A 0.15µm GATE-LENGTH PSEUDOMORPHIC HEMT

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ABSTRACT

0.15µm gate-length double heterojunction pseudomorphic HEMTs that simultaneously exhibit state-of-the-art power and noise performance are reported. Power results include record power-added efficiencies of 51%, 41% and 23% at 35, 60 and 94 GHz, respectively, and output powers of 139mW at 60 GHz and 57mW at 94 GHz. Measured minimum noise figures of 0 55dB at 18GHz and 1.8dB at 60 GHz are the lowest ever reported for passivated transistors. Based on its demonstrated performance and continued rapid rate of improvement, the pseudomorphic HEMT should be the preferred transistor for a number of millimeter wave applications, used either as a discrete device in high performance hybrid amplifiers or integrated into GaAs-based MMICs.

INTRODUCTION

The use of HEMTs in microwave and millimeter-wave low noise amplifiers has become increasingly widespread due to the superior noise performance of these transistors [1], [2]. Dramatic progress has been made in the development of HEMTs for high efficiency power applications as well. 0.25µm gate-length InGaAs pseudomorphic HEMTs have already demonstrated millimeter-wave power performance that is significantly better than that achieved with other transistors such as the heterojunction bipolar transistor (HBT) or the permeable base transistor (PBT) [3]

High efficiency millimeter-wave power transistors are desired for a number of applications, including communications, EW, seekers, smart munitions and radar. Pseudomorphic HEMTs are viewed as an attractive alternative to IMPATTs and tubes, the two technologies prevalent in millimeter-wave transmitters, because of their high efficiency, small size and anticipated excellent reliability Although current transistors are small, generating modest levels of output power, a hybrid HEMT power amplifier has demonstrated 0.25W output power at 44 GHz [4], and with increased device size, watt-level power amplifiers, power-combined to yield transmitters that radiate tens of watts of power, should be feasible. Alternatively, the pseudomorphic HEMT integrates easily into MMICs for phased arrays As frequency increases, the output power required from each element of a phased array decreases rapidly, and the typical power per element at millimeter-wave frequencies is therefore low--within the capability of existing HEMTs (100-200mW at 60 GHz, for example). The phased array, by combining the power of many individual elements in space, can radiate high power levels (10^2-10^3 watts) with excellent beam agility, and is expected to be competitive with systems based on tubes.

DEVICE DESCRIPTION

The InGaAs pseudomorphic HEMT has many advantages over the conventional AlGaAs/GaAs HEMT that lead to improved power operation, including the enhanced transport of electrons in InGaAs, a large InGaAs/AlGaAs conduction band discontinuity that permits higher two-dimensional electron gas (2DEG) density to be obtained, and improved confinement of carriers to the channel by the InGaAs quantum well

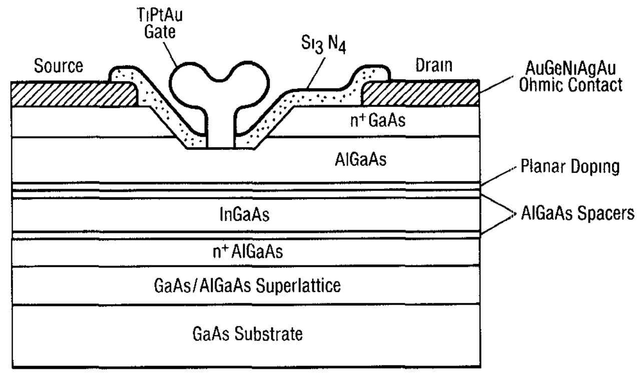

Figure 1. Cross-section of 0.15µm double heterojunction pseudomorphic HEMT.

A cross-section of the pseudomorphic HEMT structure used in this work is given in Figure 1. The primary improvement made in this device, as compared to that reported in [3], is that the gate length has been reduced from 0.25 to 0.15µm Reduction of gate length is expected to improve device gain, and hence efficiency due to increased transconductance g_m as well as lower input capacitance. Experimentally, the increased g_m and gain of ultra-short gate-length devices has been demonstrated: 0.1µm pseudomorphic HEMTs have been reported with 930mS/mm transconductance [5], and a 0.15µm pseudomorphic HEMT with a double-recessed channel structure exhibited a small-signal gain of 11dB at 94 GHz, from which a maximum frequency of oscillation, f_{max}, of 350 GHz can be extrapolated [6]

