ULTRA-LOW-NOISE MILLIMETER-WAVE PSEUDOMORPHIC HEMT'S

R.E. Lee, R.S. Beaubien
Linear Monolithics Inc.
Westlake Village, CA 91361

R.H. Norton, J.W. Bacon
Varian Research Center
Palo Alto, CA 94304

ABSTRACT

Tenth-micrometer gate length devices based on AlGaAs/InGaAs/GaAs pseudomorphic HEMT's have produced record low-noise performance at 43 GHz. The room temperature device noise figure is measured to be 1.32 dB (noise temperature =103 K) with 6.7 dB associated gain and at 17 K physical temperature, the noise figure is 0.36 dB (noise temperature =25 K) with 6.9 dB associated gain. This is the lowest noise figure yet reported for any GaAs based device at 43 GHz.

INTRODUCTION

Sub-quarter-micrometer gate-length HEMT's have demonstrated outstanding low-noise and high-gain amplification results throughout the microwave and millimeter wave frequency range [1-3]. Applications requiring ultra-low-noise, high-gain performance such as electronics warfare, satellite communication, radar, remote sensing and radio astronomy find HEMTs crucial to meet systems requirements.

Pseudomorphic HEMTs provide superior electron velocity and sheet carrier-charge densities compared to conventional HEMTs due to the improved electron transport properties in the InGaAs channel and the larger conduction band discontinuity that exists at the AlGaAs/InGaAs heterojunction interface. Pseudomorphic AlGaAs/InGaAs/GaAs HEMT's, because of their quantum well channel structure, also show improved carrier confinement and reduced "short-channel" effect compared to conventional AlGaAs/GaAs HEMTs. Minimizing short-channel effects is particularly important in tenth or sub-tenth micrometer FET structures to achieve high gain.

Precise control of layer doping and composition, gate length and recess width, and parasitic resistance and capacitance yield pseudomorphic HEMT devices with low noise figure and high gain.

DEVICE DESCRIPTION

The pseudomorphic HEMT layers are grown by molecular beam epitaxy (MBE). The layer structure (shown schematically in Figure 1) is composed of a highly doped N^+ GaAs cap layer, a transition layer of AlGaAs where both the silicon doping and aluminum composition are varied, a uniformly doped AlGaAs donor layer, a thin undoped AlGaAs spacer layer, a undoped InGaAs high mobility channel layer, an undoped GaAs buffer and an undoped GaAs/AlGaAs super lattice all grown on a high purity 3" diameter LEC substrate. Hall test samples yield mobility of 6,000 cm^2/V-sec at 300 K and 24,900 cm^2/V-sec at 77 K.

Photolithography is employed for all device layers except for the tenth-micrometer gate and the gate feed which is done using direct-write E-beam lithography. This mix-and-match lithography achieves significantly higher throughput compared to an all E-beam approach.

The pseudomorphic HEMT devices employ mesa isolation. AuGeNi is used for the Ohmic contacts and are alloyed by rapid thermal processing. The tenth-micrometer gates are aligned to the optically defined Ohmic layer and exposed using a Cambridge EBMF 10.5 E-beam lithography system. The gate exposure is done at an electron accelerating voltage of 40 KeV, beam current of 1 nA and a field size of 1.6 mm by 1.6 mm. The spray development process produces under-cut resist profiles resulting in high lift-off yield.

A highly controlled gate recess etch technique is employed to remove the N^+

CH2725-0/89/0000-0975$01.00 © 1989 IEEE

GaAs cap layer and to locate the Schottky-barrier gate electrode at a uniform distance into the AlGaAs transition layer. The recess is tightly controlled in both etch depth and E-beam resist undercut to control device transconductance and parasitic source resistance (both significant factors influencing noise figure and gain performance). The tenth-micrometer Schottky-barrier gates metal is Ti/Pt/Au (deposited using a E-gun evaporator) with a nominally trapezoidal cross-section [4]. Figure 2 shows an SEM photograph of the relative position of the gate, source Ohmic, mesa and overlay metallization. The drain contact is outside the view of this SEM photograph. The gate is separated 0.4 micrometers from the source Ohmic contact. The gate recess width is less than 0.07 micrometers to minimize the parasitic source resistance.

Air bridges are used to form low capacitance interconnects to the gate electrodes of the pseudomorphic HEMTs. Air bridges and bond pads are electroplated to 1.25 um thickness with gold to reduce parasitic resistance and enhance bondability. Figure 3 shows an overview of a 100 um by 0.1 um pseudomorphic HEMT with gate feeds air bridge connected. This is the device layout that yielded the lowest noise performance at 43 GHz.

