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ADVANCES IN HEMT TECHNOLOGY AND APPLICATIONS

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ABSTRACT

High electron mobility transistors (HEMTs) have demonstrated unsurpassed transistor performance in the millimeter-wave range--at 60 GHz, results include a minimum noise figure of 2.3 dB with 4.0 dB associated gain, maximum small-signal gain of 11.7 dB, output power of 50 mW, power density of 0.43 W/mm and maximum power-added efficiency of 28%. The principles of HEMT operation and design are described, followed by a summary of the current state-of-the-art in noise and power performance, and discussion of several applications.

INTRODUCTION

In recent years, the HEMT has evolved rapidly into a high performance transistor suitable for both low noise and power applications at frequencies well into the millimeter-wave regime. Although conventional GaAs FETs were used in the first 60 GHz amplifiers [1], further improvement in FETs over the past four years has been slow compared to the rapid progress made in HEMTs, and HEMT amplifiers have now been demonstrated at frequencies of 60 GHz [2]-[4] and 94 GHz [5].

DEVICE DESCRIPTION

The cross-section of the conventional HEMT is shown in Figure 1. The device is based on a selectively doped heterojunction--a two-dimensional electron gas (2DEG) is formed below the interface between heavily doped AlGaAs and undoped GaAs and resides in the potential well created by the conduction band discontinuity between the two materials. Since the electrons flow in an undoped region (unlike a FET), ionized impurity scattering is reduced, and high mobility and velocity are obtained. The use of a spacer layer has been found to improve mobility by further separating the 2DEG from the donor ions in the AlGaAs, but this layer must be kept thin (< 50A) or the 2DEG density will be unacceptably low. The best HEMT devices are produced on layers that possess an optimum combination of high mobility and high 2DEG density.

In addition to conventional HEMTs based on the AlGaAs/GaAs heterojunction, new device structures have shown great promise. A 0.25µm gate-length InGaAs pseudomorphic HEMT has recently been demonstrated through a collaboration between GE and the University of Illinois [6]. This HEMT contains a thin InGaAs channel layer between the AlGaAs spacer and GaAs buffer layers (see Figure 1). Although InGaAs is lattice mismatched to GaAs, the layer is sufficiently thin that the lattice strain is taken up coherently by the epitaxial layers, resulting in dislocation-free, "pseudomorphic" material. The improved RF characteristics of this HEMT are attributed to the InGaAs, which possesses higher electron mobility and velocity than GaAs and allows favorable tailoring of the conduction band profile.

Because of the thin layers and abrupt transitions required, HEMT material has traditionally been grown by MBE. More

