A HIGH POWER, HIGH EFFICIENCY MILLIMETER-WAVE PSEUDOMORPHIC HEMT

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ABSTRACT

We have developed a pseudomorphic HEMT with record output power and high efficiency at 44 GHz. The 0.15μm gate-length, 900μm gate-width device generates 500 to 700 mW of output power with power-added efficiencies ranging from 22 to 30%. Moreover, the devices are producible: DC yields for these large gate-width HEMTs are 50-80% and uniformity of electrical characteristics is excellent. Reliability aspects of the device are discussed and the results of high-temperature DC life testing of pseudomorphic power HEMTs are reported for the first time.

INTRODUCTION

Since the potential of the pseudomorphic HEMT for efficient high-frequency power amplification was first demonstrated in 1986 [1], the device has been developed extensively for transmitter applications at frequencies ranging from 10 to 94 GHz [2] - [8]. Power performance exceeds that of any other transistor : at 60 GHz, for example, power-added efficiency greater than 40% [3] and power density of 1.0 W/mm [2] have been reported. However, most of the results published to date have been obtained for small gate-width HEMTs, and hence output power levels have been relatively low--too low, in fact, to allow for system insertion.

In this paper, we report the development of a high - power pseudomorphic HEMT with state-of-the-art performance at 44 GHz. This device, with output power of more than 0.5W, high efficiency, and anticipated excellent long-term reliability, promises to replace more established technologies for the generation of moderate amounts of power (up to 20W) at 44 GHz. Compared to the conventional GaAs MESFET, the pseudomorphic HEMT exhibits higher power density, efficiency and gain. Compared with IMPATT diodes, pseudomorphic HEMTs offer enhanced efficiency, greatly improved reliability (10^7 hours expected median-time-to-failure (MTF), as compared to 10^5 - 10^6 hours MTF obtained with IMPATTs) and reduced transmitter size due to the MIC/MMIC compatibility of the HEMT and elimination of the circulators required by IMPATT amplifiers. At 44 GHz, pseudomorphic HEMT-based amplifiers will probably not be as efficient as tubes, but promise to be more reliable and more rugged.

DEVICE DESIGN

The pseudomorphic HEMTs used in this work employ a 0.15μm-long gate with a T-shaped cross-section.

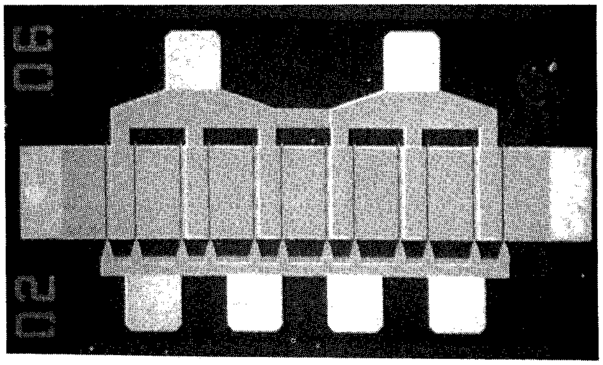

Figure 1. 900μm gate-width pseudomorphic power HEMT. Chip size is 300μm x 450μm.

The device contains a double heterojunction epitaxial layer structure and channel design identical to that presented for small gate-width HEMTs in [3]. The layout of the power device is illustrated in Figure 1. There are twelve gate fingers, each 75μm long, for a total gate width of 900μm.

Small via slots formed by reactive ion etching (RIE) are placed under each source pad in order to minimize source inductance, which degrades device high-frequency gain. An alternate layout of a 900μm HEMT employing much larger vias etched using wet chemistry is given in [8] and consists of two device "cells" with vias only on the sides of each cell. The RIE-via device topology reported here is preferable for many reasons: gain is higher due to reduced source inductance, chip size is one-third smaller, thermal characteristics are improved due to metallization on the walls of the via slots, and the air bridges used to interconnect source pads are eliminated, thus simplifying device fabrication and allowing visual inspection of the entire device channel region, a critical requirement for high-reliability applications.

Four gate bonding pads are used to minimize gate wirebond inductance, which can limit the bandwidth. In addition, the chip is thinned to 50μm to obtain low thermal resistance so that the channel temperature can be kept sufficiently low to achieve excellent long-term reliability. The developmental devices described in this paper were fabricated on 0.5-inch-square wafer pieces using a standard 0.15μm gate HEMT process first established in our laboratory in 1988.

Wafer	DC Yield	DC Yield (%)	g_m (mS/mm)	σ (mS/mm)	BV_{gds} (V)	σ (V)
A	190/360	52.8	536	33	6.4	0.3
B	291/360	80.8	536	36	5.8	0.3
C	265/360	73.6	601	32	6.6	0.9

Table 1. Summary of DC characteristics for 0.15 x 900μm HEMTs fabricated on three different wafers.

