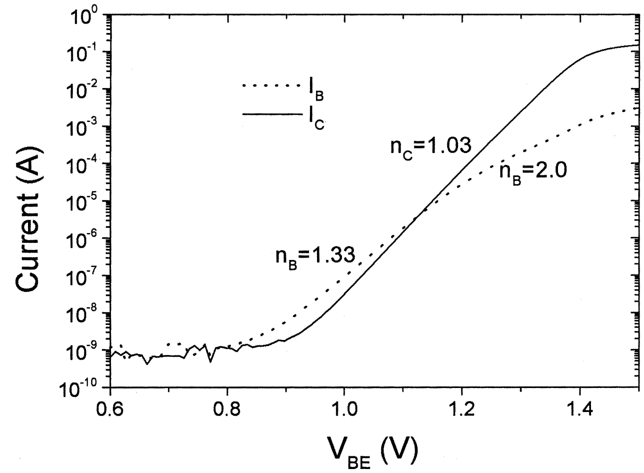


Fig. 2. Gummel plots for InGaP/GaAs/ HEBT with an emitter size of $2.8 \times 12 \times 26$ μm^2.

low current. The smaller current gain at low current is attributed to larger interface recombination located at the extrinsic base. Because the InGaP layer located at the extrinsic base has been completely depleted, the surface recombination at the exposed InGaP surface is negligible. On the other hand, due to the very low surface recombination velocity of InGaP, the interface recombination between the n-type GaAs setback layer and the n-type InGaP confinement layer is also negligible. Therefore, the dominant recombination current at low current is the interface recombination current between the p$^+$-type GaAs base layer and the n-type GaAs setback layer. This conclusion can also be demonstrated by the Gummel plots as shown in Fig. 2. It can be seen from Fig. 2 that the ideality factor of base current I_B is 1.33 at low $V_{\rm be}$, which is very close to the ideality factor of surface recombination current but far smaller than the ideality factor 2 of space charge region recombination current. At high $V_{\rm be}$, however, the base current ideality factor approaches an ideality factor 2, indicating that the dominate recombination current at high $V_{\rm be}$ is the space charge region recombination which mainly occurs in the depleted n-GaAs setback layer. Measured offset voltage is about 60 mV (inset of Fig. 1), which is significantly smaller than that of HBT. The reduction of the offset voltage is attributed to the insertion of the GaAs setback layer between the p$^+$-GaAs base and n$^-$-InGaP confinement layer. This makes the emitter-base junction become a GaAs/GaAs homojunction and therefore reduces the asymmetry between EB and BC junctions. The breakdown voltage of the base-collector junction, $\rm BV_{ceo}$, is 15 V.

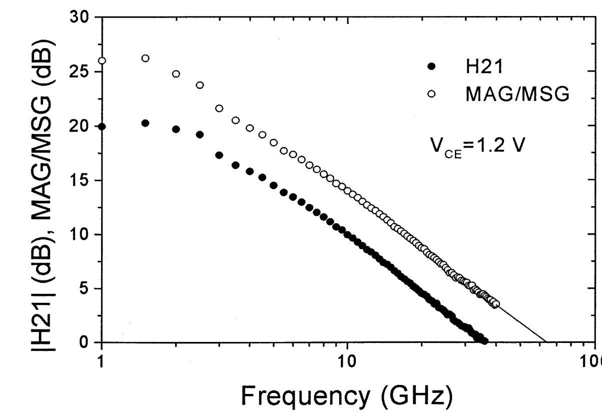


Fig. 3. Measured forward current gain, the maximum available gain as a function of frequency.

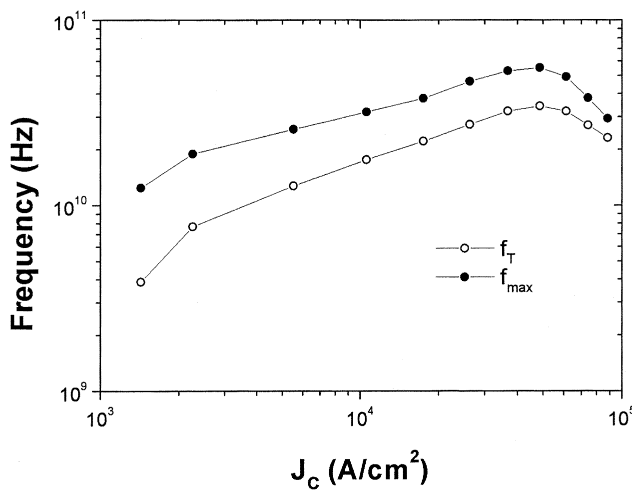


Fig. 4. Current gain cutoff frequency and the maximum oscillation frequency as a function of the collector current density.

