Sensitivity of a 40 GHz HEMT Low-Noise Amplifier to Material and Processing Variations

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***Abstract* — A monolithic, single-stage HEMT low-noise amplifier has been developed at 40 GHz for the application to satellite communication. This amplifier includes a single 0.25-μm-gate-length HEMT active device with on-chip matching and biasing circuits. A gain of 8 dB and a noise figure of 4 dB were measured from 36 to 42 GHz for an amplifier with a mushroom gate profile. Using a triangular gate profile device with a lower gate-to-drain feedback capacitance, the amplifier achieved a 10 dB peak gain at 43 GHz. The chip size is 1.1×1.1 mm^2.**

I. INTRODUCTION

HEMT's have demonstrated their superior gain and noise figure performance over conventional MESFET's [1]. State-of-the-art gain and noise figure performance has been achieved from monolithic amplifiers [2]–[4] using HEMT's at frequencies up to 60 GHz.

This paper describes a monolithic, reactively matched 40 GHz low-noise amplifier using a 0.25 μm HEMT as the active device. The amplifier with a triangular gate profile has achieved approximately 6.5 dB of gain and a 5 dB noise figure from 38 to 44 GHz. The gain of the amplifier increases to 8 dB and the noise figure decreases to 4 dB when the gate is replaced by a mushroom gate profile. An amplifier with a triangular gate profile device having lower gate-to-drain capacitance has achieved a 10 dB peak gain at 43 GHz. The 40 GHz amplifier fabricated on the pseudomorphic HEMT material has similar gain (6.5 dB) but broader bandwidth (34–44 GHz) than the amplifier processed on the conventional HEMT material.

II. DESIGN CONSIDERATIONS

A conventional HEMT epitaxial structure grown by MBE was used in this amplifier. The 0.25 μm$\times$150 μm HEMT with triangular gate profile has a measured minimum noise figure of 1.35 dB and an associated gain of 12 dB at 18 GHz. The predicted F_{min} is 2.74 dB at 40 GHz using Fukui's expression. An *MAG* of 8 dB was measured at 38 GHz, which extrapolates to an f_{max} of about 101 GHz.

An equivalent circuit model was extracted from the measured S parameters for this HEMT biased for minimum noise figure. A 44 GHz reactively matched amplifier was designed using this HEMT model [5]. This amplifier uses open stubs, shunt-shorted stubs, and transmission lines as the input and output matching elements. Nineteen design parameters, including the matching and biasing circuit elements along with the gate periphery, were optimized for a maximum flat gain performance from 42 to 46 GHz using SUPERCOMPACT. A simulated gain of 7.5 dB from 40 to 46 GHz was obtained. Simulation indicates that the amplifier is unconditionally stable from 35 to 50 GHz.

Standard MMIC processing techniques were used for the 40 GHz HEMT amplifier fabrication. The two critical process steps involved are the 0.25 μm E-beam gate and the 60×60 μm^2 backside vias using reactive ion etching. The chip size is 1.1×1.1 mm^2.

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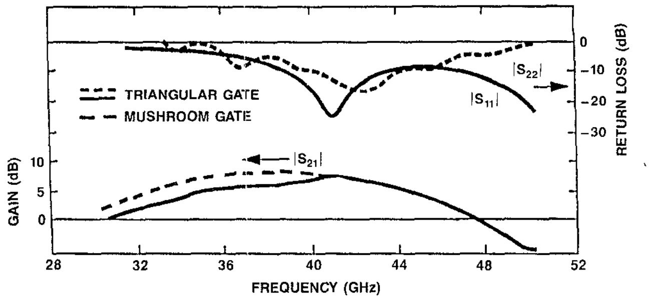

Fig. 1. Measured gain and return loss performance of the monolithic 40 GHz amplifier.

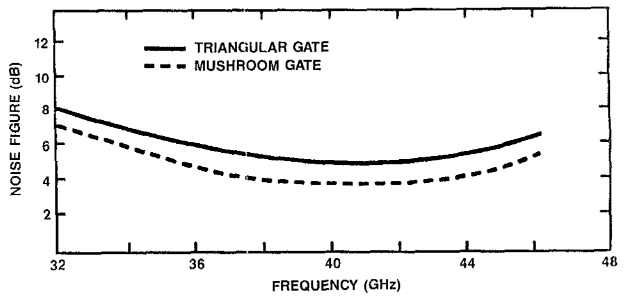

Fig. 2. Measured noise figure performance of the monolithic 40 GHz amplifier.

III. MEASURED PERFORMANCE

A gain of approximately 6.5 dB from 38 to 44 GHz (biased at $V_{ds}=3$ V and $I_{ds}=15$ mA) and an input/output return loss of better than 10 dB from 39 to 43 GHz were measured, as shown in Fig. 1. The measurement indicates that the amplifier is unconditionally stable from 36 to 50 GHz.

Fig. 2 shows a measured noise figure of approximately 5 dB for the 40 GHz amplifier from 38 to 44 GHz when biased at minimum noise bias conditions.

When biased at maximum power ($V_{ds}=3$V, $I_{ds}=21$ mA), the 1 dB compression power for the HEMT amplifier was measured to be 10 dBm at 40 GHz.

IV. PERFORMANCE OF AMPLIFIER WITH MUSHROOM GATE PROFILE

The 0.25 μm gate with a mushroom gate profile has been developed using trilevel resist and E-beam lithography for gate resistance reduction. The 0.25×150 μm^2 π-configured HEMT with a mushroom gate profile has a measured noise figure of 0.9 dB and an associated gain of 13 dB at 18 GHz.

