MILLIMETER-WAVE, CRYOGENICALLY-COOLABLE AMPLIFIERS USING AlInAs/GaInAs/InP HEMT'S

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ABSTRACT

The cryogenic performance of AlInAs/GaInAs/InP .1 μm HEMT's is reported. Collapse free d.c. operation is observed down to the ambient temperature of 18 K. The application of these devices to Q- and E-band low-noise, cryogenically-coolable amplifiers is demonstrated. The measured record-breaking noise temperature of 15 K (noise figure of .2 dB) for a multi-stage 40-45 GHz amplifier with 33 dB of gain at the ambient of 18 K is in close agreement with the prediction of a simple noise model. A very low power consumption per stage of less than 1 mW is recorded. The noise temperature of the E-band cryogenic amplifier is less than 47 K at 70 GHz, demonstrating that the performance of HEMT receivers is now competitive with that of SIS receivers in the 3-mm wavelength atmospheric window.

INTRODUCTION

Excellent noise performance at room temperature of a number of AlInAs/GaInAs/InP HEMT's, both pseudomorphic and lattice-matched, was recently reported [1]-[5]. Previous works [6], [7] demonstrated excellent cryogenic performance of conventional AlGaAs/GaAs and pseudomorphic AlGaAs/InGaAs/GaAs HEMT's. This paper reports for the first time the cryogenic properties of .1 μm gate-length AlInAs/GaInAs/InP HEMT's and their applications to Q- and E-band cryogenically-coolable amplifiers. The HEMT device structure, the d.c characteristics at cryogenic temperatures, the design of the cryogenic amplifiers and the validity of the device noise and small signal models [8] are discussed.

DEVICE

A cross-section of a HEMT structure grown using molecular beam epitaxy on a two-inch Fe-doped InP substrate is shown in Fig. 1. A silicon planar doping in AlInAs layer provides two-dimensional electron gas sheet charge density of about 3 x 10^{12} cm^{-2}. The mobilities measured on calibration wafers are typically 10,000 and 35,000 cm^2/V-sec at 297 K and 77 K, respectively. A typical lattice-matched device exhibits room temperature intrinsic transconductance of 1,000 mS/mm and cut-off frequency of 200 GHz at room temperature. Corresponding values for the pseudomorphic device ($Ga_{.4}In_{.6}As$ channel) are 1,300 mS/mm and 240 GHz. The room temperature performance of these devices and their application to millimeter-wave amplifiers has been described in [1]-[3].

CRYOGENIC CHARACTERISTICS

An example of I-V characteristics for a lattice-matched device at the ambient temperature of 18 K is shown in Fig. 2. The I-V characteristics are rather insensitive to illumination with red LED indicating low trap density. An example of the dependence of transconductance on drain current at different ambient temperatures and drain voltages is shown in Fig. 3. The maximum values of transconductance at T_a = 18 K are observed for very small drain to source voltage (.4 V) and small drain currents per unit gate width, indicating potential for very low power consumption operation. Surprisingly, there is almost no increase upon cooling in maximum value of transconductance for larger drain voltages (.8 V), a major difference if compared with cryogenic behavior of HEMT's having GaAs channels [13], [14].

NOISE MODEL

A simple noise model [7]-[9] of the device was constructed using an equivalent circuit, shown in Fig. 4, and determined from the room temperature S-parameters taken at the optimal bias for low-noise room temperature operation (V_{ds} = .8 V, I_{ds} = 8 mA for .1 x 80 μm device). For the cryogenic device, the measured changes in S-parameters can be modeled with sufficient accuracy by the change in values of transconductance g_m and drain conductance g_{ds} in the device equivalent circuit [7], [8], [10]-[12]. For the device under consideration, the measured values of g_m at the room temperature low-noise bias (V_{ds} = .8V, I_{ds} = 8 mA) was the same as for the cryogenic low-noise bias (V_{ds} = .4 V, I_{ds} = 3 mA, T_a = 18 K). Consequently, it was assumed that the equivalent circuit of Fig. 4 remains valid for the cryogenic device. The changes in noise parameters can then be described by the changes in the equivalent gate temperature (T_g = T_a) and equivalent drain temperature (T_d = 1000 K and 400 K at T_a = 297 K and 18 K, respectively.)

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A gate leakage could sometimes be a problem for an InP-based device and its influence on noise performance may not be discounted. The presence of gate leakage requires the introduction of two additional current noise sources in the device noise model (comp. Fig. 4). In the ideal case, the spectral intensity of these noise sources is given by Schottky's theorem (shot noise), although for real devices the spectral intensity of noise sources could have different frequency and current dependence (surface phenomena, avalanche breakdown). An example of the influence of 5 μA of gate-to-drain leakage current generating pure shot noise on minimum noise measure of a cryogenic device is shown in Fig. 5.