Fig. 3 illustrates the high-frequency performance of a RF device in the common-emitter configuration. The forward current gain $(\rm H_{21})$, and maximum available gain (MAG) were measured on wafer using a network analyzer from 0.1 to 40 GHz. The measurements were completed on the 2-finger HEBT with emitter size of $2.8 \times 12 \times 2$. The operating collector current density is 2.22×10^4 A/cm^2, and the collector-emitter bias $(V_{\rm CE})$ is 1.2 V. The measured cutoff frequency f_T is 35 GHz and the maximum oscillation frequency $f_{\rm max}$ extrapolated from MAG using a 20-dB/dec slope is 62 GHz. These high frequency results are decent since the device structure is not aimed at achieving the best small-signal performance. Instead, the epitaxial structure, which includes a thick collector doped at low concentration, is designed for large-signal power performance. The measured f_T and $f_{\rm max}$ as functions of collector current density are shown in Fig. 4. Peaks of f_T and $f_{\rm max}$ were obtained at

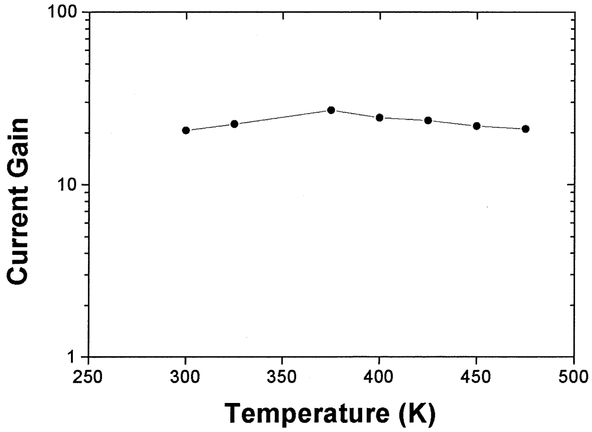


Fig. 5. Measured current gain as a function of temperature for a 2-finger HEBT.

$J_C = 4.9 \times 10^4$ A/cm^2, which is the threshold current density of the device. This value provides a good agreement with theoretical calculation by $J = qN_C \nu_{\rm sat}$.

The thermal stability of current gain is an important issue for power devices. Fig. 5 shows the measured current gain as a function of temperature for a 2-finger HEBT. The current gain shows a temperature coefficient that is slightly positive in the low temperature range and slightly negative in the high temperature range. This result is significantly different from that of the conventional InGaP/GaAs and AlGaAs/GaAs HBT [9] in which the current gain degrades with increase in temperature. This finding indicates that the HEBTs have a weak temperature dependence of current gain and it may be preferable to choose HEBTs for power applications. It is well known that there are two thermal phenomena in power HBTs, i.e., thermal runaway and the collector current collapse, which are caused by current crowding effect. When the current crowding effect exists in a device, the temperature dependence can provide an electrical-thermal positive feedback loop that gives rise to thermal runaway for a positive current gain coefficient and current collapse for a negative current gain coefficient. However, if the current gain were independent of temperature, there would not be a feedback mechanism to produce a catastrophic effect. In our devices, we have obtained a positive differential resistance directly from the slightly positive temperature coefficient of the current gain at low temperature. Since the feedback effect is a weak positive one, it would effectively restrain current gain degradation and collector current collapse in initial stage. In addition, since the temperature in this stage is not high enough, catastrophic current localization would not take place. At high temperature, the temperature coefficient of the current gain becomes negative, implying that the current gain decrease at high temperature brings back the negative differential resistance at high current and high bias. This effect prevents the device from thermal runaway.

