Low-Noise Cryogenic X-Band Amplifier Using Wet-Etched Hydrogen Passivated InP HEMT Devices

Isaac López-Fernández, Juan Daniel Gallego Puyol, *Member, IEEE*, Otte J. Homan, *Member, IEEE*, and Alberto Barcia Cancio

***Abstract*—The performance of a cryogenically cooled X-band amplifier for the geodetic VLBI X-band (8.1–9.0 GHz) is presented. The amplifier incorporates hydrogen passivated InP devices with 0.2 × 200 μm gate. A comparison of the noise performance with selected commercially available GaAs high electron mobility transistor (HEMT) devices of similar dimensions is presented. The InP amplifier shows lower noise temperature (Tn = 4.8 K, NF = 0.07 dB) than GaAs, with very low power dissipation (2 mW per stage). This is the first report on the cryogenic noise performance of hydrogen passivated InP HEMT's in this frequency band.**

***Index Terms*—Cryogenic amplifier, high electron mobility transistor (HEMT), HFET, InP, low noise, VLBI.**

I. Introduction

It is well known that certain applications, like deep space communications, radio astronomy or geodetic VLBI, need receivers with the ultimate sensitivity and noise performance. Today, most of the receivers in these applications use a cryogenic amplifier with GaAs high electron mobility transistor (HEMT) devices in the front-end [1], [2]. During recent years an impressive effort has been made to demonstrate the excellent cryogenic performance of InP devices at millimeter-wave frequencies and its superiority over GaAs [3]–[5]. However, not much data is available on the possible advantages of InP devices at lower microwave frequencies. A notable exception is the work presented in [6], were InP and GaAs HEMT devices were used in a 1–5-GHz cryogenic amplifier integrated in a SIS mixer.

In this letter we present the results obtained with a three-stage cryogenic 8.1–9-GHz front-end amplifier designed for the geodetic VLBI band. The goal of the design was to obtain a good compromise in the band between low noise, flat gain, and low input and output reflection. The design was done to accommodate experimental InP HEMT's (0.2 × 200 μm) and commercial GaAs Mitsubishi MGFC 4418 HEMT's (0.25 × 200 μm)[1] with only minor tuning changes. The GaAs Devices were chosen from a selected batch with well-known good cryogenic performance. The InP devices were built with a similar geometry, and no attempt was made to optimize their properties for cryogenic operation.

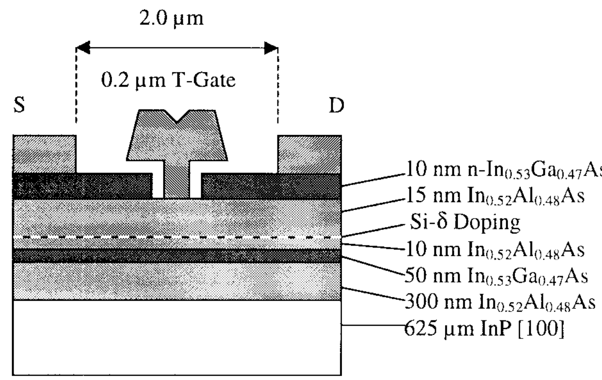

Fig. 1. 0.20-μm lattice matched InP-based HEMT. The gate recess of the n-type InGaAs cap layer was done using a selective wet chemical etch process and was followed by a H_2 passivation plasma treatment prior to metallization. The substrates were thinned mechanically to nominally 155 μm and diced into 380 × 450 μm chips.

