High-Performance InP-based HEMT Millimeter-wave Low-Noise Amplifiers

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ABSTRACT

Quarter-micron InAlAs/InGaAs planar-doped HEMTs lattice-matched to InP developed in our laboratory have exhibited state-of-the-art noise and gain performance at frequencies up to 94 GHz. Minimum noise figures of 0.5, 1.2, and 2.1 dB have been measured at 18, 60, and 94 GHz, respectively. Small signal gains as high as 15.4 and 12.0 dB have also been obtained at 63 and 95 GHz, respectively. Using 0.25 μm InP-based HEMTs, a V-Band three-stage amplifier yields an average noise figure of 3.0 dB with a gain of 22.0 ± 0.2 dB from 60 to 65 GHz. At W-Band, a two-stage amplifier exhibits a noise figure of 4.5 dB with a gain of 10.2 dB at 90.4 GHz and a three-stage amplifier shows a noise figure of 4.8 dB with a gain of 15.0 dB at 90.4 GHz. These results clearly show the great potential of InP-based HEMTs for high performance millimeter-wave low noise receiver applications.

INTRODUCTION

Present and future DoD and NASA radar and communication systems demand high performance millimeter wave devices that operate from Ka-Band up to W-Band. AlGaAs/GaAs High Electron Mobility Transistors (HEMTs) have recently demonstrated superb low noise performance in microwave and millimeter-wave regions[1,2]. HEMT devices will be used as the preferred devices for most receiver applications. One of the major problems of previous transistors is that the devices usually have insufficient power gain to allow effective operation at 94 GHz. Due to improvements in material structure, as well as device design and processing techniques, 0.1 - 0.15 μm AlGaAs/GaAs based HEMTs can now provide sufficient noise, power, and gain performance up to 94 GHz[3-5,11].

HEMTs based on the InAlAs/InGaAs/InP material system, have attracted considerable attention due to the large conduction band discontinuity between InAlAs and InGaAs, and the superb carrier transport properties--high electron mobility and peak velocity in the InGaAs channel compared to the conventional AlGaAs/GaAs and pseudomorphic AlGaAs/InGaAs/GaAs HEMTs[6-9]. The high conduction band offset (0.5 eV) leads to higher two dimensional electron gas (2 DEG) concentrations and should lead to reduced parasitic conduction in confining layers. Both the improved DC characteristics and microwave performance have been reported[8-10]. In this paper, we report the results of 0.25 μm gate-length InAlAs/InGaAs/InP HEMTs with record high gain and noise performance from 18 to 94 GHz and present state-of-the-art V-Band and W-Band low noise amplifier performance.

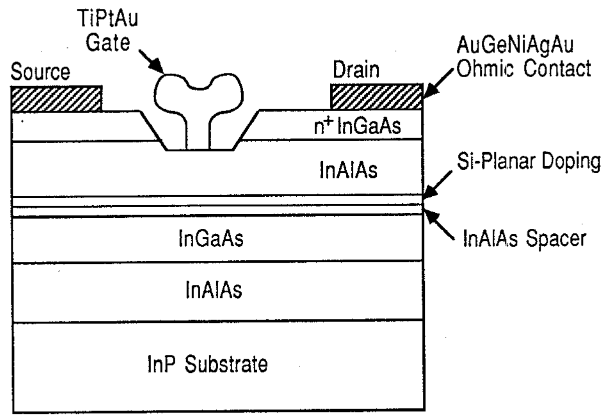

Figure 1. Cross-section of the InAlAs/InGaAs/InP HEMT.

DEVICE DESCRIPTION

The devices were fabricated on selectively doped InAlAs/InGaAs heterostructures grown by molecular beam epitaxy on InP substrates. The details of material growth can be found in [11]. Figure 1 shows the cross-section of the InAlAs/InGaAs/InP HEMTs. Atomic planar doping has been used to obtain high sheet density while allowing a high gate aspect ratio [12] and low doping under the gate to improve the breakdown voltage. The DC I-V characteristics of the 0.25 μm InP-based HEMTs are displayed in Figure 2. Extrinsic transconductance, g_m, as high as 900 mS/mm was obtained at room temperature with good pinch-off characteristics. Besides the relatively low output conductance, there exist no kinks in the I-V curves as have been observed by other groups[8,10]. This is probably due to the high quality of the InAlAs buffer layer.