AMPLIFIER DESIGN AND PERFORMANCE

Two amplifiers were designed and built with the objective of achieving the smallest possible noise temperature over the band of interest at the ambient temperature of 18 K.

The Q-band amplifier employed a 0.1 x 80 μm AlInAS/GaInAs/InP device in the input stage and a 0.1 x 100 μm pseudomorphic AlGaAs/InGaAs/GaAs [15] in the subsequent four stages as the cryogenic performance of that device was previously known [6]. The comparison of measured and modeled performances is shown in Fig. 6 for ambient temperatures of 297 K and 18 K. The measured performance is referred to the input waveguide flange of the amplifier and no corrections are made for WG-to-MS transitions. The cryogenic noise temperature of 15 K is the lowest ever recorded at Q-band for any solid-state device with sufficient gain (inclusive of SIS mixer/HEMT IF amplifier tandems).

A similar approach was adopted to the design of a three-stage, E-band amplifier using 0.1 x 40 μm devices. It was intended as a full WR-12 waveguide bandwidth amplifier and its room temperature version came close to the original goal (Fig. 7). The noise data for the room temperature version are referred to the input waveguide flange.

For the reason of assuring the amplifier stability at cryogenic temperatures, the bandwidth of the cryogenic version was smaller (Fig. 8). The cryogenic data are referred to the dewar window and include the contribution of the mylar window and the pyramidal horn, also cooled to 18 K. The measured performance is competitive with the performance of 4 K SIS mixer/HEMT IF amplifier receivers [16] in this frequency range.

Both amplifiers were realized in hybrid technology using pure PTFE substrates (5 mils thick) [17] and wide band, E-plane probe, waveguide-to-microstrip transitions (Fig. 9).

CONCLUSIONS

A successful operation of AlInAs/GaInAs/InP HEMT's at cryogenic temperatures with very low power consumption has been described. The lowest ever noise temperature for solid-state devices with gain has been recorded at Q-band frequencies. The performance of cryogenic HEMT receivers is now competitive with SIS receivers in the 3-mm wavelength atmospheric window.

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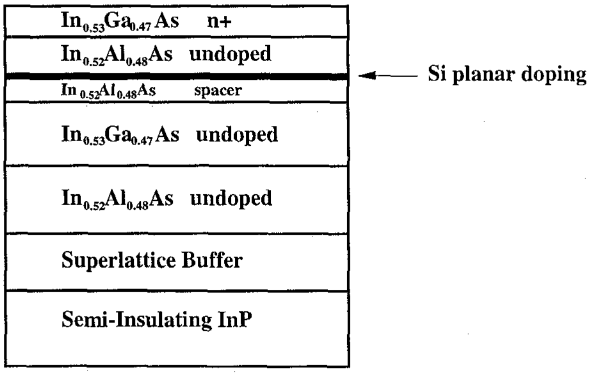

Fig. 1. A cross-section of a HEMT structure.

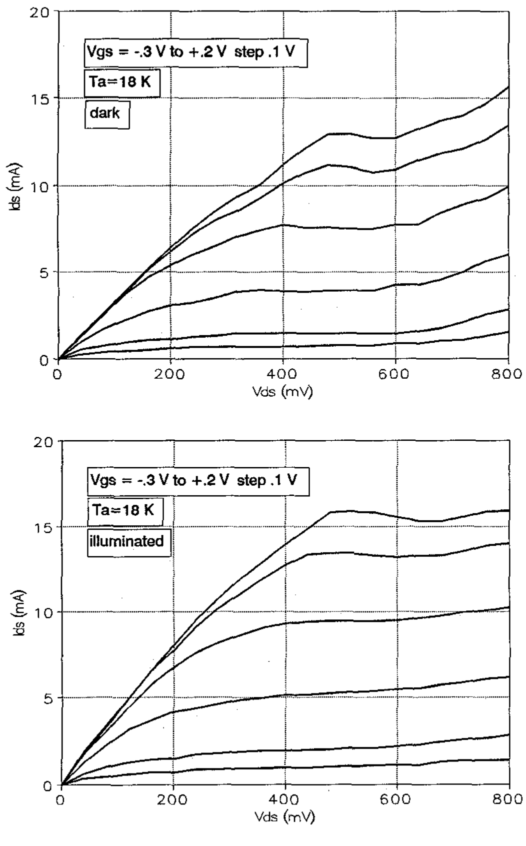

Fig. 2. Examples of I-V characteristics of the lattice-matched device at the ambient temperature of 18 K with and without illumination.