DC, MICROWAVE, AND MILLIMETER WAVE PERFORMANCE

Figure 4 shows "typical" measured transconductance and source/drain current as a function of gate voltage for a 100 um X 0.1 um pseudomorphic HEMT device. The measurements were carried out at a drain bias of 2.0 volts. The maximum external transconductance is 44 mS (corresponding to 440 mS/mm) and the saturated current (at Vg=0) is 36 mA (corresponding to 360 mA/mm) with a pinch-off voltage of 0.85 volts.

Although the transconductance of the devices is significantly smaller than those reported for other pseudomorphic HEMT's [3], the gate/source capacitance is commensurately reduced such that the noise figure, as projected by the Fukui expression [6], is enhanced:

$$F_{\min} = 1 + k_1 f C_{gs} \sqrt{\frac{R_g + R_s}{g_m}}. \qquad (1)$$

where, Fmin is the minimum noise figure, f is the frequency of operation, Cgs is the equivalent gate/source capacitance, gm is the intrinsic transconductance, Rg is the equivalent gate resistance, Rs is the equivalent source resistance and K_f is an empirical factor related to material quality.

Trading lower transconductance, gm, for reduced gate capacitance is seen as beneficial to the noise figure so long as the parasitic fringing component of Cgs is small compared to the depletion layer component of Cgs. For example, the 0.08 um gate length pseudomorphic HEMT's [3] have higher transconductance, gm = 740 - 920mS/mm but also have correspondingly high gate capacitance, Cgs = 1.6pF/mm. The pseudomorphic HEMT's reported here have gm = 440 - 500 mS/mm but with gate capacitance of Cgs = 0.86 pF/mm as determined by S-parameter measurements and optimum noise matching impedance. The ratio of $Cgs/\sqrt{gm}$, which appears in the minimum noise figure equation (1) is smaller for our HEMT's 1.30×10^{-12} vs 1.86×10^{-12} $F/\sqrt{S\text{-}mm}$ for those previously reported [3].

S-parameter measurements were carried out on pseudomorphic HEMT's embedded in co-planar transmission lines on the wafer surface. These structures are tested using a Cascade Microtech on-wafer probe station and a Hewlett-Packard 8510 B automatic network analyzer extended to 40 GHz. On-wafer RF testing using co-planar test structures is advantageous for FET device testing because it eliminates bond-wire parasitics, hence improving the accuracy of the device model.

The Maximum Available Gain/Maximum Stable Gain (MAG/MSG) is determined from the on-wafer S-parameter measurements taken from 2-40 GHz. The result is displayed in Figure 5. MAG/MSG is typically 13.7 dB at 18 GHz and 7.4 dB at 40 GHz. The device ft, as determined by extrapolating the measured H_{21} (including all parasitics) vs frequency to $H_{21} = 0$ yields a device cut-off frequency of 95 GHz.

NOISE FIGURE MEASUREMENT

The noise figure of several 50 um X 0.1 and 100 um X 0.1 pseudomorphic HEMT was measured at 43 GHz in a precision wave guide-to-microstrip test system [5] at the National Radio Astronomy Observatory. A detailed description of the test system and comparative test results on various HEMT devices at 43 GHz is given in another paper in this symposium Digest, "Millimeter-Wave Noise Parameters of High Performance HEMT's at 300 K and 17 K", by S. Weinreb, R. Harris and M. Rothman. Room temperature device noise figure is measured to be 1.32 dB (corresponding to a minimum noise temperature Tmin = 103 +/-8 K) while the 17 K device noise figure drops to 0.36 dB (Tmin = 25 +/-1.0 K). The corresponding associated gain is 6.7 dB at room temperature and 6.9 dB at 17 K. The noise figure of an infinite cascade of identical devices, assuming interstage noise match, is 1.62 dB (T cascade = 131 +/- 10 K) at room temperature. To our knowledge, these are the best noise figure results reported for GaAs based transistors at this frequency. Using realistic estimates of matching circuit and transition losses of about 0.4 dB at 43 GHz projects a multi-stage room temperature amplifier noise figure of 2.0 dB with the pseudomorphic HEMT's reported here.

CONCLUSION

We report state-of-the-art low-noise device performance based on tenth-micrometer pseudomorphic HEMT's. The devices are optimized for low noise figure and low sensitivity to both temperature and circuit matching. The 43 GHz device results (1.32 dB N.F. with 6.7 dB associated gain at room temperature and the large gm/Cgs ratio) show significant promise for applications in ultra-broad-bandwidth and ultra-low-noise systems.

These transistors show unprecedented low-noise performance and should find significant applications in: electronics warfare, radar, satellite communication, remote sensing and radio astronomy.