It should be pointed out that these devices typically exhibit lower gate to drain breakdown voltage (2-3 Volts) and much higher gate leakage current than those obtained for AlGaAs/InGaAs pseudomorphic or conventional AlGaAs/GaAs HEMTs. These may be due to the traps in the InAlAs layer under the gate and also to the tunneling through the very thin InAlAs layer. Based on the preliminary high temperature DC life tests, the InP-based HEMTs have significantly worse reliability than GaAs-based HEMTs. Ongoing work at improving the gate characteristics and ohmic contacts is expected to improve the device reliability.

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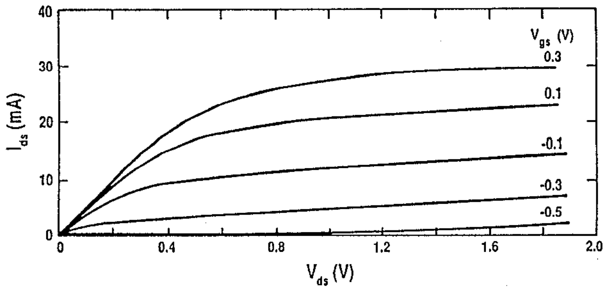

Figure 2. I-V characteristics of the 0.25 µm InAlAs/InGaAs/InP HEMT.

Frequency (GHz)	NF (dB)	Ga (dB)	F_∞ (dB)
18	0.5	15.2	0.51
60	1.2	8.5	1.37
94	2.1	6.4	2.57

Figure of Merit for Circuit Design $F_\infty = F + \frac{F-1}{G} + \frac{F-1}{G^2} + \ldots\ldots = \frac{FG-1}{G-1}$

Table 1. Noise Performance of 0.25µm InAlAs/InGaAs/InP HEMTs at 300K.

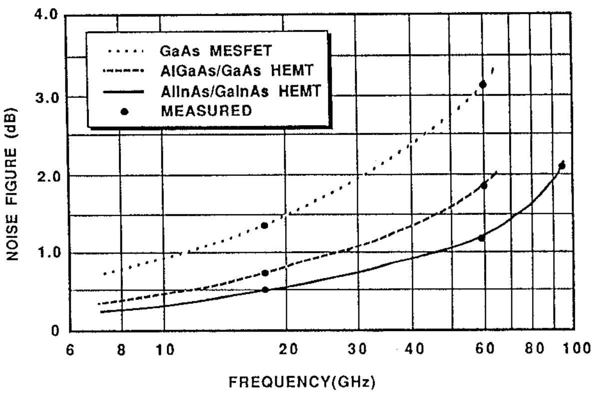

Figure 3. Noise figure versus frequency for various 0.25 µm devices.

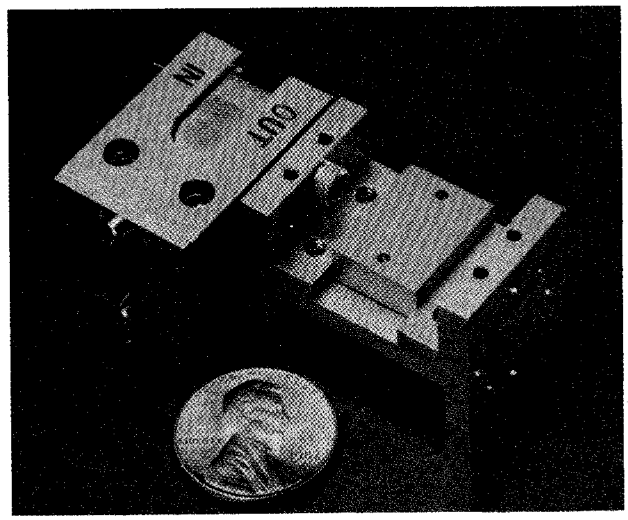

Figure 4. V-Band 3-stage HEMT LNA.

The devices have demonstrated maximum small signal gain of 15.2 and 12.0 dB at 63 and 95 GHz, respectively. The data at both frequencies is consistent, in that both points extrapolated at -6 dB/octave yield a maximum frequency of oscillation, f_{max}, of 380 GHz. Room temperature noise measurements have been performed on these devices from 18 to 94 GHz. Minimum noise figures of 0.5, 1.2, and 2.1 dB with associated gains of 15.2, 8.5, and 6.4 dB have been measured at 18, 60, and 94 GHz, respectively. The noise results from 18 to 94 GHz correspond quite well with the Fukui-type frequency dependence exhibited by other HEMT material systems and MESFETs fabricated in our laboratory. Figure 3 illustrates the noise comparison for 0.25 µm devices : GaAs MESFETs, AlGaAs/GaAs HEMTs, and InP-based HEMTs. The noise performance of 0.25 µm AlGaAs/InGaAs pseudomorphic HEMTs, not shown in the above figure,lies between that of the AlGaAs/GaAs HEMTs and the InP-based HEMTs. Table 1 summarizes the 0.25 µm InP-based 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. It is a useful figure of merit for circuit design that closely approximates the noise figure attainable in a multi-stage amplifier, neglecting circuit losses.