As shown in Figure 1, the 0.15µm gate has a T-shaped cross-section to reduce series resistance. The gate is produced with relative ease and high yield by electron beam lithography using a tri-layer resist technique [7]. The gate is placed off-center in the channel, close to the source, in order to minimize the source resistance, a critical parasitic element. The channel is passivated with a thin layer of Si_3N_4

The epitaxial layer structure was designed for power--a double heterojunction (DH) approach was taken, in which carriers are introduced into the InGaAs quantum well by doping the AlGaAs on both sides of the InGaAs. This results in high channel current and hence high power handling capability. In addition, as compared to the DH HEMT reported in [3], the mole fraction of In in the InGaAs has been increased to 22% and the mole fraction of Al in the AlGaAs has been raised to 25%. Higher In mole fraction results in improved electron transport properties and an increased conduction band discontinuity, while increased Al composition allows higher 2DEG density.

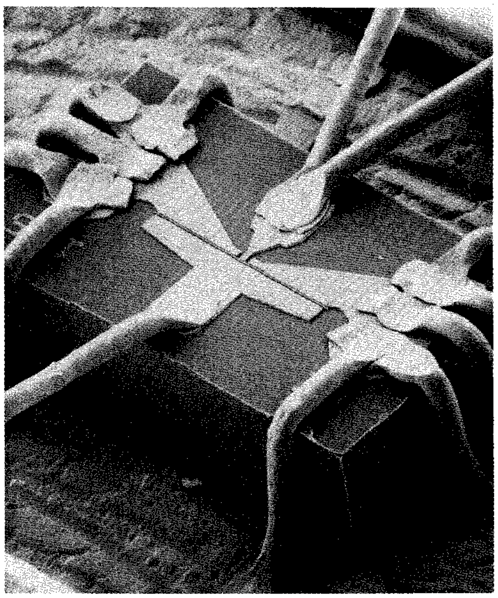

Figure 2. 150µm gate width HEMT with bonding wires attached.

Frequency (GHz)	Gate Width (µm)	Output Power (mW)	Power Density (W/mm)	Power-Added Efficiency (%)	Power Gain (dB)
35	50	32	0.64	51*	9.0
		42	0.83*	37	8.5
	150	95	0.63	50*	8.0
		137	0.91*	40	7.6
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. Measured power performance of 0.15µm gate length pseudomorphic HEMTs.

The HEMTs reported here are of simple geometry, having a single gate stripe fed at the center, with total gate widths of 50 and 150µm. The 150µm gate width HEMT is depicted in Figure 2.

The devices exhibit excellent DC characteristics: typical g_m of 700mS/mm (peak g_m of 830mS/mm), full channel current of 750mA/mm, and gate to source-drain breakdown voltage of 8.5V.

POWER PERFORMANCE

The power performance of the 0.15 x 50µm and 0.15 x 150µm pseudomorphic HEMTs was measured at 35, 60 and 94 GHz using test fixtures and test circuits as described in [3]. All data reported here has been properly corrected for fixture losses, reflecting true device performance.

The power test data is summarized in Table 1. At each frequency and for each device, the DC bias conditions and impedance matching were adjusted to separately maximize output power and efficiency. Maximum efficiency is typically obtained at a drain bias of 4V, while maximum power occurs at >5V.

At 35GHz, the HEMTs exhibit record power-added efficiency and power gain--the maximum efficiency is 51%, occurring with a power gain of 9.0dB. The high gain and high resulting efficiency can be attributed to the reduced gate length. At this frequency, 0.25µm gate length devices have exhibited efficiencies of 41-44% with power gains of only 5-6dB [3],[8].

At 60 GHz, the 0.15 x 50µm HEMT displays a maximum efficiency of 41% with 6.0dB power gain. Again, this is substantially better than results previously reported for 0.25µm HEMTs, where a comparable gate width device typically yields power gain at maximum efficiency of only 3-4dB [9]. Higher gain is significant in that it allows larger devices, capable of higher power with high efficiency and useful gain (3dB minimum), to be realized. The 0.15µm x 150µm 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 power obtained from a single transistor at 60 GHz.