In order to further examine the thermal stability of the HEBTs and find out the difference of thermal performance between the HEBTs and HBTs, the regression characteristics of both HEBTs and HBTs were measured. The HBT and the HEBT have the same structure and doping except the setback layer in the HEBT and they were fabricated in the same batch. For

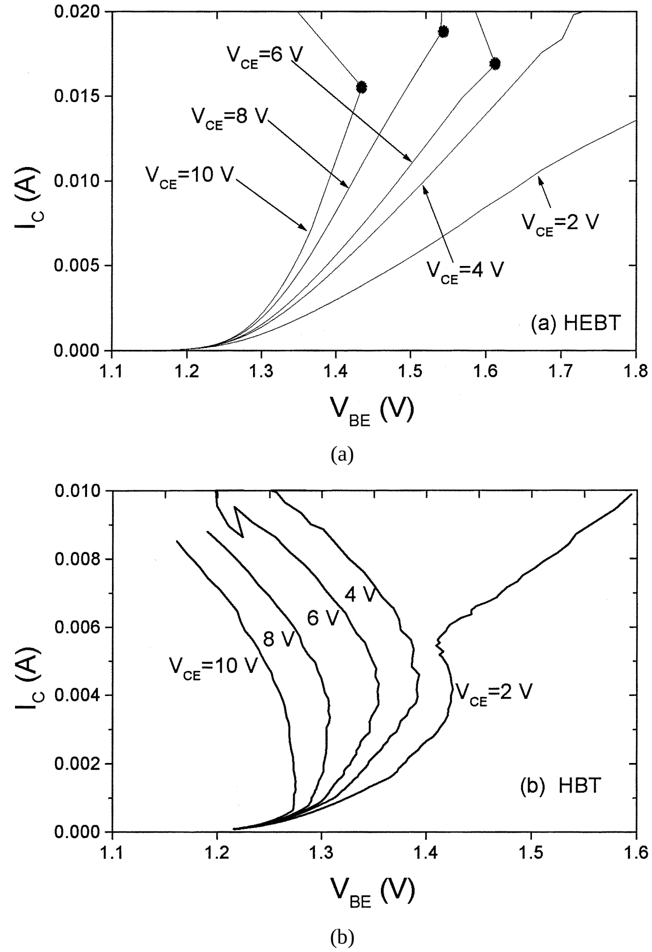


Fig. 6. Measured $V_{\rm be}$ regression plots for (a) HEBT and (b) HBT. Both $V_{\rm be}$ and I_C are measured as I_B varies for different collector-emitter biases.

the HEBT, the measured base sheet resistance, base contact resistivity and current gain were 182 Ω/sq, 5.5×10^{-7} Ω cm^2, and 36, respectively. For the HBT, corresponding data were 185 Ω/sq, 5.8×10^{-7} Ω cm^2, and 100, respectively. The measured regression characteristics of a single-finger HEBT are shown in Fig. 6(a) and the regression characteristics of a HBT with the same emitter size are shown in Fig. 6(b), which were obtained by applying certain $V_{\rm ce}$ and measuring both collector current and base-emitter voltage as the base current I_B increased like literature [10]. As shown in Fig. 6, there is significant difference in the regression characteristics for the HEBT and the HBT. For example, at the condition of $V_{\rm ce} = 6$ V, the regression point for the HEBT is at $V_{\rm be} = 1.54$ V but the regression point for the HBT is at $V_{\rm be} = 1.30$ V, indicating that the collapse of the current gain more easily occurs in the HBT than in the HEBT. Since the HEBT and the HBT have almost the same base sheet resistance and base contact resistance, the influence of the base resistances on the regression characteristics can be excluded. In addition, the influence of the current gain on the regression characteristics is not manifest. Therefore, good thermal stability of the HEBT results from device structure itself.

The improvement of the thermal stability is derived from the special transport mechanism of the hole current, which reduces current gain dependence on the junction temperature. As we know, the main reason of current gain degradation in HBTs is