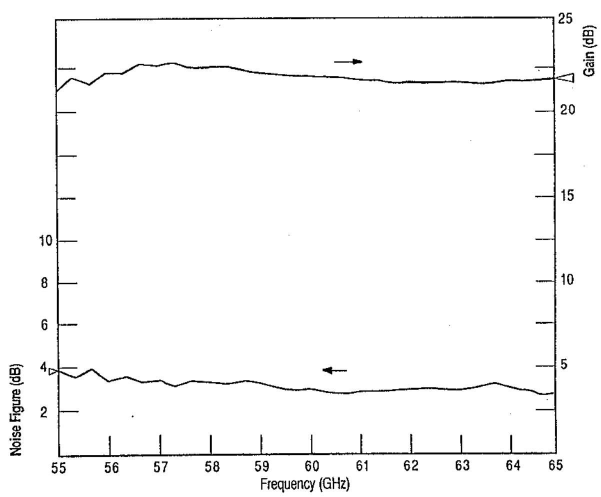

Figure 5. Gain and noise performance of V-Band 3-stage HEMT LNA.

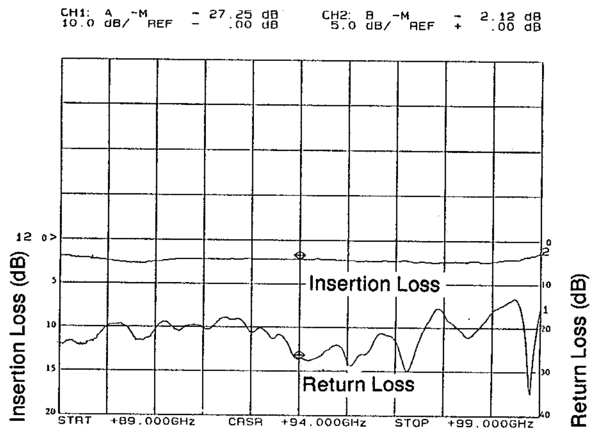

Figure 6. Measured performance of W-Band E-field probe fixture with a 50 ohm through line.

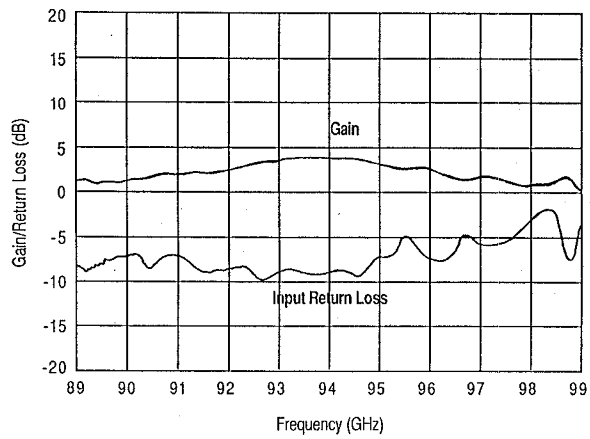

Figure 7. Gain and noise performance of W-Band single-stage amplifier.

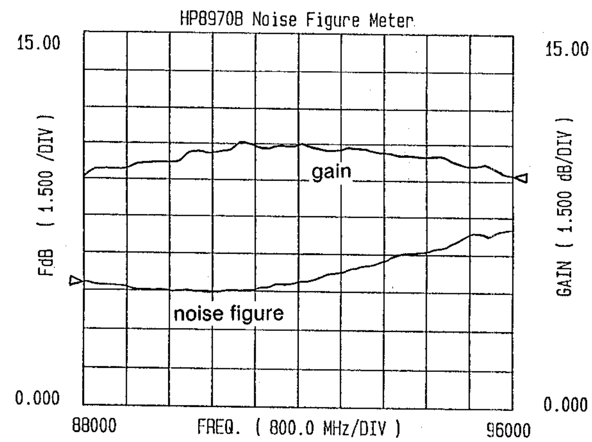

Figure 8. Gain and noise performance of W-Band 2-stage HEMT LNA.