A 40 GHz reactively matched amplifier with a mushroom gate profile was fabricated on the conventional HEMT material. This amplifier gave 8 dB of gain and a 4 dB noise figure over the 36–42 GHz band (shown in Figs. 1 and 2 as dashed curves).

V. AMPLIFIER WITH 10 dB GAIN AT 43 GHz

A recent wafer was processed with a triangular gate profile utilizing a new gate etchant (ammonia), which created a gate recessed channel profile different from that on the previous wafers which used HF as the etchant. The device on this new wafer has a significantly lower gate-to-drain capacitance (0.011 pF) than the device on the previous wafers (0.02 pF).

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TABLE I
SIMULATED MAG^*/MSG AND STABILITY k FACTOR FOR $0.25 \times 120\ \mu m^2$ HEMT DEVICE AT 40 GHz

C_{gd} (pF) / L_s (nH)	0.02		0.01	
	k	MAG*/MSG	k	MAG*/MSG
0.02	1.27	7.5*	1.42	9.7*
0.01	1.0	9.5*	1.08	11*
0	0.79	9.0	0.76	11.5

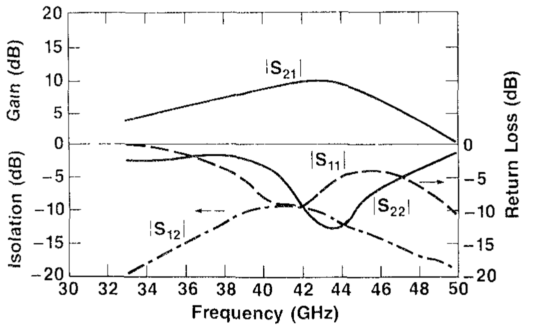

Fig. 3. Measured gain, return loss, and isolation of the monolithic 40 GHz amplifier on a recent wafer.

Simple theory gives an optimum value for C_{gd} of

$$C_{gd} = 2\omega C_{gs}^2 r_i (g_{ds}/g_m)$$

for maximum power gain. Using values from the HEMT equivalent circuit model, an optimum value of 0.003 pF is obtained. For values of C_{gd} above this optimum value, the sensitivity of the gain upon C_{gd} is unity, meaning that the gain will change by the same factor that C_{gd} is changed by. Indeed, a reduction in C_{gd} by a factor of 2 results in a gain improvement of nearly 3 dB, as shown in Table I. (The MAG of a $0.25 \times 120\ \mu m^2$ HEMT increases from 7.5 to 9.7 dB at 40 GHz when the gate-to-drain capacitance is reduced from 0.02 to 0.01 pF with 0.02 nH source inductance.)

Fig. 3 shows the measured gain, input/output return loss, and isolation performance for the amplifier on this recent wafer. The amplifier has a higher peak gain (10 dB) and higher peak frequency (43 GHz) than those from the previous wafers (7 dB peak gain at 41 GHz) shown in Fig. 1. Measurement indicates that the amplifier is conditionally stable ($k < 1$) from 35 to 45 GHz and that the amplifier is stable in a 50 Ω operation system from 33 to 50 GHz.

The transition from unconditional to conditional stability is probably due to a lower source inductance of the amplifier. Measurement indicates that the device on this wafer has a lower source resistance than the device on the previous wafers. This may imply a lower source inductance for devices on this wafer due to a different plating thickness. Simulation shows that lowering the source inductance of the device from 0.02 to 0.01 nH (with $C_{gd} = 0.01$ pF) increases the MAG of the device by 1.3 dB

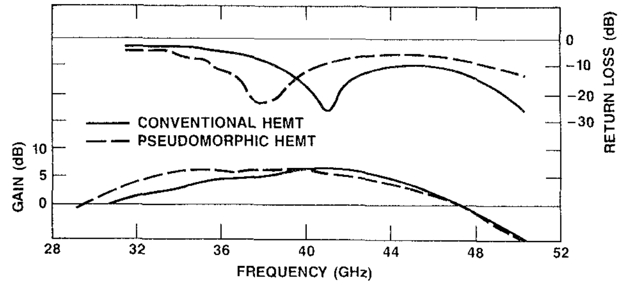

Fig. 4. Measured gain and input return loss performance of the monolithic 40 GHz amplifiers fabricated on conventional and pseudomorphic HEMT materials.

(from 9.7 to 11 dB) at 40 GHz, while increasing the instability of the device, as listed in Table I. This change in inductance plus the lower feedback capacitance is enough to account for the 3 dB improvement in gain that this amplifier achieves over the Section III results.

VI. Pseudomorphic HEMT Amplifier Performance

Excellent noise and gain performance for the AlGaAs/InGaAs pseudomorphic HEMT has been reported. Submicron-gate pseudomorphic HEMT's are expected to have superior potential as low-noise, high-gain, and high-power devices in the millimeter-wave region.

The 40 GHz amplifier was processed on the pseudomorphic HEMT material using 0.25 μm triangular gate profile. Fig. 4 shows a comparison of the gain and input return loss performance between conventional and pseudomorphic HEMT amplifiers. The pseudomorphic HEMT amplifier has a higher gain–bandwidth product (6.5 dB from 34 to 44 GHz) than the conventional HEMT amplifier (6.5 dB from 38 to 44 GHz). The noise figure of the pseudomorphic HEMT amplifier was measured to be 5 dB from 38 to 44 GHz, which is the same as the conventional HEMT amplifier.

VII. Conclusions

A monolithic low-noise reactively matched amplifier has been developed at 40 GHz for satellite communication applications. It uses 0.25 μm HEMT technology to produce gain as high as 10 dB at 43 GHz with a noise figure as low as 4 dB—the best reported results for a MMIC amplifier over this bandwidth.

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