W-Band InGaAs HEMT Low Noise Amplifiers

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Abstract

0.15 µm gate length GaAs-based and InP-based InGaAs channel HEMTs developed in our laboratory have exhibited state-of-the-art noise and gain performance well up to 100 GHz. 94 GHz noise figures of 2.4 and 1.4 dB with gains of 5.4 and 6.5 dB have been measured from GaAs and InP based HEMTs respectively. High performance W-Band multi-stage amplifiers have been built using these devices. A two-stage GaAs-based amplifier exhibits a noise figure of 4.2 dB with gain of 9.7 dB at 93 GHz and a three-stage amplifier yields 4.5 dB noise figure with 14.8 dB gain at 94 GHz. The best two-stage amplifier built with InP-based HEMTs exhibits a minimum noise figure of 3.2 dB with gain of 11.5 ± 0.4 dB from 88 to 96 GHz. A noise figure as low as 3.3 dB with gain of 17.3 ± 0.5 dB from 88 to 96 GHz has also been demonstrated from a three-stage amplifier. The characteristics and performance of both devices will be presented in the paper.

Introduction

Significant progress has been made recently in the High Electron Mobility Transistor(HEMT) technology[1-4], which opens a whole new area for HEMTs in millimeter-wave radar, satellite communication, electronic warfare, and surveillance system applications. Three terminal transistors can now be useful components up to frequencies of 100 GHz[5,6]. HEMTs with a single quantum well active channel composed of InGaAs grown on GaAs and InP substrates are establishing new standards of performance at millimeter-wave frequencies. In this paper, we report record low noise and gain performance of 0.15 µm gate-length AlGaAs/InGaAs/GaAs and InAlAs/InGaAs/InP HEMTs from 18 to 94 GHz and present W-Band amplifier performance.

GaAs-Based Pseudomorphic HEMTs

The GaAs-based pseudomorphic(PM) HEMTs differ from the conventional AlGaAs/GaAs HEMTs in that a thin(typically 50-200 A°) layer of $In_xGa_{1-x}As$(x=.15 - .35) is inserted between the AlGaAs layer and GaAs buffer(see Figure 1). The device is therefore based on the AlGaAs/InGaAs heterojunction, with electrons flowing in the strained quantum well of the undoped InGaAs channel. GaAs-based PM HEMTs have shown excellent noise and power performance[7,8]. InAs mole fraction as high as 35% is employed to have large conduction band discontinuity at AlGaAs/InGaAs interface which allows high sheet charge density and hence high transconductance. The details of material growth can be found in Reference [9].

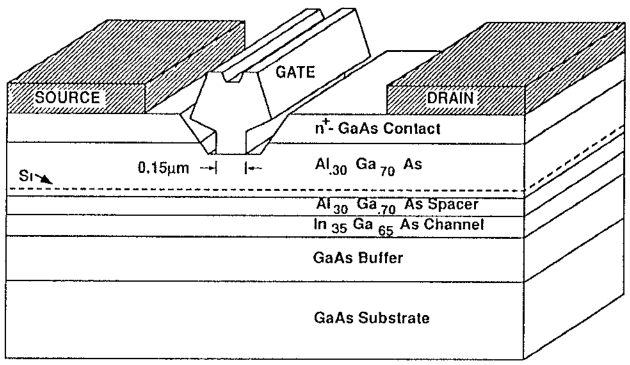

Figure 1. Cross-section of the AlGaAs/InGaAs/GaAs HEMT.

Freq. (GHz)	F_{min} (dB)	G_a (dB)	F_∞ (dB)
18	0.5	15.1	0.52
60	1.6	7.6	1.87
94	2.4	5.4	3.09

Table 1. Noise Performance of 0.15µm AlGaAs/InGaAs/GaAs HEMTs at 300K.

DC/RF characterization was performed on these devices. Extrinsic transconductance, g_m, of 0.15 µm devices is typically 800 mS/mm. The S parameters of 50 µm wide devices were measured from 0.1 - 40 GHz using on-wafer probing to obtain the device extrinsic unit current gain cutoff frequency, f_t. The extrinsic f_t value of 135 GHz was determined from the h_{21} extrapolation for these devices. Table 1 summarizes the 0.15 µm GaAs-based PM HEMT noise performance from 18 to 94 GHz. F_∞ in Table 1 is defined as the noise figure of an infinite chain of cascaded single-stage amplifiers, which closely approximates the noise figure attainable in a multi-stage amplifier. Minimum noise figures of 0.5 and 1.6, with associated gains of 15.2 and 7.6 dB have been measured at 18 and 60 GHz, respectively. Figure 2 shows the noise performance of a 30 µm wide GaAs-based PM HEMT from 90 to 98 GHz. The device exhibits a minimum noise figure of 2.4 dB with 5.4 dB associated gain at 94 GHz. These results are the best reported low noise performance for GaAs-based HEMTs to date.