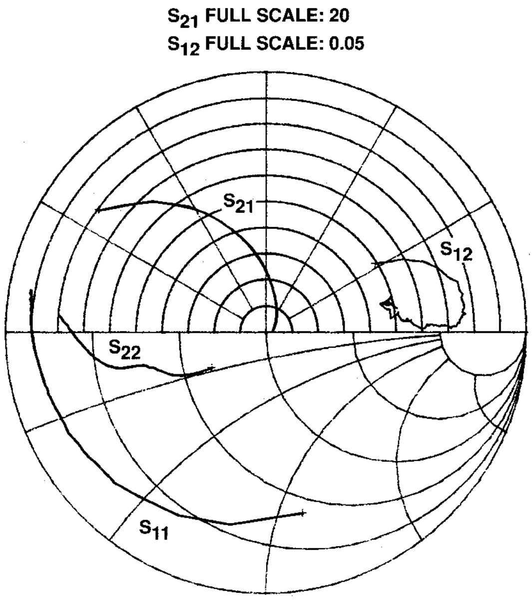

Figure 2. 1-40 GHz S-parameters measured at V_{ds}=5V, I_{ds}=240 mA. Gate and drain wirebonds are included in data.

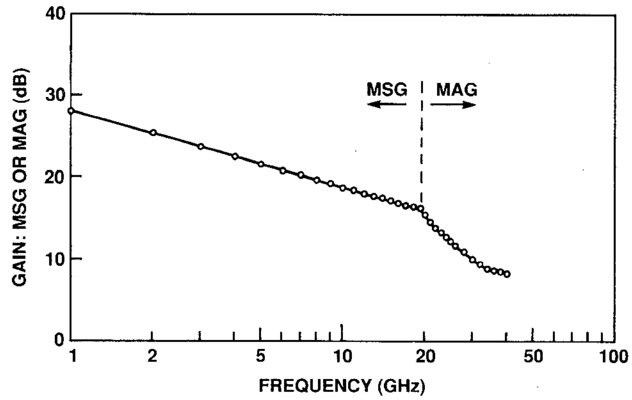

Figure 3. Device small-signal gain vs. frequency.

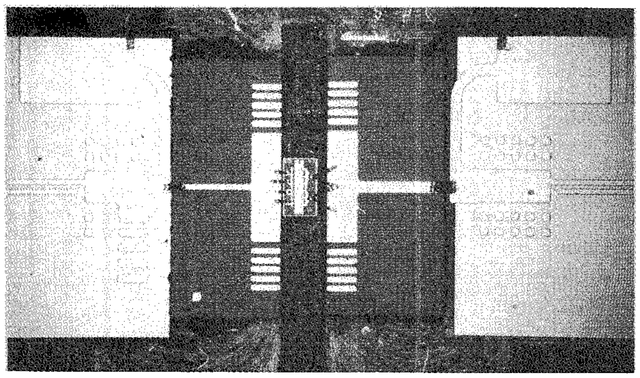

Figure 4. Matching circuitry for 44 GHz power testing. Substrates adjacent to the device are alumina.

DEVICE PERFORMANCE

The DC characteristics for devices from three different wafers are summarized in Table 1. Transconductance g_m averages 540 to 600 mS/mm, with values as high as 660 mS/mm observed. Gate reverse breakdown voltage, defined as the voltage at which 1 mA/mm of gate current flows, is approximately 6 - 7 V with both source and drain grounded (BV_{gds}), and 8V with only the drain grounded (BV_{gd}). Despite the short gate length and relatively large gate width, DC yields are high (ranging from 50 to 80%), and uniformity of electrical characteristics is excellent: (standard deviations of g_m and breakdown voltage are typically 5%).

HEMT chips were mounted onto microstrip carriers and S-parameters measured from 1 to 40 GHz. The S-parameter data, measured at power bias and plotted in Figure 2, has several unusual features that merit discussion. From the curling in of S_{11} at low frequencies it is apparent that the input of the device is not a simple series RC circuit, as is normally the case for FETs and HEMTs. Instead, an additional AC resistance is required in parallel with the input capacitance C_{gs} to model the non-ideal behavior of the gate diode at high drain bias voltages. S_{22} exhibits a curious "double hump" response which initially was thought to be due to measurement inaccuracy, but is now believed to be physical since it has been fit precisely using a standard equivalent circuit model. Finally, S_{12} is quite small ($0.02 < |S_{12}| < 0.04$), and is difficult to measure accurately at the highest frequencies due to parasitic effects.

The small-signal gain of the device, calculated from the measured S-parameters, is given as a function of frequency in Figure 3. Maximum stable gain (MSG) is plotted for stability factor k less than one, while maximum available gain (MAG) is shown for k greater than one. Maximum available gain is 8.4dB at 40 GHz, and the HEMT is unconditionally stable at frequencies above 20 GHz.

The HEMTs were power tested at 44 GHz using an E-field probe-type test fixture of the type described in [9]. The impedance-matching circuitry shown in Figure 4 was designed using measured S-parameters and a load-line approximation for the output match, and was implemented on a combination of 5-mil-thick alumina and fused silica substrates.

Power data, obtained at various drain bias voltages and levels of gain compression, is summarized in Table 2.

As is normally the case, maximum power occurs at the highest drain voltage, while highest efficiency is obtained at a lower drain voltage. Maximum output power is 689 mW. Peak efficiency is 30%, with an associated output power of 551 mW and 4.0dB gain.