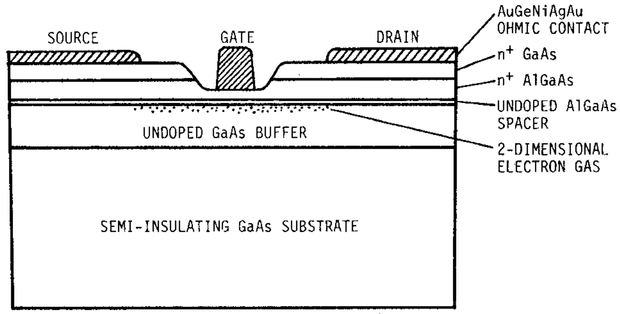

Figure 1. Cross-section of HEMT

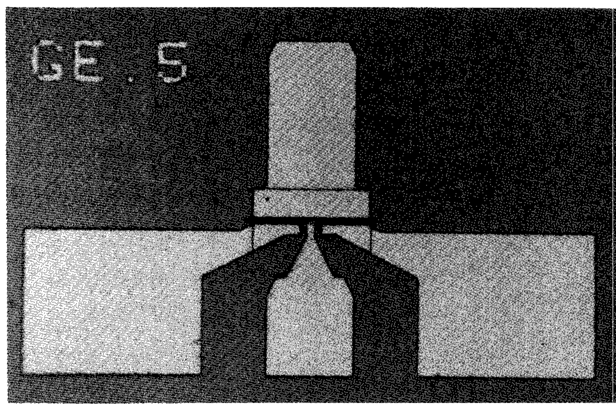

Figure 2. Millimeter-wave Low Noise HEMT

recently, high quality HEMT material has also been demonstrated using MOCVD [7]. The short gates (0.2 - 0.3µm) necessary for best millimeter-wave operation are patterned using electron-beam lithography. In many respects, the HEMT fabrication process is similar to that used for FETs--alloyed AuGe ohmic contacts are employed for source and drain, and the gates are recessed--although the exact conditions differ. Also due to the similarity in structure, HEMT device layouts bear a striking resemblance to those of FETs. As an example, a 0.25µm gate-length, 50µm gate width millimeter wave low noise HEMT is shown in Figure 2. Because of this similarity, HEMTs can perform the same functions as FETs (see [8]), and can be "dropped into" FET MICs or integrated into MMICs.

DEVICE CHARACTERISTICS

HEMTs display very high transconductance. Our 0.25µm HEMTs have yielded maximum transconductance of 600 mS/mm, and typical values in excess of 400 mS/mm. High

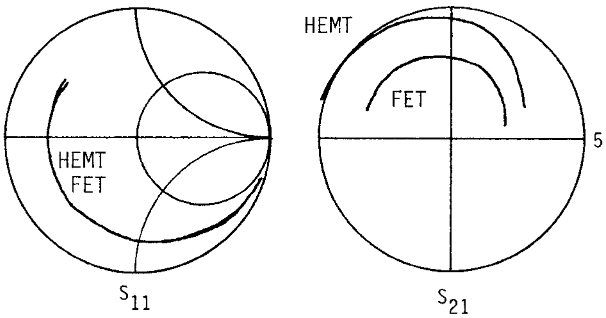

Figure 3. 2-20 GHz S_{11} and S_{21} of 0.25 x 150µm FET and HEMT

FREQ (GHz)	DEVICE	F_{min} (dB)	G_a (dB)	F_∞ (dB)
8	CONV	0.4	15.2	0.41
18	CONV	0.7	13.2	0.73
30	CONV	1.5	10.0	1.6
40	CONV	1.8	7.5	2.1
62	CONV	2.6	5.7	3.3
62	PM	2.3	4.0	3.3

Table 1. Noise Performance of 0.25µm Conventional and Pseudomorphic (PM) HEMTs at 300K.

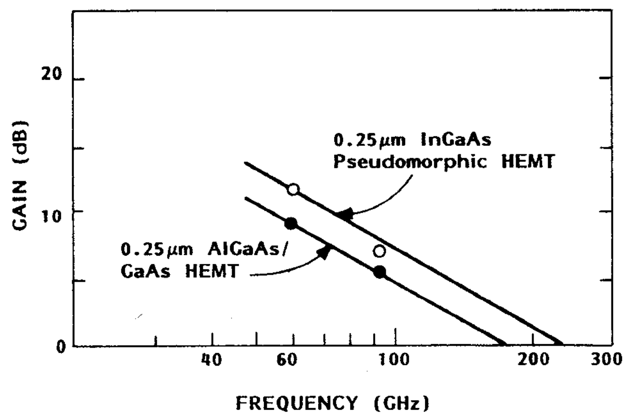

Figure 4. Maximum Small-Signal Gain of 0.25µm HEMTs (GE Devices)