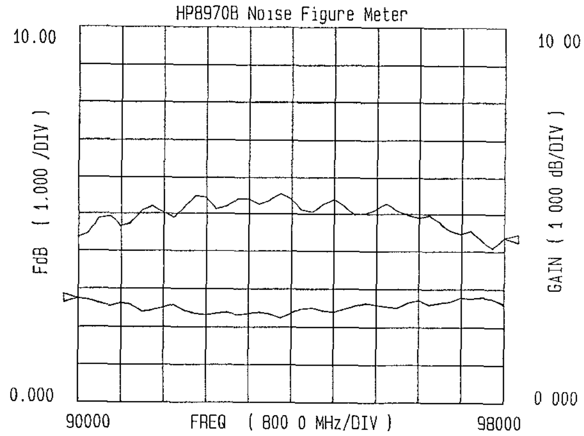

Figure 2. Measured W-band noise and gain performance of a 0.15 µm x 30 µm GaAs-based PM HEMT. The device was biased at V_{ds} = 2.5 V and I_{ds} = 5.1 mA.

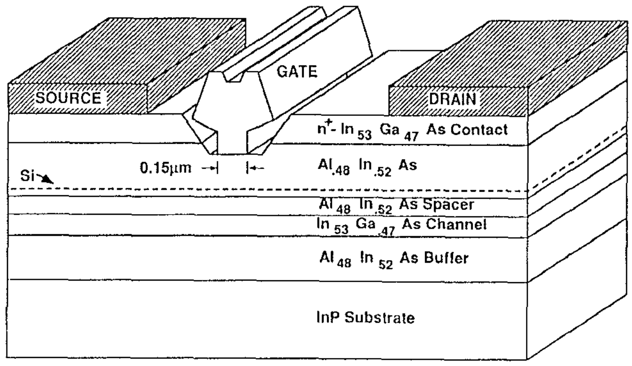

Figure 3. Cross-section of the InAlAs/InGaAs/InP HEMT.

Freq. (GHz)	F_{min} (dB)	G_a (dB)	F_∞ (dB)
18	0.3	17.1	0.31
60	0.9	8.6	1.03
94	1.4	6.5	1.73

Table 2. Noise Performance of 0.15µm InAlAs/InGaAs/InP HEMTs at 300K.

InP-Based HEMTs

One way to improve the HEMT performance is to increase the InAs mole fraction in the InGaAs channel. The devices can be fabricated on selectively doped InAlAs/InGaAs heterostructures grown by MBE on InP substrate(see Figure 3). The InAlAs/InGaAs/InP lattice-matched HEMT has 53% InAs in the channel. The higher InAlAs/InGaAs conduction band discontinuity and low energy bandgap of the $In_{.53}Ga_{.47}As$ channel offer high electron sheet charge density and better carrier confinement in the channel, resulting in superior electron transport property to achieve higher g_m, f_t, and lower noise figure than GaAs-based HEMTs[10,11].

Extrinsic g_m as high as 1450 mS/mm was obtained in the 0 15 µm InP-based HEMT. The f_t value of these devices is 186 GHz. Device small signal gain as high as 12.6 dB has been measured at 95 GHz. Table 2 displays the room temperature noise and gain performance of the 0.15 µm InP-based HEMTs from 18 to 94 GHz. Minimum noise figures of 0.3 and 0.9 dB with associated gains of 17.1 and 8.6 dB have been measured at 18 and 60 GHz, respectively. The W-band noise performance of a 30 µm wide lattice-matched InP-based HEMT is shown in Figure 4. Minimum noise figure of 1.4 dB with 6.5 dB gain has been measured at 94 GHz.

DC drain voltage at low noise condition is typically 0.9 - 1.1 Volt, which is about half of that for GaAs-based HEMT. The drain currents at low noise bias for both devices are about the same, which means the total DC power consumption for InP-based HEMT amplifiers is approximately half of that for GaAs-based amplifiers. Since the device is quite new, it still suffers from a few problems such as kink effects in the I-V curves, poor gate characteristics, and low breakdown voltage[12]. Pseudomorphic gate layer and channel approaches can be applied to improve the characteristics. Breakdown voltage as high as 10 V has been achieved recently with proper layer structure design.