II. Devices

InP HEMT's were fabricated from commercially grown lattice matched heterostructure material. The material structure was designed for optimum gain performance at ambient temperature rather than minimum noise [7]. It has a room-temperature electronic mobility of $\mu_e = 11\,500$ cm^2/Vs and an ungated carrier density of $1.85 \cdot 10^{12}$ cm^{-2}. The 0.2-μm T-gates were formed in a 4 × 50-μm linear geometry using electron beam lithography. Fig. 1 shows a cross section of the device. Gate recess through the n-doped $In_{0.53}Ga_{0.47}As$ cap layer into the $In_{0.52}Al_{0.48}As$ Schottky barrier layer was done using a highly selective wet chemical etching process, followed by a hydrogen plasma processing. The H-ion treatment is assumed to be responsible for deep-level trap passivation below the gate, reducing impact ionization, kink-effect and low-frequency noise contribution [8], [9].

The S parameters of the HEMT's were measured at cryogenic temperature (T = 13 K) with a HP8510C Vector Network Analyzer and a specially designed microstrip test

Manuscript received May 18, 1999; revised August 4, 1999. This work was supported in part by Projects PNIE ESP97-1688-E and CAICYT PB98-0104.

I. López-Fernández, J. D. Gallego Puyol, and A. B. Cancio are with the Centro Astronómico de Yebes, Observatorio Astronómico Nacional, 19080 Guadalajara, Spain.

O. J. Homan is with the Laboratory for Electromagnetic Fields and Microwave Electronics, Electrical Engineering Department, Swiss Federal Institute of Technology, Zürich, Switzerland.

Publisher Item Identifier S 1051-8207(99)08538-4.

[1] Mitsubishi Electric Corporation, Tokyo, Japan.

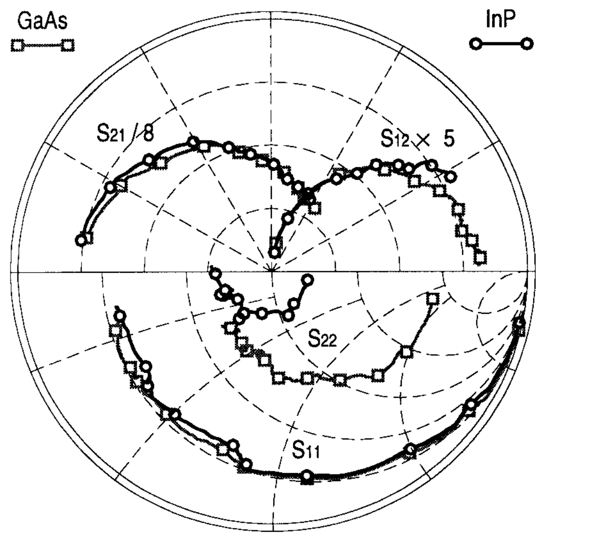

Fig. 2. Comparison of the S parameters of the InP and the GaAs Devices measured at 13K in the 1–20-GHz frequency range, biased for optimum noise (see bias in Table I). The effect of the bonding wires is included. The lower value of R_{ds} for InP is clear from the S_{22} curves.

TABLE I
NOISE PARAMETERS OF HEMT'S (SEE TEXT). $T_{\text{amb}} = 13$ K, $f = 8.5$ GHz

PARAMETER		MGFC4418 GaAs 200×0.25 μm	ETH200 InP 200×0.20 μm
NOISE	T_{min} (K)	7.3	3.5
	R_{opt} (Ω)	24.6	27.8
	X_{opt} (Ω)	77.5	75.2
	g_n (mS)	0.42	0.20
BIAS	V_{ds} (V)	2.5	0.40
	I_{ds} (mA)	5.0	5.0

$$T_n = T_{min} + \frac{T_0 \cdot g_n}{R_{in}} \cdot \left[(R_{in} - R_{opt})^2 + (X_{in} - X_{opt})^2 \right]$$