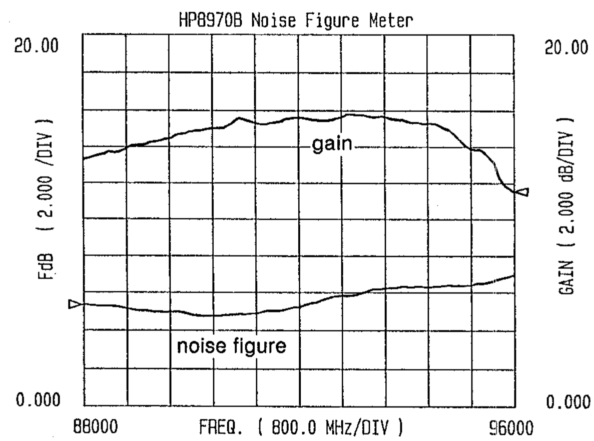

Figure 9. Gain and noise performance of W-Band 3-stage HEMT LNA.

AMPLIFIER PERFORMANCE

Figure 4 is a photograph of the V-Band three-stage HEMT low noise amplifier(LNA). A stepped ridge waveguide to microstrip transition was utilized in the amplifier to obtain broadband performance. The amplifier design was based on 0.25 x 50 µm devices[13]. The noise and gain performance from 55 to 65 GHz is shown in Figure 5. The amplifier exhibits an average noise figure of 3 dB from 60 to 65 GHz. Note that the gain response is 22.0 ± 0.2 dB from 60 to 65 GHz.

E-field probe circuits were designed for the W-Band waveguide to microstrip transition. Figure 6 shows the performance of a 0.3 inch long 50 Ω through-line containing two quarter-wave coupled line sections (necessary to provide DC blocking for the amplifier), which was fabricated on a 5 mil quartz substrate. The insertion loss of an end-to-end through connection (from input waveguide flange to output waveguide flange) is approximately 2 dB at 94 GHz. The input return loss is better than 15 dB from 89 to 99 GHz. Figure 7 illustrates the frequency response of a single stage amplifier biased at a drain voltage of 1.1 V and drain current of 7.5 mA, not corrected for the fixture loss. It gives a noise figure of 3.2 dB and gain of 4.4 dB with a return loss of 9 dB at 94 GHz. With the correction, the 0.25 µm device yields a noise figure of 2.1 dB with gain of 6.4 dB at 94 GHz. This W-Band noise performance is the best ever observed for any type of transistor.

A two-stage LNA was also built with the InP-based HEMTs. The performance is displayed in Figure 8. The minimum noise figure is 4.5 dB with a gain of 10.2 dB at 90.4 GHz. The input return loss at this point is better than 8 dB. The gain response is 9.9 ± 0.6 dB from 88 to 96 GHz. Figure 9 shows the performance of the three-stage LNA from 88 to 96 GHz. The minimum noise figure is 4.8 dB with a gain of 15.0 dB at 90.4 GHz.

In general, the drain bias voltage for the InP based HEMTs is around 1 Volt, while the AlGaAs/GaAs based HEMTs operate at 2 to 3 Volts with about the same drain currents. So the total DC power for the InP based HEMT amplifiers is approximately half of that for the conventional HEMT amplifiers. The lower noise figure of the InP-based HEMTs may reduce the output power requirements of future millimeter-wave transmitters for millimeter-wave communications applications. Further improvements in the device performance can be achieved by reducing the gate length to 0.1 - 0.15 µm and optimizing the material structure and fabrication process.

CONCLUSION

We have demonstrated state-of-the-art low noise and high gain performance from our 0.25 µm InP-based HEMT devices: minimum noise figures of 1.2 and 2.1 dB at 60 and 94 GHz, and gain as high as 15.4 and 12.0 dB at 63 and 95 GHz, respectively. Using these devices, multi-stage V-Band and W-Band LNAs have shown superb low noise performance: a V-Band three-stage LNA gives an average noise figure of 3.0 dB with gain of 22.0 ± 0.2 dB from 60 to 65 GHz and a W-Band two-stage (three-stage) LNA yields a noise figure of 4.5 dB (4.8 dB) with a gain of 10.2 dB (15.0 dB) at 90.4 GHz. The results clearly show the great potential of InP-based HEMTs for millimeter-wave electronic systems. Rapid progress in the development of this new HEMT is expected to continue.

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