ACKNOWLEDGMENTS

The authors wish to thank S. Weinreb, R. Harris, and other staff members of the National Radio Astronomy Observatory, Charlottesville, VA for performing the 43 GHz noise and gain measurements and useful technical discussions. Special thanks also to C. Nishimoto and M. Glenn of Varian Research Center, Palo Alto, CA for device testing.

REFERENCES

[1] K.H.G. Duh, P.C. Chao, P.M. Smith, L.F. Lester, B.R. Lee, J.M. Ballingall and M.Y. Kao, "Millimeter Wave Low-Noise HEMT Amplifiers", IEEE MTT-S Digest, pp. 923-930, 1988.

[2] P.C. Chao, M.S. Shur, R.C. Tiberio, K.H.G. Duh, P.M. Smith, J.M. Ballingall, P. Ho, and A.A. Jamba, "DC and Microwave Characteristics of Sub-0.1-um Gate-Length Planar-Doped Pseudomorphic HEMT's", IEEE Transactions on Electron Devices, ED-36, March 1989.

[3] P.C. Chao, R.C. Tiberio, K.H.G. Duh, P.M. Smith, J.M. Ballingall, L.F. Lester, B.R. Lee, A. Jabra, and G. Gifford, "0.1um Gate-length Pseudomorphic HEMT's, IEEE Electron Letters, EDL-8 October, 1987.

[4] R.S. Beaubien, R.E. Lee, "Sub-micron E-beam Lithography for GaAs Integrated Circuits", IEEE Workshop on Micrometer and Submicrometer Lithography, Hyannis, MA, 1984.

[5] S. Weinreb, R. Harris, and M. Rothman, "Millimeter-Wave Noise Parameters of High Performance HEMT's at 300 K and 17 K". This Digest.

[6] H. Fukui, "Design of Microwave GaAs MESFET's for Broad-Band Low-Noise Amplifiers". IEEE Trans. Microwave Theory and Tech., MTT-27, July 1979.

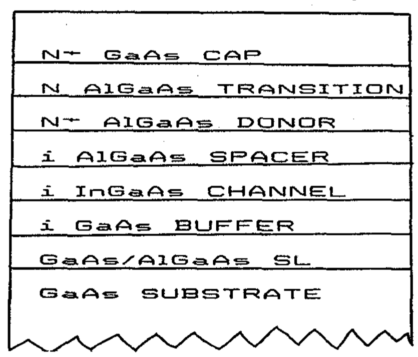

FIGURE 1. MBE LAYER PROFILE OF PSEUDOMORPHIC HEMT.

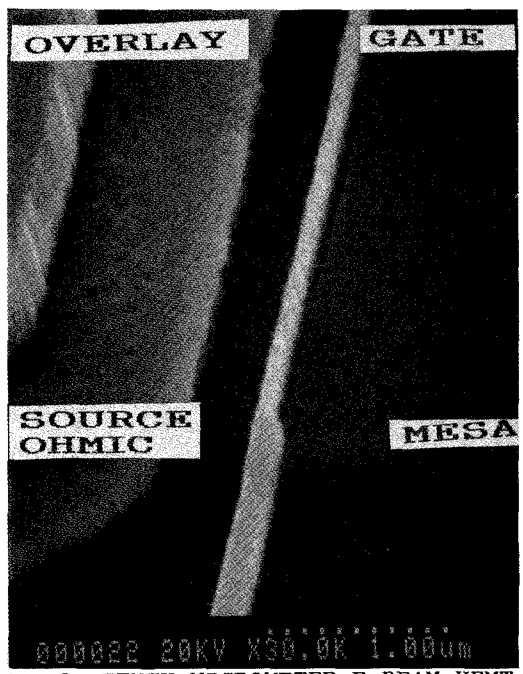

FIGURE 2. TENTH-MICROMETER E-BEAM HEMT GATE. GATE OFF-SET TOWARD SOURCE TO REDUCE RESISTANCE.

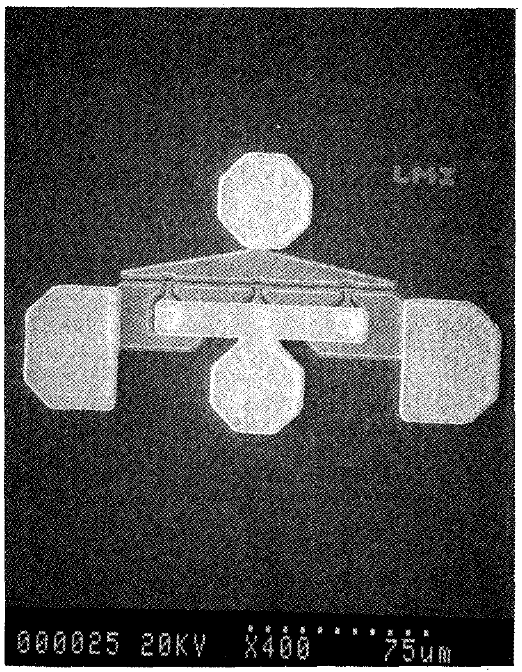

FIGURE 3. DEVICE OVERVIEW OF 100um X 0.1um HEMT. PAD AREAS PLATED FOR LOWER RESISTANCE AND IMPROVED BONDING.