The tradeoff between output power, efficiency and gain at a fixed drain bias is evident in the data of Table 2 for V_{ds} of 5V. Maximum efficiency occurs at a power gain of about 4dB (roughly 2dB gain compression), with an output power of approximately 600 mW. In order to overcome circuit losses in practical multistage power amplifiers, however, higher gain is often desirable. At a gain of 4.6dB, output power is still relatively high, at 500 mW.

The power saturation characteristic measured at V_{ds} of 5.4V is plotted in Figure 5. Linear gain is 6.1 dB, and output power saturates at approximately 700mW.

The output powers obtained with these pseudomorphic HEMTs are by far the highest yet reported for single transistors at 44 GHz. Using these transistors, it will now be possible to construct efficient watt-level power amplifiers. For example, an MIC-type amplifier combining four of these devices in the output stage (such as is described in [10]) would be able to produce 1.5 to 2W output power at 44 GHz. If desired, higher power levels could then be realized using low-loss n-way power combining structures to combine the power of many individual amplifier modules.

RELIABILITY

Enhanced reliability is expected to be one of the most significant advantages of the pseudomorphic HEMT as compared to existing millimeter-wave transmitter technologies (i.e., IMPATTs and tubes). The HEMTs reported here have been designed to operate at channel temperatures well below 150°C. A thermal resistance of 73°C/W was calculated using three-dimensional finite element numerical modeling. With a chip backside temperature of 70°C, and under typical RF operating conditions (550 mW output power, 30% efficiency and 4dB gain), a maximum channel temperature of 126°C is predicted.

Although life testing has shown that low-noise pseudomorphic HEMTs are extremely reliable [11], extensive reliability testing is still needed to demonstrate that pseudomorphic power HEMTs, which operate at much higher drain voltages and currents and under significant RF drive, are also reliable. Clearly, high-temperature life tests with an applied RF signal are required, and will be conducted. However, in order to provide a preliminary indication of any potential reliability problems, high-temperature DC life tests have been performed on power HEMTs under DC bias conditions consistent with large-signal device operation.

150μm gate-width HEMTs with the same channel design as the large devices described in this paper were life tested at baseplate temperatures of 225°C and 237°C. With a dissipated power of 135mW, the corresponding channel temperatures were estimated to be 275°C and 287°C. Eight or nine devices were tested at each temperature, and failure was defined as a 20% degradation of g_m. Median-times-to-failure at the 275°C and 287°C channel temperatures were 1172 and 444 hours, respectively. These lifetimes are significantly longer than those obtained for low-noise pseudomorphic HEMTs at these temperatures, probably due to the higher breakdown voltage of the power HEMT structure. From this data, an activation energy of 2.14 eV and an extrapolated lifetime MTF of 7.67 x 10^8 hours at 150°C channel temperature have been determined. Hence, initial DC life tests on pseudomorphic power HEMTs have indicated no life-limiting failure modes, and suggest that excellent reliability will be possible.

V_{ds} (V)	Output Power (mW)	Power-Added Efficiency (%)	Power Gain (dB)
4.8	551	30	4.0
5.0	390	22	5.0
	500	26	4.6
	572	28	4.2
	628	28	3.6
5.4	647	26	3.7
	689	24	3.0

Table 2. Measured 44 GHz power performance for HEMT from wafer A.

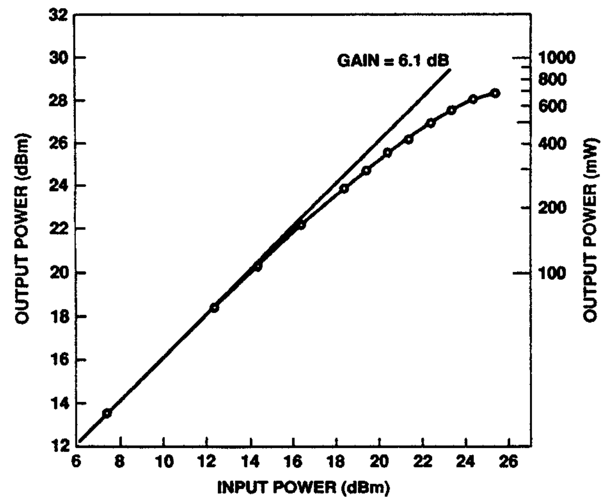

Figure 5. 44 GHz power saturation characteristic at V_{ds} of 5.4V.

SUMMARY

Pseudomorphic power HEMTs with record output power and high efficiency at 44 GHz have been demonstrated. These devices have been fabricated with high DC yields and uniform electrical characteristics. Moreover, they promise to be extremely reliable: channel temperature is low during device operation due to low thermal resistance, and initial DC life test results have revealed no inherent reliability limitations of the power HEMT structure.

Once the long-term reliability of power HEMTs has been fully established, the devices will undoubtedly find widespread use in millimeter-wave transmitters because they offer a combination of high performance, FET-like reliability, and ease of integration into both MIC and MMIC-based hardware.

ACKNOWLEDGEMENT

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