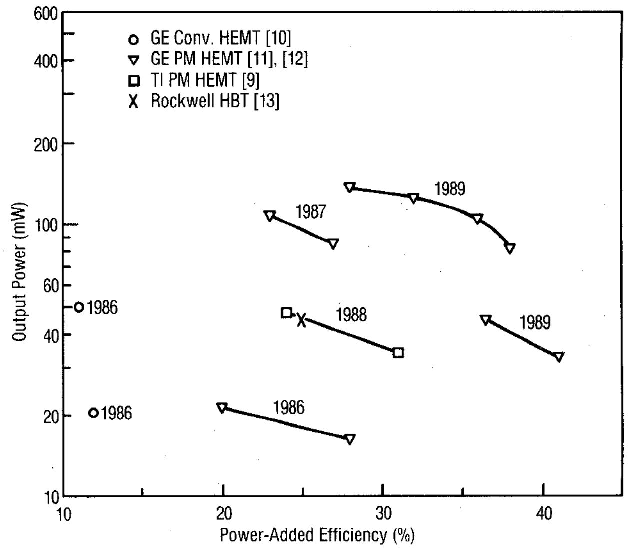

Figure 3. 60 GHz power and efficiency reported vs. time for GE HEMTs, and comparison with other recently reported PM HEMT and HBT results.

The 60 GHz power performance of GE HEMTs (conventional and pseudomorphic) reported since 1986 is plotted in Figure 3, along with recent results for the HBT [13] and a 0.25µm pseudomorphic HEMT from another laboratory [9]. Output power and efficiency are shown since they are the two most important figures of merit for a power transistor, and are applicable to all transistor types. (Another figure of merit, power density, is only meaningful when comparing devices of the same type such as FETs and HEMTs, and cannot be used to compare HEMTs with HBTs or PBTs). From Figure 3, it is apparent that HEMT power performance has improved rapidly over the past 3 years, with factors of 3 improvement in both output power and efficiency. Progress has come primarily from incorporation of pseudomorphic

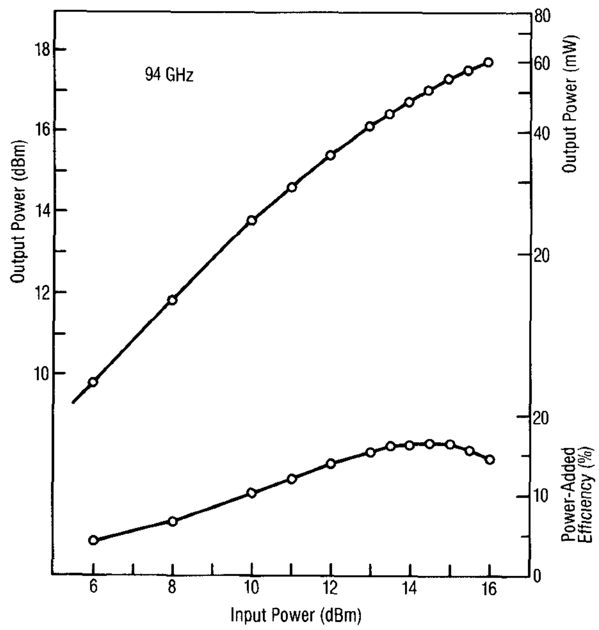

Figure 4. Power saturation characteristic of 0.15 x 150μm PM HEMT at 94 GHz.

InGaAs [11], the use of a double heterojunction structure [12] and, as reported here, reduction of the gate length to 0 15μm.

The 94 GHz power performance of the 0.15μm pseudomorphic HEMTs, presented in Table 1, represents a significant improvement over the best previously reported 94 GHz results, obtained for a 0.25 x 50μm pseudomorphic HEMT--9mW output power and 14% maximum power-added efficiency [3]. A 0.15 x 50μm 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 behavior shown in Figure 4. Linear gain is 3.8dB. At a gain of 3.0dB, output power is 45mW with 16% efficiency, and with the gain compressed to 2.0dB, output power is 57mW with 16% efficiency.

The current state-of-the-art of millimeter-wave transistor efficiency is summarized in Figure 5. As seen in the figure, the efficiencies reported here for the 0.15μm DH pseudomorphic HEMT are significantly higher than the best values reported for any other transistor, including HEMTs, FETs and HBTs, across the entire 30-100GHz frequency range.

Continued improvement of pseudomorphic power HEMTs can be expected, and will consist of further optimization of the channel parameters (i.e. gate length, layer structure, etc.) using small devices, and the fabrication of larger gate width HEMTs capable of efficiently generating higher power levels. It is evident from the data given in Table 1 that as gate width increases from 50 to 150μm, efficiency and gain are degraded, largely as a result of two parasitics--the source inductance, the value of which is essentially independent of gate width and whose effect thus increases with gate width and frequency, and the gate resistance, the effect of which increases as the square of the gate width (since gate resistance for devices of the geometry used increases linearly with gate width while other device elements such as R_s and R_i vary inversely with gate width). Experiments at 35 GHz indicate that the gain and efficiency of 150μm gate width HEMTs can be improved considerably by using low inductance via-hole source grounding. In order to obtain higher power from pseudomorphic HEMTs, large gate periphery devices composed