$$T_0 = 290 \cdot K$$

fixture. A two-tier TRL calibration [10] was used to de-embed the effects of the fixture and the ambient to cryogenic transitions. The measured S parameters of the two devices used for the design of the amplifier are compared in Fig. 2. Its noise was simulated with the Pospieszalski model [11]. In this model the noise is represented by two frequency-independent parameters, named T_g and T_d (gate and drain equivalent temperatures) associated with two resistors (R_{gs}, R_{ds}) of the equivalent circuit of the transistor. In our case, the equivalent circuit was obtained by fitting to the measured cryogenic S parameters. T_g was assumed equal to ambient temperature of the device (13 K), and T_d was estimated by fitting to cryogenic noise temperature measurements of other C- and X-band test amplifiers built with the same HEMT's. Table I presents the comparison of the noise parameters obtained by this method. The most significant differences between InP and GaAs equivalent circuit elements are in T_d and R_{ds}. The ETH device yields $T_d = 210$K and $R_{ds} = 87\ \Omega$ while the Mitsubishi HEMT presents $T_d = 1150$K and $R_{ds} = 234\ \Omega$. From the inspection of the S and noise parameters, it is clear the superiority of the InP device for its lower minimum noise temperature, wider noise bandwidth, and easier-to-match

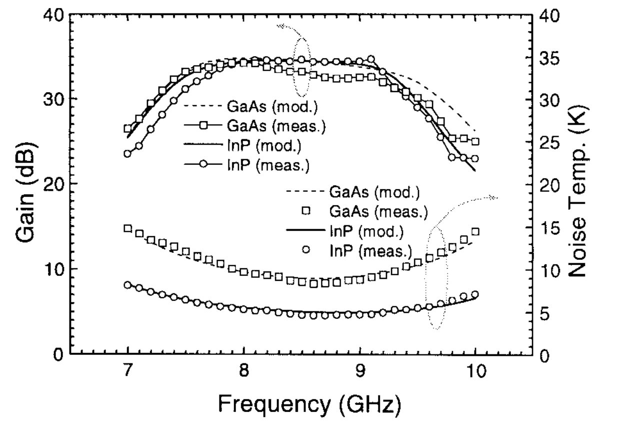

Fig. 3. Measured noise temperature and gain obtained with the InP (circles) and GaAs (squares) HEMT amplifiers. The results of the models are presented for comparison.

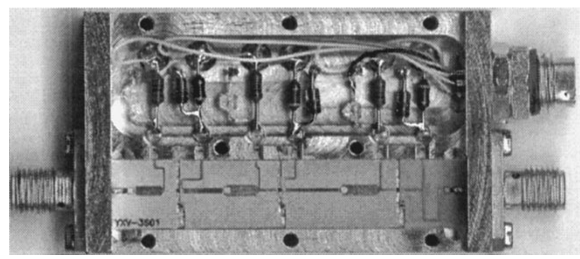

Fig. 4. Photograph of the amplifier without cover.

output impedance. The power dissipated in the InP HEMT when biased for minimum noise is only 2 mW per transistor, a factor of six lower than in the GaAs HEMT. This result is similar to the scaled values obtained with other InP devices at higher frequency [12].

III. AMPLIFIER PERFORMANCE

The noise temperature and gain of the amplifiers were measured in a cryostat at 13 K ambient temperature using the cold attenuator method, as in [13]. Fig. 3 presents the gain and noise obtained for the InP and GaAs amplifiers. The predictions from the noise model are also shown in the same graph. The validity of the noise model used is confirmed by the excellent match with the experimental results. The minimum noise temperature measured in the band with InP is 4.6 K, and the average noise temperature is 4.8 K The estimated absolute accuracy of noise measurements is ±1 K. The worst case input and output reflection loss in the band were 12 and 14 dB, respectively. The measured gain was 34.5 ± 0.2 dB in the band. The performance of the amplifier was not sensitive to illumination.

IV. CONCLUSIONS

We have demonstrated an X-band cryogenic amplifier with hydrogen passivated InP HEMT Devices, obtaining an average noise temperature of 4.8 K ($NF = 0.07$ dB) in the band when cooled to 13 K. The noise temperature is almost a factor of two, and the power dissipation a factor of six lower than those obtained with selected GaAs HEMT Devices. The results are very promising for applications like wide band cryogenic IF amplifiers for millimeter- and submillimeter-wave receivers and space applications.