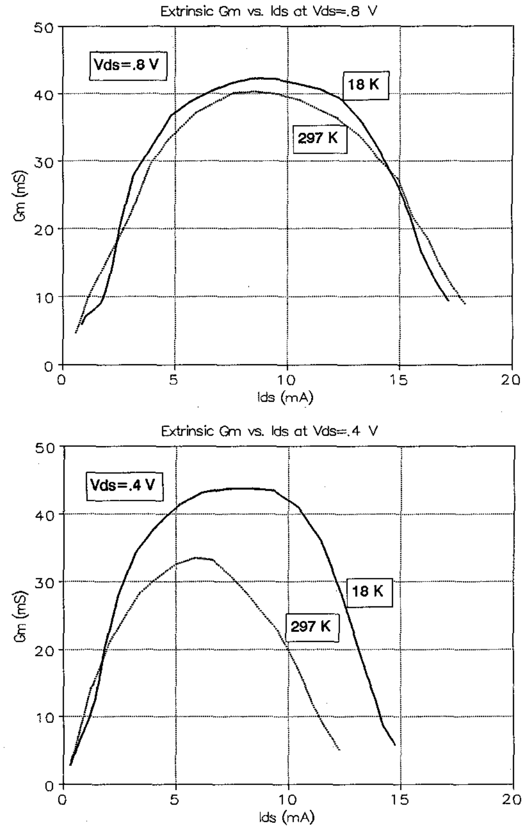

Fig. 3. Examples of extrinsic g_m vs. I_{ds} characteristics of the lattice-matched device at different ambient temperatures and drain voltages.

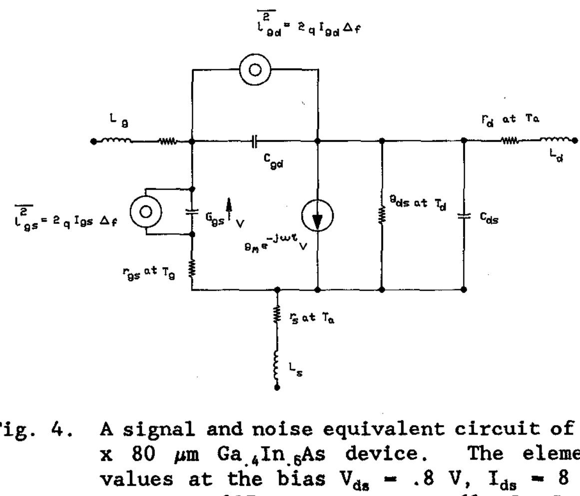

Fig. 4. A signal and noise equivalent circuit of .1 x 80 μm $Ga_{.4}In_{.6}As$ device. The element values at the bias V_{ds} = .8 V, I_{ds} = 8 mA and T_a = 297 K are: g_m = 61 mS, C_{gs} = .041 pF, r_{gs} = .9 ohms, r_g = 3.75 ohms, r_s = 1.6 ohms, r_d = 2.6 ohms, $1/g_{ds}$ = 108 ohms, τ = .1 ps, L_g = .014 nH, L_d = 0.014 nH, and L_s = .001 nH. The noise parameters are computed assuming that T_g = T_a, T_d = 1000 K at V_{ds} = .8 V, I_{ds} = 8 mA and T_d = 400 K at V_{ds} = .4 V, I_{ds} = 3 mA and T_a = 18 K (see text for additional comments.)

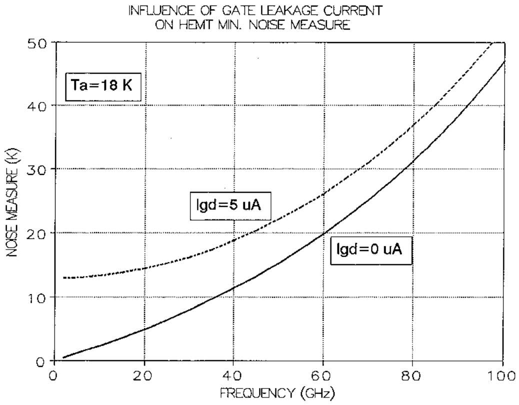

Fig. 5. An illustration of the influence of the gate-to-drain leakage current generating pure shot noise on the minimum noise measure of the device of Fig. 4 at T_a = 18 K (see text for additional comments).