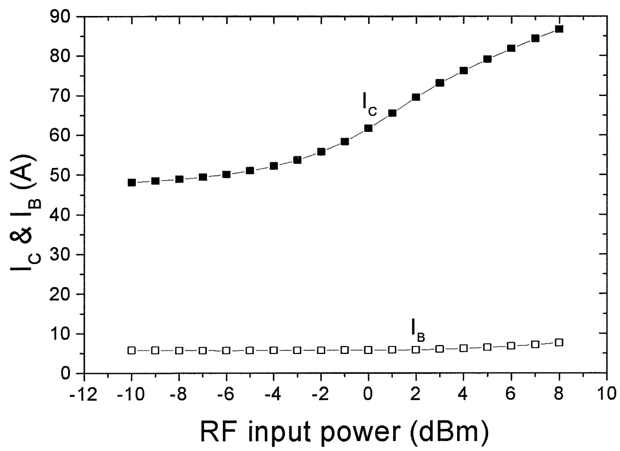
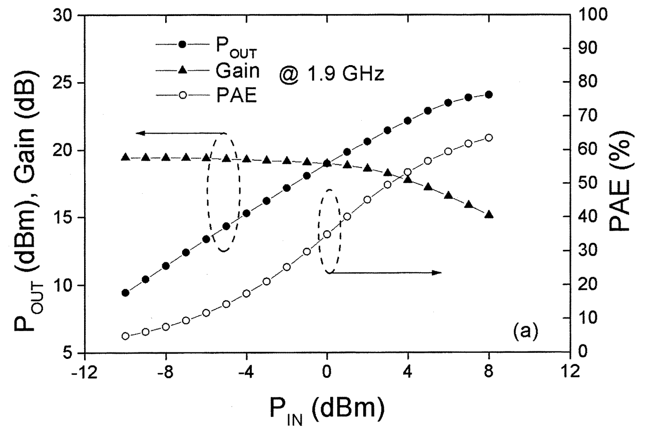
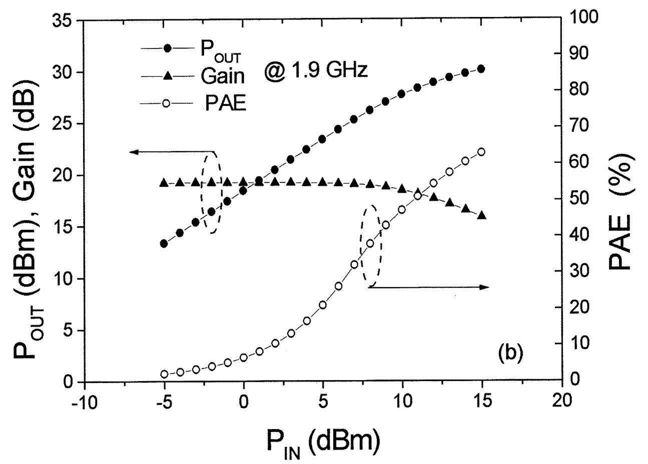


Fig. 7. Bias collector and base currents as a function of the RF input power.



(a)



(b)

Fig. 8. RF output power, power gain, and power-added efficiency as a function of RF input power for (a) the 26-finger HEBT and (b) 104-finger HEBT.

believed to be the low valence band offset (ΔE_v) at the heterojunction [9]. It is based on the assumption that diffusion dominates the holes injected from the base to the emitter. For the HEBT, however, by assuming that the heterostructure-emitter is similar to the polysilicon emitter [11], the hole current from the base to emitter is dominated by thermionic emission at high temperature. The temperature dependence of the diffusion current is described by $T^{3+\gamma/2}$ [12]. The $\gamma/2$ term describes the temperature effect of the ratio of the diffusion coefficient to diffusion length that is negligible in most cases. Ignoring the exponential kT term that cancels out, the thermionic emission current has a temperature dependence of $\sim T^2$ and the diffusion current has a temperature dependence of T^3. Hence, the current gain is less dependent on the junction temperature than when the hole current is dominated by thermionic emission. A detailed theoretical analysis can be found in [13].

The large-signal performance of the multifinger HEBTs was tested at 1.9 GHz, which is the typical frequency for wireless communication applications. The devices were tuned with external tuners having a 15:1 VSWR tuning range. The collector bias $V_{\rm ce}$ maintained at 3.5 V while the CW input power was varied between 40 and 320 mW. The base–emitter junction bias $V_{\rm be}$ was 1.37 V. Fig. 7 shows the operating dc collector and base currents as a function of the RF input power for the 26-finger HEBT. The collector current increases monotonically with the input power. The base current also exhibits the same variation trend but the variation is not as remarkable as the collector current. This observation indicates that the device was operated in the class-AB mode. The operating collector currents per finger range between 1.85 mA and 3.33 mA, corresponding to current densities between 0.55×10^4 A/cm^2 and 0.99×10^4 A/cm^2. Fig. 8 shows the RF output power $P_{\rm out}$, power gain and power-added efficiency PAE as functions of RF input power for the 26-finger HEBT. It can be seen that the device successfully delivered the output power of 0.25 W and PAE of 63.5% with an associated power gain of 19 dB. For the power device composed of four cells, output power level of 1.0 W with PAE of 63% has been achieved at the optimum conditions of impedance matching.

