Extended Abstracts of the 21st Conference on Solid State Devices and Materials, Tokyo, 1989, pp. 277-280

D-3-1

Invited

V- and W-Band Power and Low-Noise HEMTs

P.C. CHAO, P.M. SMITH, K.H.G. DUH, and J.M. BALLINGALL

Electronics Laboratory, General Electric Co.,

Syracuse, NY 13221 USA

0.15µm gate-length GaAs-based and InP-based high electron mobility transistors with state-of-the-art power and noise performance at 60 and 94GHz are reported. The GaAs-based pseudomorphic HEMTs have shown excellent noise performance, reliability, and the best V- and W-band power results. The power results include record power-added efficiencies of 41% and 23% at 60 and 94GHz, respectively, and output powers of 139mW at 60GHz and 57mW at 94GHz. In spite of the relatively short development history, the InP-based lattice-matched HEMTs have already demonstrated state-of-the-art noise performance -- measured minimum noise figures of 0.3dB at 18GHz, 0.9dB at 60GHz and 1.4dB at 94GHz are the lowest ever reported for any transistor. Due to the poor Schottky gate characteristics, however, the InP lattice-matched HEMT is not yet a viable power device. With improved material growth technique and layer structure design, the InP-based HEMTs are expected to compete with or even outperform GaAs-based pseudomorphic HEMTs for millimeter-wave power applications in the long term.

1. INTRODUCTION

Extremely-low noise devices and high efficiency millimeter-wave (MMW) power transistors are desired for a number of applications, including satellite communications, EW, seekers, smart munitions and radar. The use of high electron mobility transistors (HEMTs) in MMW low-noise and power amplifiers for above system applications has become increasingly widespread due to the superior noise and power performance of these transistors. Particularly, HEMTs with single quantum well active layers composed of InGaAs grown on GaAs and InP are establishing new standards of performance at MMW frequencies. At GE, we have been developing GaAs-based pseudomorphic HEMTs with outstanding noise and power performance since 1986. We have also recently developed InP-based lattice-matched HEMTs with state-of-the-art noise performance. This paper reviews the V-band (50-75GHz) and W-band (75-110GHz) noise and power performance of these HEMTs. The factors determining the device MMW noise and power performance are also discussed.

2. AlGaAs/InGaAs/GaAs PSEUDOMORPHIC HEMT

The GaAs-based pseudomorphic HEMT differs from the conventional AlGaAs/GaAs HEMT in that a thin (typically 50-200Å) layer of $In_xGa_{1-x}As$ (x=0.15-0.35) is inserted between the doped AlGaAs barrier layer and the GaAs buffer. The device is therefore based on the AlGaAs/InGaAs heterojunction, with electrons flowing in the strained quantum-well InGaAs channel[1]. The benefits of using InGaAs as the channel include the enhanced electron transport in InGaAs as compared to GaAs, improved confinement of carriers due to the quantum well, and the large conduction band discontinuity at the AlGaAs/InGaAs heterointerface which allows high sheet charge density and hence high current density and transconductance.

Excellent MMW noise performance and good reliability have been demonstrated with pseudomorphic HEMTs. The devices typically exhibit noise figures that are comparable to those obtained with conventional AlGaAs/GaAs HEMTs, but with 1-2dB higher associated gain at MMW frequencies. The higher gain in the pseudomorphic HEMTs is a result of the higher transconductance and better carrier confinement in the quantum-well channel, providing a clear advantage at high frequencies by reducing F_∞. F_∞ is the noise figure of an infinite chain of cascaded stages (each with the noise and gain of the HEMT), and approximates the noise figure obtainable in a lossless, high gain multi-stage amplifier.

Pseudomorphic HEMTs have demonstrated state-of-the-art MMW power performance, primarily as a result of the high transconductance, high breakdown voltage, excellent pinchoff characteristics, and low output conductance obtainable with the device layer structure. The pseudomorphic power HEMTs reported in this paper have 0.15µm low-resistance T-shaped gates.

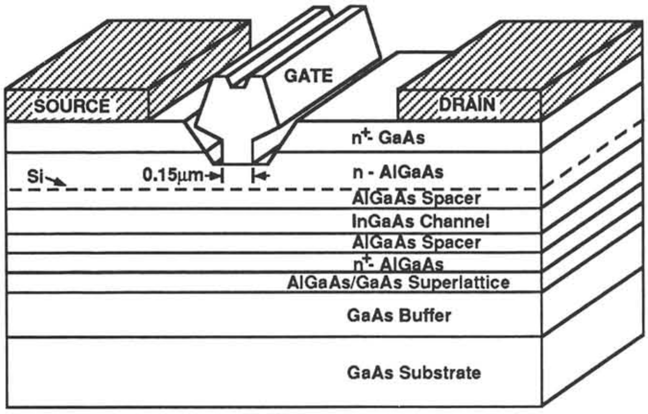

Fig. 1 The cross-section of a 0.15µm gate-length GaAs-based double-heterojunction pseudomorphic HEMT.