ACKNOWLEDGMENT

The authors would like to thank the technical assistance of R. García and D. Geijo in amplifier and substrate fabrication. They also acknowledge the fine work of H. Meier at the ETH for fabrication of the HEMT's and helpful discussions with M. W. Pospieszalski of NRAO.

REFERENCES

[1] R. D. Norrod, G. H. Behrens, F. D. Ghigo, and B. J. Levin, "Design and implementation of a low-noise prime focus S/X receiver system for radio astronomy," *Proc. IEEE*, vol. 82, pp. 768–775, May 1994.

[2] S. Weinreb, M. W. Pospieszalski, and R. Norrod, "Cryogenic HEMT low noise receivers for 1.3 to 43 GHz range," in *Proc. 1988 IEEE MTT-S Int. Microwave Symp. Dig.*, p. 945.

[3] M. W. Pospieszalski, W. J. Lakatosh, R. Lai, K. L. Tan, D. C. Streit, P. H. Liu, R. M. Dia, and J. Velebir, "Millimeter-wave, cryogenically coolable amplifiers using AlInAs/GaInAs/InP HEMT'S," in *Proc. 1993 IEEE MTT-S Int. Microwave. Symp. Dig.*, pp. 515–518.

[4] R. Lai, J. J. Bautista, B. Fujiwara, K. L. Tan, G. I. Ng, R. M. Dia, D. Streit, P. H. Liu, A. Freudenthal, J. Laskar, and M. W. Pospieszalski, "An ultra-low noise cryogenic Ka-band InGaAs/InAlAs/InP HEMT front-end receiver," *IEEE Microwave Guided Wave Lett.*, vol. 4, pp. 329–331, Oct. 1994.

[5] M. W. Pospieszalski, W. J. Lakatosh, and E. Woollak, "Millimeter-wave, waveguide-bandwidth cryogenically-coolable InP HEMT amplifiers," in *Proc. 1997 IEEE MTT-S Int. Microwave. Symp. Dig.*, pp. 1285–1288.

[6] S. Padin, D. P. Woody, J. A. Stern, H. G. LeDuc, R. Blundell, C. Y. E. Tong, and M. W. Pospieszalski, "An integrated SIS mixer and HEMT IF amplifier," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 987–990, June 1996.

[7] H. C. Duran, B. U. H. Klepser, and W. Bächtold, "Low-noise properties of dry gate recess etched InP HEMT's," *IEEE Electron Device Lett.*, vol. 17, pp. 482–484, Oct. 1996.

[8] H. C. Duran, L. Ren, M. Beck, M. A. Py, M. Ilegems, and W. Bächtold, "Low frequency noise properties of selectively dry etched InP HEMT's," *IEEE Trans. Electron Devices*, vol. ED-45, pp. 1219–1225, June 1998.

[9] H. C. Duran, "High performance InP-based HEMT's with dry etched gate recess," Ph.D. dissertation, ETH Zürich (*Series in Microelectronics*), 1999, vol. 78.

[10] R. B. Marks, "A multiline method of network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1205–1215, July 1991.

[11] M. W. Pospieszalski, "Modeling of noise parameters of MESFET'S and MODFET'S and their frequency and temperature dependence," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1340–1350, Sept. 1989.

[12] M. W. Pospieszalski, L. D. Nguyen, M. Lui, T. Liu, M. A. Thompson, and M. J. Delaney, "Very low noise and low power operation of cryogenic AlInAs/GaInAs/InP HFET's," in *Proc. IEEE MTT-S Int. Microwave. Symp. Dig.*, 1994, pp. 1345–1346.

[13] J. D. Gallego and M. W. Pospieszalski, "Design and performance of cryogenically coolable ultra low noise, L-Band amplifier," in *Proc. 20th European Microwave Conf.*, Budapest, Hungary, Sept. 1990, pp. 1755–1760.