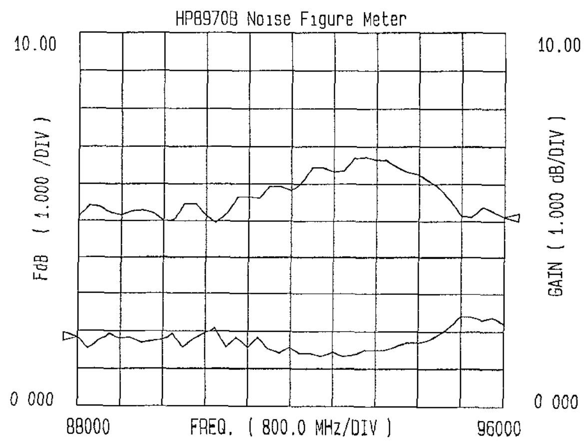

Figure 4. Measured W-band noise and gain performance of a 0.15 µm x 30 µm InP-based HEMT. The device was biased at V_{ds} = 0.9 V and I_{ds} = 5.0 mA.

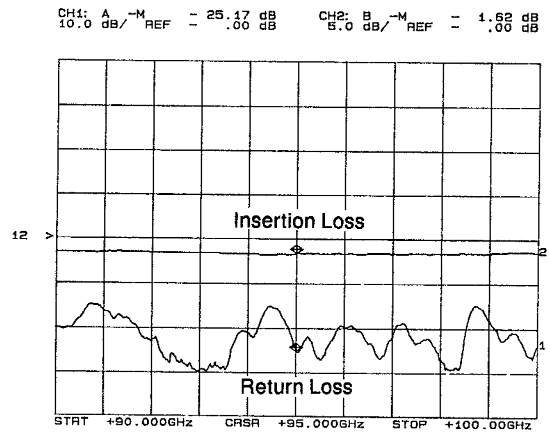

Figure 5. Measured performance of W-Band stepped-ridge waveguide to microstrip fixture with a 50 ohm through line.

Amplifier Performance

W-Band E-field probe circuits and stepped-ridge waveguide to microstrip transitions were developed for the amplifier applications. For a 0.5 inch long 50 Ω through line containing two edge-coupled lines of E-field probe circuits, the insertion loss of end-to-end through connection (from input waveguide flange to output waveguide flange) is approximately 1.9 dB at 94 GHz. The input return loss is greater than 16 dB from 89 to 99 GHz. Figure 5 illustrates the insertion and return losses of a stepped-ridge fixture that consists of two stepped-ridge transitions connected back-to-back with a 0.5 inch long 50 Ω microstrip line which was fabricated on a 5 mil quartz substrate. The input and output ports utilize a broad-band WR10-to-stepped ridge waveguide-to-microstrip transition. It gives a flat insertion loss of approximately 1.7 dB with better than 16 dB return loss from 90 to 100 GHz.

The input and output matching networks for the amplifiers were designed based on fitting measured S parameters at the low noise bias condition to the device equivalent circuit model from 2 to 40 GHz. From this model, high frequency performance was extrapolated through W-band. Measured W-band noise and gain response under several conditions (minimum noise, 50 Ω, maximum gain, etc.) were measured to adjust the device lumped equivalent circuit elements for the design parameters. The matching circuits were fabricated on 5 mil quartz substrate. The edge-coupled symmetric microstrip transmission line structure was selected to provide low loss DC blocking, and to serve as a bandpass filter to improve out of band stability.

Figure 6 shows the noise and gain performance of a two-stage amplifier using 0.15 µm GaAs-based PM HEMTs. Noise figure as low as 4.2 dB with gain of 9.7 dB was measured at 93 GHz. The three-stage amplifier built with same devices gave a minimum noise figure of 4.5 dB with 14.8 dB at 94 GHz as shown in the Figure 7. The two-stage amplifier using 0.15 µm InP-based HEMTs demonstrated a minimum noise figure of 3.2 dB at 92 GHz. The flat gain response of the amplifier is 11.5 $\pm$ 0.4 dB from 88 to 96 GHz as shown in Figure 8. Figure 9 displays the performance of the three-stage InP-based HEMT amplifier. A minimum noise figure of 3.3 dB occurs at 92 GHz with associated gains of 17.3 $\pm$ 0.5 dB from 88 to 96 GHz. The noise figure is less than 4.5 dB across the whole test band. The noise figure of W-band amplifiers using GaAs-based PM HEMTs is typically 1.0 to 1.5 dB higher than those of InP-based HEMTs. The typical 1 dB compression point of InP-based amplifiers is around 1 to 3 dBm while that for GaAs-based amplifiers is in the range of 6 to 9 dBm. The lower 1 dB compression point in the InP-based HEMTs is due primarily to the lower drain voltage, but could also be influenced by the inferior gate characteristics.

The noise source used in the W-band measurement is periodically calibrated by the hot/cold method and cross-checked with other established laboratories to ensure the measurement accuracy.