A double-heterojunction pseudomorphic layer structure (Fig. 1) was used for these power HEMTs. In the double-heterojunction HEMTs, carriers are introduced into the InGaAs pseudomorphic channel by doping the AlGaAs on both sides of the InGaAs. This results in high channel current density and hence high power handling capability. The devices typically have g_m of 650-850mS/mm, a full channel current density of 650-800mA/mm, and a gate breakdown voltage of 8-10V.

Table 1 Measured 60 and 94GHz power performance of 0.15µm gate-length GaAs-based double-heterojunction pseudomorphic HEMTs.

Frequency (GHz)	Gate Width (µm)	Output Power (mW)	Power Density (W/mm)	Power Added Efficiency (%)	Power Gain (dB)
60	50	32	0.64	41*	6.0
		42	0.84*	37	5.9
	150	82	0.55	38*	4.7
		125	0.83*	32	4.5
94	50	18	0.36	23*	3.3
		22	0.43*	19	3.2
	150	45	0.30*	16	3.0
		57	0.38*	16	2.0

*** Biased and impedance-matched to maximize this parameter.**

Table 1 summarizes the DC and MMW power performance of the pseudomorphic HEMTs. At 60GHz, the 0.15x50µm double-heterojunction HEMTs display a maximum efficiency of 41% with 6dB power gain. Higher gain is significant in that it allows larger devices, capable of higher power with high efficiency and useful gain, to be realized. The 0.15x150µm HEMT yields a maximum efficiency of 38% with 4.7dB gain and 82mW output power, and a maximum power of 125mW with 4.5dB gain and 32% efficiency. This device, when driven into saturation, delivered 139mW output power with 3dB gain and 28% power added efficiency. This is the highest output power obtained from a single transistor at 60GHz.

The 94GHz power performance of the 0.15µm pseudomorphic HEMTs represents a significant improvement over the best previously reported 94GHz results -- 9mW output power and 14% maximum power-added efficiency[2]. A 0.15x50µm HEMT has yielded maximum efficiency of 23% with 18mW output power and 3.3dB gain, and maximum output power of 22mW. The 150µm gate width device, when biased and tuned for maximum power, exhibited the power saturation characteristics shown in Fig. 2. At a gain of 3.0dB, output power is 45mW with 16% efficiency, and with the gain of 2dB, output power as high as 57mW was obtained with 16% efficiency.

The current state-of-the-art of MMW transistor efficiency is summarized in Fig. 3. As seen in the figure, the efficiencies for the 0.15µm double-heterojunction pseudomorphic HEMTs are significantly higher than the best values reported for any other transistor, including GaAs-based conventional HEMTs[3], MESFETs[4], PBTs[5], and HBTs[6], across the entire 30-100GHz frequency range.

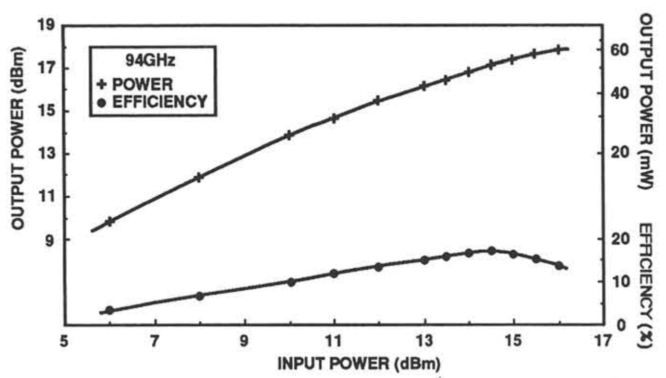

Fig. 2 Power saturation characteristics of 0.15µmx150µm pseudomorphic HEMT at 94GHz. Linear gain is 3.8dB.

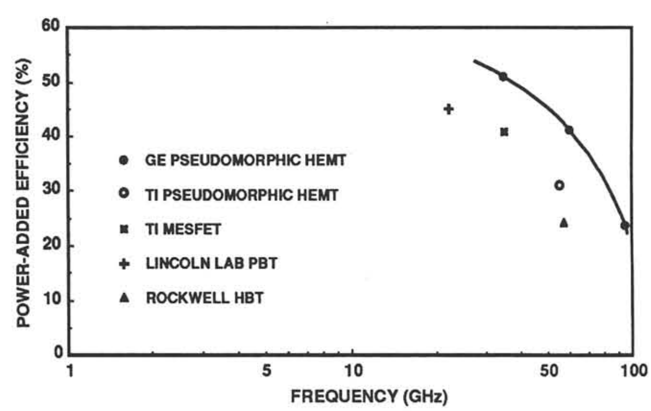

Fig. 3 Best reported MMW transistor efficiencies.