From the point of view of practical applications, it is necessary to comprehensively evaluate device performances. The HEBTs exhibit the advantages in low offset voltage, thermal management. Usually, however, they suffer a low current gain because of the large interface recombination current. Although a current gain of more than 10 is enough for microwave power application, the large recombination current will constitute a main concern of the device reliability. In addition, since the current gain of the HEBT is not uniform from small to high current, the linearity of HEBT may not be as good as that of HBT.

IV. Conclusion

In summary, HEBT devices with different power capability for wireless communication applications have been designed and fabricated. Excellent power performance and capability of the HEBTs have been demonstrated. Output power of 0.25 W with PAE of 63.5% at 1.9 GHz has been achieved from a 26-finger power cell. Output power of 1.0 W with PAE of 63% has been demonstrated from the composition of four above-mentioned power cells at the optimum conditions of impedance matching. The thermal performance of the HEBT is presented and discussed. The results show that the HEBTs have better thermal management than conventional HBTs. The experimental results demonstrate good power performance and capability of the HEBTs.

ACKNOWLEDGMENT

The authors acknowledge the support and encouragement of Dr. O. Wu and the excellent technical support of Dr. W. Qian of Global Communication Semiconductors, Inc.

REFERENCES

[1] W. Liu, E. Beam, III, T. Kim, and A. Khatibzadeh, "Recent developments in GaInP/GaAs heterojunction bipolar transistors," in *Current Trends in Heterojunction Bipolar Transistors*, M. F. Chang, Ed, Singapore: World Scientific, 1995, p. 241.

[2] W. Liu, *Handbook of III-V Heterojunction Bipolar Transistors*. New York: McGraw-Hill, 1998.

[3] X. Wu, Y. Q. Wang, L. F. Luo, and E. S. Yang, "An AlGaAs/GaAs heterostructure-emitter bipolar transistor," *IEEE Electron Device Lett.*, vol. 11, pp. 264–266, June 1990.

[4] W. C. Liu and W. S. Lour, "An improved heterostructure-emitter bipolar transistor (HEBT)," *IEEE Electron Device Lett.*, vol. 12, pp. 474–476, Sept. 1991.

[5] H. R. Chen, C. Y. Chang, C. P. Lee, C. H. Huang, J. S. Tsang, and K. L. Tsai, "High current gain, low offset voltage heterostructure emitter bipolar transistors," *IEEE Electron Device Lett.*, vol. 15, pp. 336–338, Sept. 1994.

[6] Y. F. Yang, C. C. Hsu, and E. S. Yang, "Prevention of base dopant out-diffusion using heterostructure-emitter in GaInP/GaAs heterojunction bipolar transistors," *Semicond. Sci. Technol*, vol. 10, pp. 339–343, 1995.

[7] E. S. Yang, Y. F. Yang, C. C. Hsu, H. J. Ou, and H. B. Lo, "Temperature dependence of current gain of GaInP/GaAs heterojunction and heterostructure-emitter bipolar transistors," *IEEE Trans. Electron Devices*, vol. 46, pp. 320–323, Feb. 1999.

[8] B. P. Yan, E. S. Yang, Y. F. Yang, X. Q. Wang, and C. C. Hsu, "InGaP/GaAs power heterostructure-emitter bipolar transistor," *Electron. Lett.*, vol. 37, no. 20, pp. 1262–1264, Sept. 2001.

[9] W. Liu, S. K. Fan, T. Henderson, and D. Davito, "Temperature dependences of current gains in GaInP/GaAs and AlGaAs/GaAs heterojunction bipolar transistors," *IEEE Trans. Electron Devices*, vol. 40, pp. 1351–1353, July 1993.

[10] W. Liu, A. Khatibzadeh, J. Sweder, and H. F. Chau, "The use of base ballasting to prevent the collapse of current gain in AlGaAs/GaAs heterojunction bipolar transistors," *IEEE Trans. Electron Devices*, vol. 43, pp. 245–251, Feb. 1996.

[11] C. C. Ng and E. S. Yang, "A thermionic-diffusion model of polysilicon emitter," in *IEDM Tech. Dig.*, 1986, pp. 32–35.

[12] S. M. Sze, *Physics of Semiconductor Devices*. New York: Wiley, 1981, ch. 2.