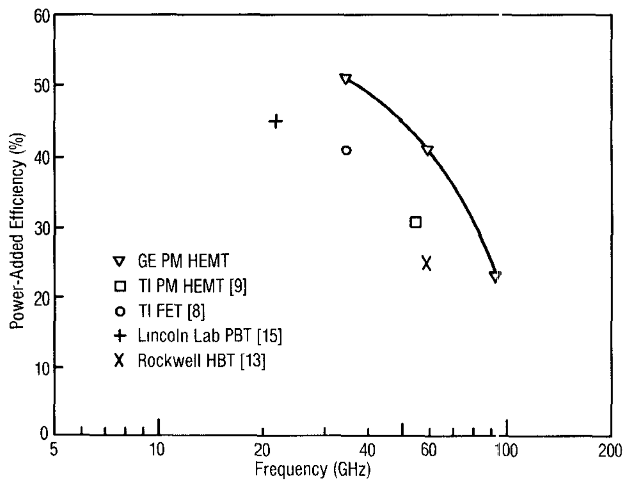

Figure 5. Best reported mm-wave transistor efficiencies.

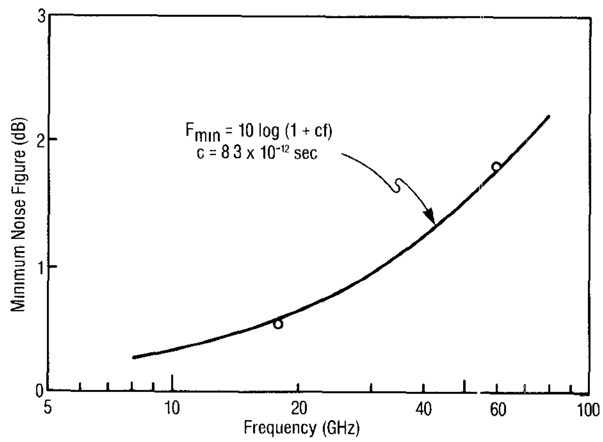

Figure 6. Frequency dependence of minimum noise figure for 0.15 x 50μm PM HEMT.

of many interdigitated fingers are required. With proper layout to minimize the effects of source inductance and gate finger resistance and obtain low thermal resistance, these power HEMTs should produce high output power with high efficiency and gain and excellent reliability Single device powers of 500mW at 60 GHz and 200 mW at 94 GHz are likely within the next few years

NOISE PERFORMANCE

The 0.15μm DH pseudomorphic HEMT, originally intended for power applications, exhibits excellent noise performance as well. At 18 GHz, minimum noise figure of 0.55dB was measured with 15.2dB associated gain, and at 60 GHz, minimum noise figure of 1.8dB was obtained with an associated gain of 6.4dB. The measured noise figure is plotted as a function of frequency in Figure 6. As seen in the Figure, we have found that the frequency dependence of device noise figure suggested by Fukui [15] fits the measured data quite well. Note that the measured noise figures given here are the lowest ever reported for passivated HEMTs at 18 or 60 GHz. Although it is possible to obtain lower noise figures when the HEMT structure is optimized for noise performance, it is remarkable that a device designed for power amplification also demonstrates such impressive noise figures.

There are several applications for which a device capable of both excellent power and noise performance is well-suited. Low noise amplifiers with greatly improved dynamic range could be produced by biasing the first gain stages for noise figure and the output stages for high output power at 1dB gain compression. Secondly, low noise and power MMICs based on these devices could easily be integrated onto the same chip without compromising the performance of either function, and could ultimately lead to single chip MMIC T/R modules.

SUMMARY

InGaAs pseudomorphic HEMTs continue to improve rapidly. 0.15μm gate-length double heterojunction devices exhibit record efficiency and power gain across the lower portion of the millimeter-wave spectrum, from 30 to 100 GHz. Relatively small HEMTs have generated the highest powers yet observed for three-terminal devices at both 60 and 94 GHz, and prospects for increasing output power are excellent. Although designed for power, the 0.15μm HEMTs also exhibit extremely low noise figure at 18 and 60 GHz.

Based on their current performance and rapid rate of progress, pseudomorphic HEMTs are expected to play a dominant role in future millimeter-wave systems--as discrete devices in high performance hybrid amplifiers, and embedded in MMICs for phased arrays and other applications where circuit cost and size are critical.

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