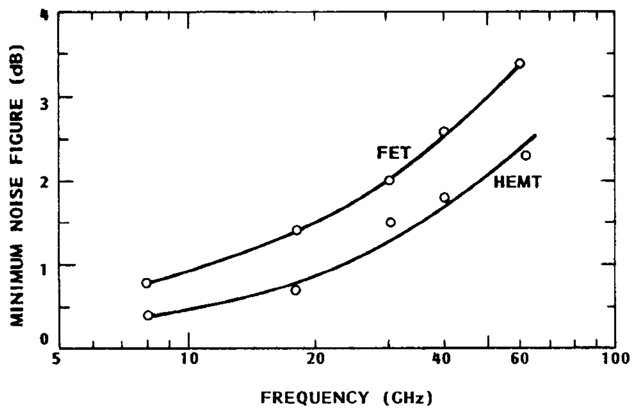

Figure 5. Comparison of 0.25µm FET and HEMT Noise Figure

transconductance, coupled with low input capacitance (due to the short gate) leads to excellent high frequency characteristics. S_{11} and S_{21} of a 0.25µm FET and HEMT of comparable geometry are compared in Figure 3. S_{11} is identical, indicating equal input impedance, yet S_{21} of the HEMT is significantly higher across the entire frequency range. The intrinsically larger gain-bandwidth product of the HEMT makes it ideally suited to broadband applications such as distributed amplifiers.

For purposes of millimeter-wave testing, HEMT single-stage amplifiers employing microstrip matching circuitry are designed using S-parameters measured at lower frequencies. Microstrip test fixtures with E-field probe-type waveguide-microstrip transitions are used, and the devices are empirically fine-tuned for the desired gain, noise or power condition.

Measured small-signal gain of conventional and InGaAs pseudomorphic HEMTs at 60 and 94 GHz is plotted in Figure 4. The conventional HEMT has yielded gains of 9.1 and 5.3 dB at 60 and 94 GHz, respectively, while the pseudomorphic HEMT has exhibited gains of 11.7 and 6.7 dB at the same frequencies. Clearly, present HEMTs have useful gain at frequencies up to at least 100 GHz.

LOW NOISE APPLICATIONS

0.25µm low noise HEMTs fabricated in our laboratory have been evaluated from 8 to 62 GHz; the results, shown in Table 1, represent the lowest noise figures yet reported for microwave transistors, and are compared with state-of-the-art 0.25µm FETs [9] in Figure 5. Table 1 also includes F_∞, which we define as the noise figure of an infinite chain of cascaded single-stage amplifiers, since it is a figure of merit that closely approximates the noise figure attainable in a multi-stage, high gain (>15 dB) amplifier. If one then includes transition losses (coaxial-to-microstrip at low frequencies, waveguide-to-microstrip at high frequencies), the upper curve shown in Figure 6, representing the noise figure of a multi-stage, high gain amplifier at its input connector, is obtained. Using present 0.25µm HEMTs, noise figures of 1.7, 2.6 and 3.7 dB are achievable at 30, 44 and 60 GHz, respectively.

HEMT low noise amplifiers are currently under development for applications at several frequencies, where the goal is to achieve the performance indicated in Figure 6. One example is the V-band 3-stage amplifier shown in Figure 7; the first such amplifier yielded 5.0 dB noise figure with 13.4 dB gain at 62 GHz.

Because of greatly enhanced performance at low temperatures, HEMTs are attractive for use in cryogenic receivers. Mochizuki et al. demonstrated that HEMTs exhibit greater improvement in noise performance with cooling than FETs over the 80-300 K temperature range [10]. Low noise HEMTs optimized specifically for low temperature operation have been developed by GE for JPL, and have demonstrated a minimum noise temperature of 6.5 K with 14 dB associated gain at 8 GHz