In order to obtain higher power from pseudomorphic HEMTs, shorter gate length and larger gate periphery devices composed of many interdigitated fingers are required. However, it is evident from the data given in Table 1 that as gate width increases from 50 to 150µm, efficiency and gain are degraded. This is largely as a result of two parasitics -- the source inductance and the gate resistance. With proper layout to minimize the effects of source inductance (e.g., the use of via holes) and gate resistance (e.g., shorter unit finger width and the use of airbridge design), and obtain low thermal resistance, the pseudomorphic power HEMTs should produce high output power with high efficiency, gain, and reliability. Single device powers of 500mW at 60GHz and 250mW at 94GHz are likely within the next few years.

3. AlInAs/InGaAs/InP LATTICE-MATCHED HEMTs

One way of improving the performance of the pseudomorphic HEMT is to increase the InAs mole fraction in the device channel. We have recently developed 0.15µm gate-length $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As/InP$ lattice-matched HEMTs. These heterojunction InP-based lattice-matched HEMTs, with up to 53% InAs in the channel, are superior to the GaAs-based pseudomorphic HEMTs for millimeter-wave low-noise applications for the following reasons: a) larger $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ conduction band discontinuity and higher doping efficiency of Si in AlInAs give a very high electron sheet charge density in the channel, b) lower energy bandgap of $In_{0.53}Ga_{0.47}As$ channel results in better carrier confinement in the channel, and c) relatively high electron mobility and peak drift velocity in the device channel. These properties increase device transconductance, maximum frequency of oscillation and current gain cutoff frequency, and reduce noise figure.

The devices, shown in Fig. 4, typically exhibit very high transconductance values. An extrinsic transconductance, g_m, as high as 1,350mS/mm was obtained at room temperature with good pinchoff characteristics for the device. With a device source resistance of 0.4Ω·mm, this corresponds to a maximum intrinsic g_m of 3,000mS/mm for the device. However, due to the relatively immature material growth technology and the non-optimized channel design and

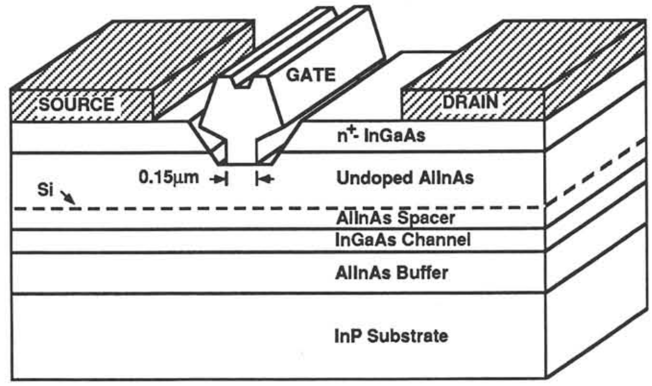

Fig. 4 The cross-section of a 0.15µm gate-length InP-based lattice-matched HEMT. The HEMT structure allows an InAs mole fraction in the channel as high as 53%.

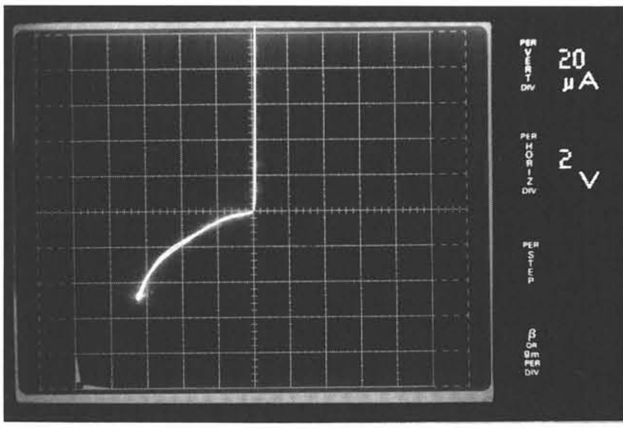

Fig. 5 Leaky Schottky characteristics of a 0.15µmx50µm InP-based lattice-matched HEMT. Small gate forward turn-on and reverse gate breakdown voltages were observed.

layer structure used, today's InP-based lattice-matched HEMTs typically have a kink-effect in the drain I-V characteristics, and also exhibit low breakdown and very leaky gate characteristics (see Fig. 5). The kink effect, resulting from the poor quality of the AlInAs buffer, in the drain I-V characteristics does not seem to affect the device microwave performance[7]. The poor Schottky characteristics, however, prevent the lattice-matched HEMTs of becoming a great power device.