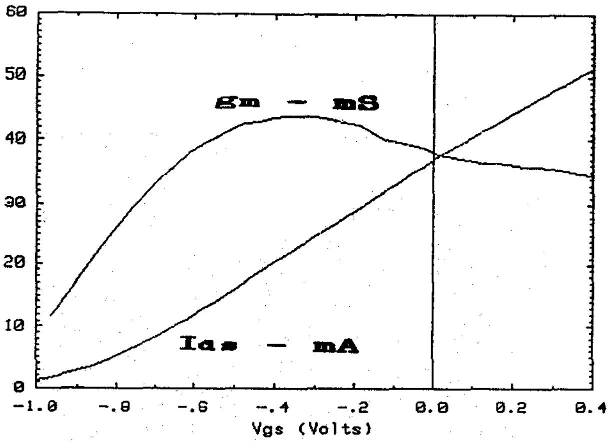

FIGURE 4. DC DEVICE CHARACTERISTICS OF 100um X 0.1um HEMT.

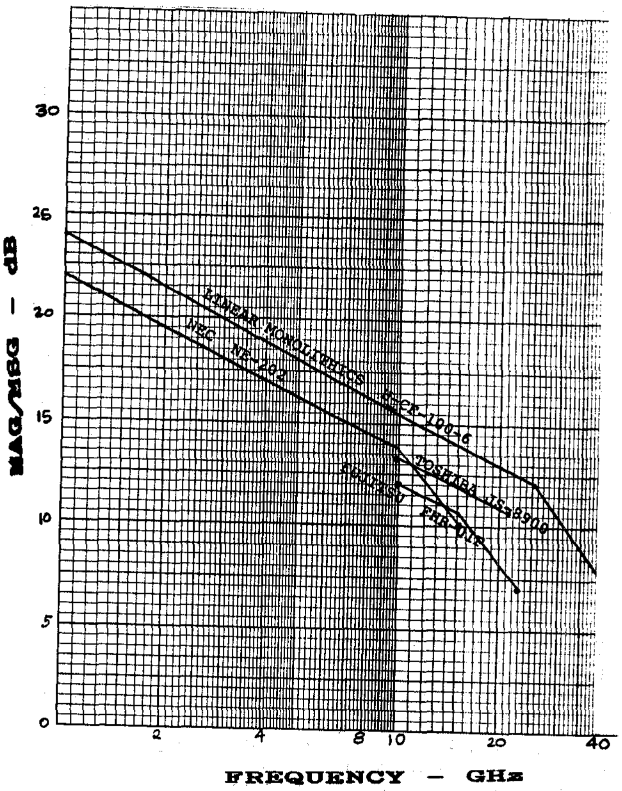

FIGURE 5. MEASURED MAXIMUM AVAILABLE GAIN/MAXIMUM STABLE GAIN VERSUS FREQUENCY.

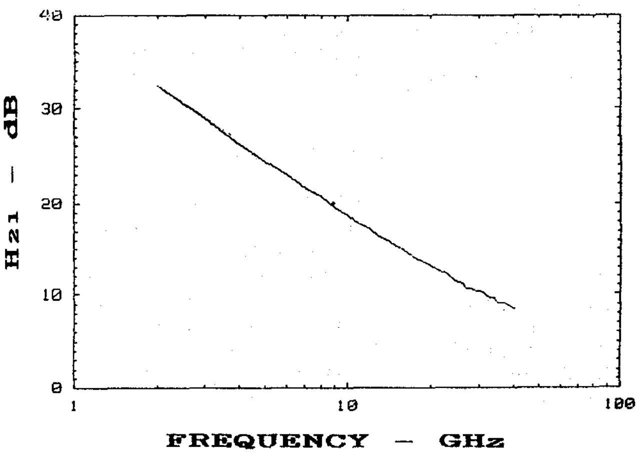

FIGURE 6. ESTIMATED CUT-OFF FREQUENCY PROJECTED FROM H21 MEASUREMENTS FROM 2 TO 40GHz.