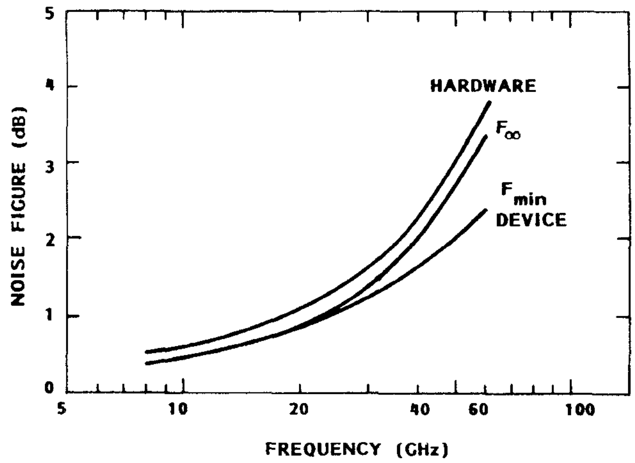

Figure 6. Amplifier Performance Attainable with Present 0.25μm HEMTs

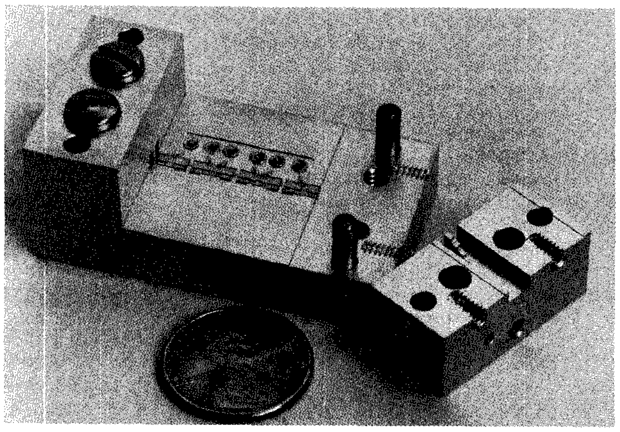

Figure 7. 3-Stage V-band LNA

DEVICE	POWER DENSITY (W/mm)	MAXIMUM POWER-ADDED EFFICIENCY (%)
CONVENTIONAL HEMT	0.41	14
PSEUDOMORPHIC HEMT	0.43	28
GaAs FET	0.24	9

Table 2. 60 GHz Power Performance of Various Devices. W_G = 50μm, Gain = 3.0 dB.

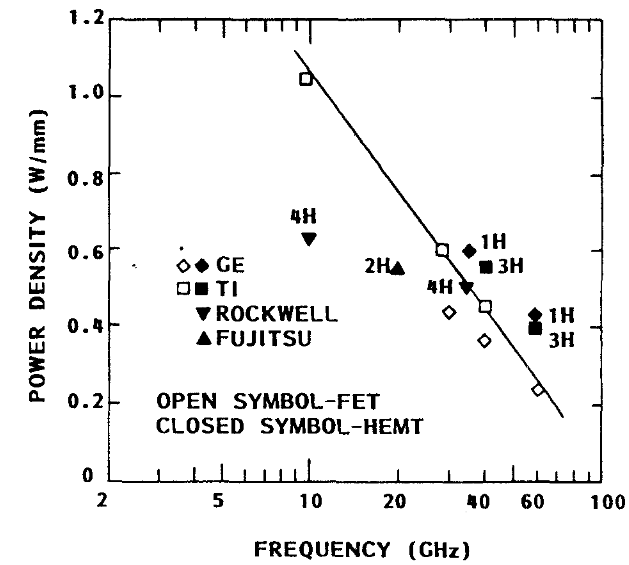

Figure 8. Best Reported Power Densities for HEMT and GaAs FET [2], [4], [6], [13]-[17]. 1H, 2H Etc. Refers to Number of Heterojunctions.

when cooled to 13 K [11]. HEMT amplifiers are beginning to replace masers in some radio astronomy receiver applications.

Compared to the FET, HEMT noise figure is much less sensitive to variations in drain current or source impedance. 0.25μm HEMTs exhibit 50Ω unmatched noise figure of 1.3 dB with 9.6 dB gain at 18 GHz. Low unmatched noise figure and reduced sensitivity to source mismatch are due to a combination of high optimum source resistance R_{opt} and low noise conductance g_n, as observed by Pospieszalski et al. [12], and result in much larger noise bandwidth for HEMTs than FETs.