The poor gate characteristics may be due to the tunneling of electrons through the poor quality AlInAs layer under the Schottky gate. Since the lattice-matched HEMTs are operated at very low drain voltages (V_{ds} ~0.7-1.1V) for minimum noise figure, low breakdown of the device may not be a concern for low-noise applications. The device reliability and noise performance, however, will be improved through further reduction in the gate leakage current by employing a high quality AlInAs layer under the gate.

The lattice-matched HEMT typically has significantly higher S_{21} (due to high g_m) and smaller S_{12} values than the GaAs pseudomorphic device. This results in a much higher microwave small signal gain for the lattice-matched HEMT. The current gain h_{21} of the 50μm wide device was calculated from the measured S parameters. An extrinsic unity current gain cutoff frequency, f_T, of 165GHz was extrapolated from the h_{21} values at -6dB/octave with the devices. Maximum available gain (MAG) of 12.6dB was also measured in a single-stage amplifier at 95GHz. The MAG, extrapolated at -6 dB/octave, yields a maximum frequency of oscillation, f_{max}, of 405GHz -- the highest ever reported for any transistor.

At 18GHz, a minimum noise figure of 0.3dB with an associated gain of 17.2dB was measured for the device. The device also demonstrated minimum noise figures of 0.9dB with 8.6dB associated gain and 1.4dB with 6.6dB associated gain at 60 and 93GHz, respectively. The V- and W-band noise figures are typically ~0.5-1.0dB lower than the GaAs pseudomorphic HEMTs. As shown in Fig. 6, the 18, 60 and 93GHz minimum noise figures of the lattice-matched HEMTs correspond very well with the Fukui-type frequency dependence

$$F_{min}\,(dB) = 10 \log (1 + cf) \qquad (1)$$

where F_{min} is minimum noise figure, c is a constant ($= 4.0 \times 10^{-3}$ second in this case), and f is frequency in GHz. Similar frequency dependence has also been found in GaAs-based conventional and pseudomorphic HEMTs.

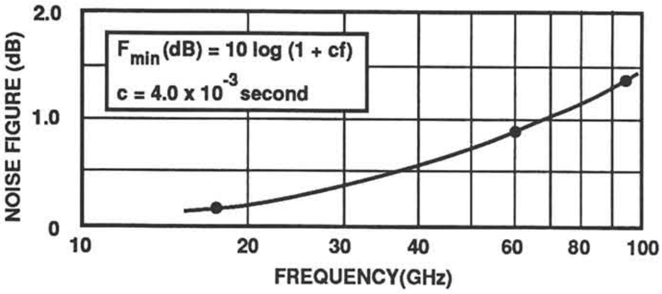

Fig. 6 Measured noise and gain performance of a 0.15μm InP-based lattice-matched HEMT.

Clearly, the InP-based HEMT offers superior low-noise performance. Although the lattice-matched HEMTs have the advantages of a high current density and transconductance, the device power performance is presently limited by the very leaky gate and low breakdown voltage. We have measured the power performance of the lattice-matched HEMTs at 35 and 60GHz, and found that it is significantly worse than that of the GaAs-based pseudomorphic HEMTs. It should, however, be noted that the lattice-matched HEMTs have potential advantages of high thermal conductivity of the InP substrate and higher current density, transconductance, and power gain. With improved material growth technique and optimized device layer structures, the lattice-matched HEMTs could eventually compete with or even outperform GaAs pseudomorphic HEMTs for MMW power applications.

4. CONCLUSION

HEMTs with InGaAs quantum well active layers grown on GaAs and InP substrates are establishing new standards of power and low-noise performance for MMW applications. This is due to recent progress in the MBE growth of InGaAs heterostructures coupled with developments in very short gate length device fabrication technology. The GaAs pseudomorphic HEMTs are fairly mature, and with demonstrated excellent V- and W-band noise and power performance, the devices are ready for MMW system applications. The InP-based HEMTs, with increased InAs mole fraction of the quantum well channel providing substantial enhancement of the active layer electron confinement, electron sheet charge density, mobility, and velocity, have demonstrated state-of-the-art MMW noise and gain performance. More work, however, still needs to be done in optimizing the layer structures and the material growth technique to further improve the device breakdown, gate leakage current, and reliability to fully exploit the potential of the InP-based HEMTs for MMW power applications.

5. REFERENCES

1) T. Henderson, et al; IEEE Electron Device Lett. EDL-7 (1986) 645.
2) P.M. Smith, et al; IEEE MTT-S Dig. (1988) 927.
3) B. kim, et al; IEEE IEDM Tech. Dig. (1988) 168.
4) B. Kim, et al; IEEE Electron Device Lett. 9 (1988) 57.
5) L.J. Kushner, et al; IEEE MTT-S Dig. (1988) 525.
6) J.A. Higgins; GaAs IC Symposium Dig. (1988) 33.
7) J.B. Kuang, et al; IEEE Electron Device Lett. 9 (1988) 630.