[13] E. S. Yang, C. C. Hsu, H. B. Lo, and Y. F. Yang, "Modeling of current gain's temperature dependence in heterostructure-emitter bipolar transistors," *IEEE Trans. Electron Devices*, vol. 47, pp. 1315–1319, July 2000.

Bei-Ping Yan received the B.Eng. degree from Beijing Institute of Technology, Beijing, China, in 1992, and the M.Eng. and Ph.D degrees from Xi'an Jiaotong University, Xi'an, China, in 1986 and 1995, respectively.

From 1982 to 1983, he was with the Xi'an Institute of Applied Optical Technology as a Technician. From 1986 to 1998, he was with Xidian University, Xi'an, as a Lecturer, an Assistant Professor, and an Associate Professor, respectively. From 1998 to 2000, he was a Research Fellow at the Nanyang Technological University, Singapore, where he was involved in the development of GaAs-based HBTs. Since 2000, he has been with the Department of Electrical and Electronic Engineering of The University of Hong Kong, where he is a Postdoctoral Fellow and responsible for the development of InP and GaAs power HBTs. He has published over 30 technical papers related to his research. His current research interests are InP- and GaAs-based compound semiconductor device physics, fabrication technology, and characterization.

Edward S. Yang (S'60–M'61–SM'74–F'92) joined the Electrical Engineering Faculty at Columbia University, New York, in 1965, became a full Professor in 1975 and was Chairman from 1986 to 1989 and 1993–1996. He was responsible for a major expansion of the department, including recruitment of distinguished faculty and development of world-class research programs in microelectronics, telecommunications, and photonics. He was also affiliated with IBM, Poughkeepsie, NY (1961–1963) and Yorktown Heights, NY (1970–1991). In addition to two textbooks in semiconductor devices published by McGraw-Hill 1978 and 1988, he has published over 150 articles and has made original contributions in polyemitters, thin-metal Schottky barriers, high-speed GaAs HBTs and HEMTs, HTC supperconductor on silicon, solar cells, p-n-p-n switches and SiGe devices.

Yue-Fei Yang (M'95) received the B.S. degree in physics from East China Normal University, Shanghai, in 1982, the M. S. degree in electrical engineering from Shanghai Institute of Metallurgy, Chinese Academy of Sciences, Shanghai, in 1985, and the Ph.D degree in electrical engineering from Columbia University, New York, in 1995.

From 1985 to 1990, he was a Research Associate at the Shanghai Institute of Metallurgy, where he conducted research on III-V compounds and short-channel GaAs MESFET. From 1991 to 1992, he worked on hot electron transistors in the Department of Electronic and Electrical Engineering, Sheffield University, Sheffield, U.K. From 1995 to 1997, he was a Postdoctoral Fellow and later Associate Research Scientist in the Department of Electrical Engineering, Columbia University, where he worked on HBTs, HEMTs, and RTDs. Since 1998, he has been Member of Technical Staff, Global Communication Semiconductors, Inc., Torrance, CA. His main interests include developing high-speed heterostructure devices such as HBTs, HEMTs, and integrated circuits for digital and microwave applications.

Xiao-Qin Wang received the B.S. degree from Northwest University, Xi'an, China, in 1986.

From 1986 to 1998, she had been with the Xi'an Institute of Navigation Technology, Xi'an, China, as an Assistant Process Engineer and a Process Engineer, respectively. From 1998 to 2000, she worked at Printed Circuit, Inc., Singapore, as a Process Engineer. Since 2000, she has been with the Department of Electrical and Electronic Engineering of The University of Hong Kong, where she is a Research Assistant. Her current research interests are CAD and CAM for compound semiconductor devices and circuits.

Chung-Chi Hsu graduated in electrical engineering from National Taiwan University, Taipei, Taiwan, R.O.C., in 1976. He received the M.S.E.E. degree from Purdue University, West Lafayette, IN, in 1979, and the Ph.D. degree from University of Utah, Salt Lake City, in 1985.

He worked for the Xerox Palo Alto Research Center, Palo Alto, CA, as a Research Intern from 1979 to 1980. He joined Lasertron, Inc., Sunrise, FL, working on organometallic vapor phase epitaxy for long wavelength laser development. He went back to Taiwan in 1987 and joined Material Research Laboratories. He migrated to Hong Kong in early 1989 to take the post of Lecturer at Hsinchu Chinese University of Hong Kong. His current research interests are high speed optoelectronics, crystal growth, and organometallic vapor phase epitaxy.