POWER PERFORMANCE

Until recently, HEMTs were not believed to be viable power transistors due to relatively low sheet carrier density (10^{12} cm^{-2}) and reports of low breakdown voltage. To increase the current capability, HEMTs with multiple doped heterojunctions have been fabricated at various laboratories [4], [13]- [15]. We have found that even single heterojunction HEMTs can exhibit RF power density in excess of that possible with FETs at millimeter-wave frequencies.

A comparison of 60 GHz power data for different device types of identical geometry is made in Table 2. As seen in the table, the HEMTs display power density in excess of 0.4 Watts/mm, compared to 0.24 W/mm for the FET. The pseudomorphic HEMT displays a record 28% power-added efficiency due to several factors, including high gain, high breakdown voltage, low output conductance and highly linear drain I-V characteristics.

At 35 GHz, a 0.25 x 50μm pseudomorphic HEMT yielded a maximum power density of 0.60 W/mm with 6.0 dB gain and 32% power-added efficiency, and a maximum efficiency of 42% with 0.49 W/mm power density and 5.7 dB gain.

The current state-of-the-art of power density for FETs and HEMTs is summarized in Figure 8. The most recent HEMT results

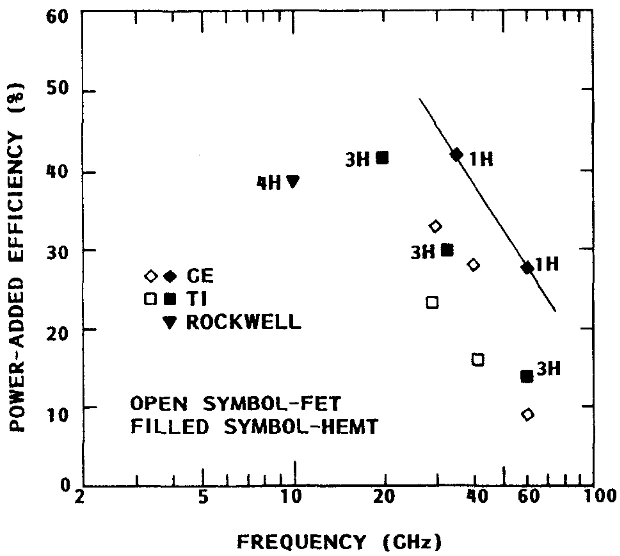

Figure 9. Best Reported Efficiencies for HEMT and FET [2], [4], [6], [13], [15], [17].

have crossed over the line that fits FET power density data. FET and HEMT efficiency are compared in Figure 9. The pseudomorphic HEMT displays power-added efficiency that is 10-15% higher than the best FET or conventional HEMT at any frequency in the 30-60 GHz range.

Using a 150μm gate width conventional HEMT, a maximum output power of 50 mW with 3 dB gain and 11% efficiency was measured at 60 GHz. Further development of larger gate width HEMTs for higher output power will focus on optimization of the device topology, and can be expected to yield single device output powers of 1 Watt at 35 GHz and 0.25 Watt at 60 GHz. Although higher power levels can presently be obtained with IMPATTs and tubes, the HEMT offers several advantages, including suitability for small size, low cost planar integration (MIC or MMIC), better part uniformity and the potential for improved reliability.

SUMMARY

HEMT technology has advanced rapidly in recent years. HEMTs now provide unsurpassed low noise transistor performance at frequencies from 1 to 60 GHz at both room and cryogenic temperatures, impressive millimeter-wave power performance, and useful gain at frequencies up to at least 100 GHz. In addition, the HEMT is ideally suited to broadband applications due to its large gain-bandwidth product and large noise bandwidth.

Future work will emphasize continued improvement of the device, as well as integration into MMICs. Two promising areas of HEMT device research are the investigation of new material systems (such as InGaAs) and the reduction of gate length to the 0.1-0.2μm range.

As an enabling technology, the HEMT not only promises dramatic improvement in the performance of existing systems, but will stimulate the conception and realization of the next generation of microwave and millimeter-wave systems.

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