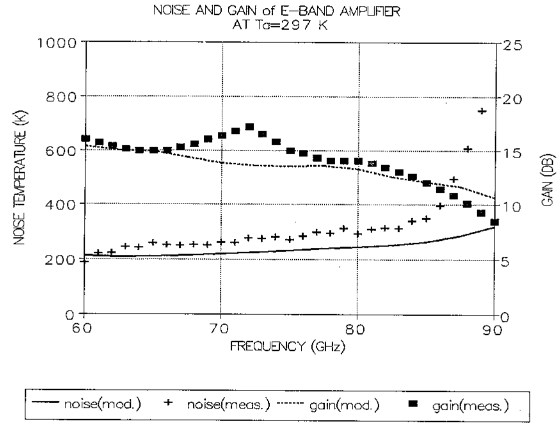

Fig. 7. Measured and modeled performance of a three-stage 60-90 GHz amplifier at room temperature.

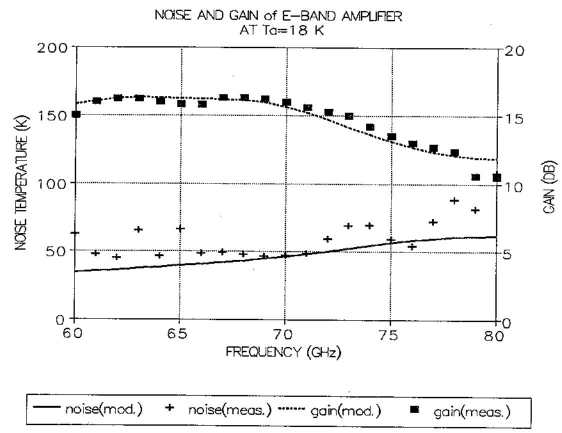

Fig. 8. Measured and modeled performance of a three-stage 60-80 GHz cryogenic amplifier at the ambient temperature of 18 K.

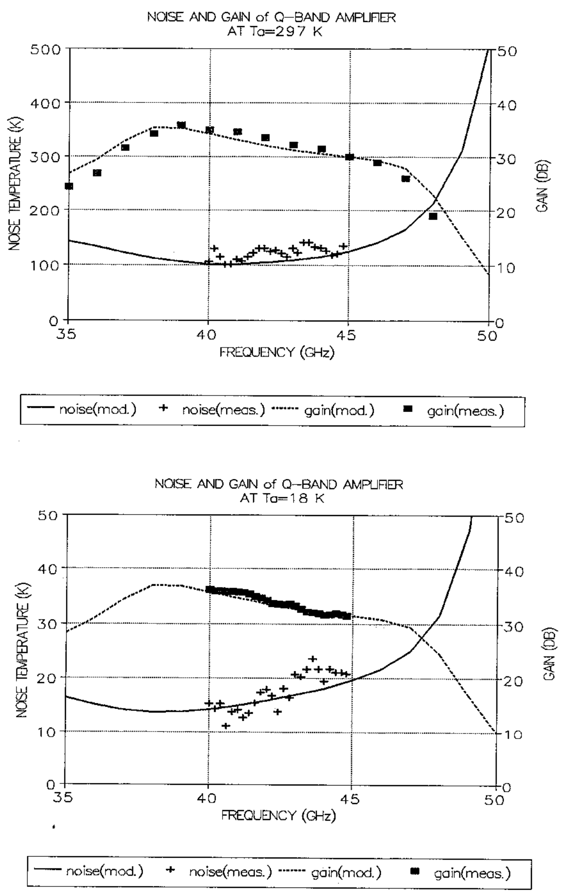

Fig. 6. Modeled and measured performance of the Q-band amplifier at room and cryogenic temperatures.

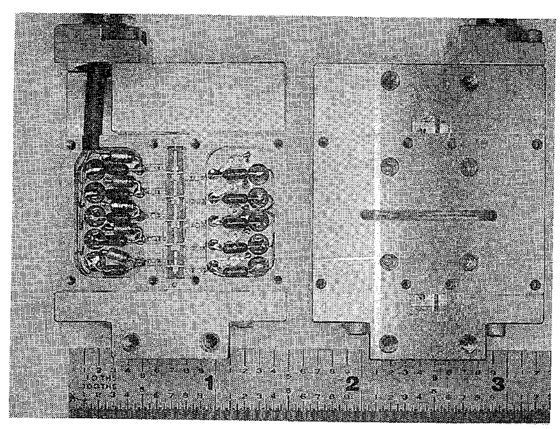

Fig. 9. A view of a Q-band amplifier.