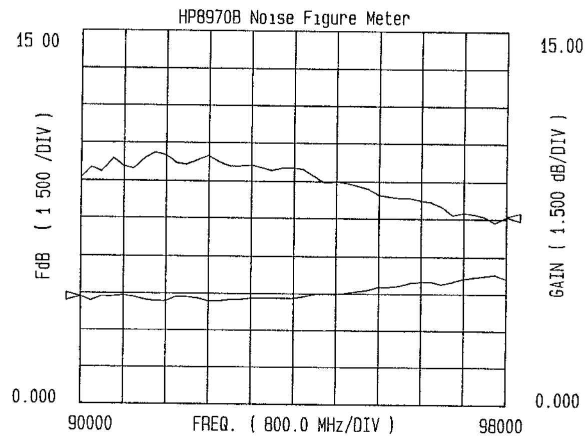

Figure 6. Gain and noise performance of W-Band 2-stage HEMT amplifier using GaAs-based PM HEMTs.

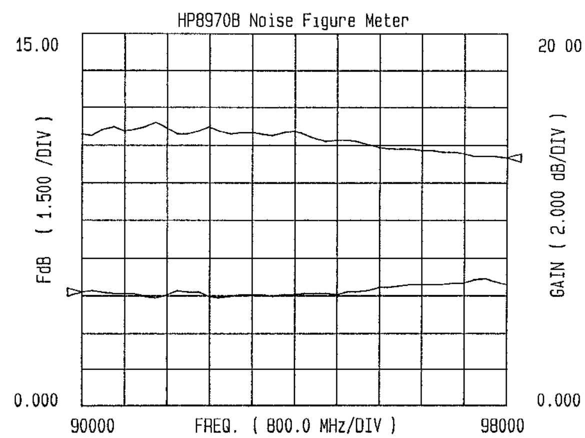

Figure 7. Gain and noise performance of W-Band 3-stage HEMT amplifier using GaAs-based PM HEMTs.

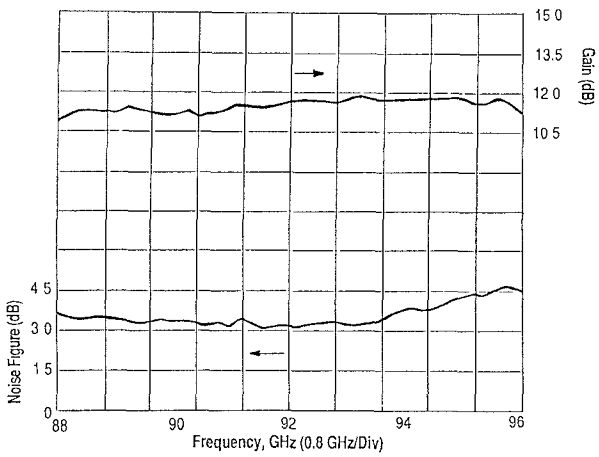

Figure 8. Gain and noise performance of W-Band 2-stage HEMT amplifier using InP-based HEMTs.

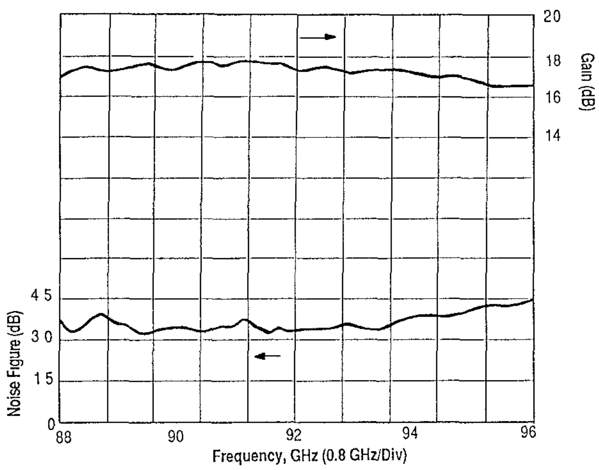

Figure 9. Gain and noise performance of W-Band 3-stage HEMT amplifier using InP-based HEMTs.

Conclusion

We have demonstrated state-of-the-art low noise performance from our 0.15 µm GaAs-based pseudomorphic(35% InAs) and InP-based(53% InAs) InGaAs HEMTs. Minimum noise figures of 0.3, 0.9, and 1.4 dB with gains of 17.1, 8.6, and 6.5 dB have been measured at 18, 60, and 94 GHz, respectively from InP-based HEMTs. For GaAs-based HEMTs, noise figures of 0.5, 1.6, and 2.4 dB with gains of 15.2, 7.6, and 5.4 dB have been obtained at 18, 60, and 94 GHz, respectively. High performance W-band low noise amplifiers are also reported. Multi-stage hybrid amplifiers based on these devices have demonstrated excellent W-band performance. A two-stage InP HEMT amplifier exhibits 3.2 dB noise figure while a two-stage GaAs-basea PM HEMT amplifier yields 4.2 dB noise figure at W-band. These results highlight the potential of InGaAs HEMTs for W-band high performance receiver applications.

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