FET'S AND HEMT'S AT CRYOGENIC TEMPERATURES - THEIR PROPERTIES AND USE IN LOW-NOISE AMPLIFIERS

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ABSTRACT

This paper reviews the performance of a number of FET's and HEMT's at cryogenic temperatures. Typical d.c. characteristics and X-band noise parameters are presented and qualitatively correlated wherever possible with other technological or experimental data. While certain general trends can be identified, further work is needed to explain a number of observed phenomena. Design examples of three-stage, X-band HEMT and FET amplifiers are briefly discussed. Typical noise temperatures at 8.4 GHz are T_n = 22K,for all FET amplifiers and 11K for amplifier with HEMT's in the input stage.

Introduction

The feasibility of cooling GaAs FET amplifiers has been very well documented [1], [2]. Recently, very low noise temperatures for cryogenically-cooled HEMT's have also been reported [3], [4]. It has, however, long been recognized that cryogenic performance of either HEMT's or FET's may not be inferred from room temperature performance. In fact, for both HEMT's and FET's several different phenomena were observed which render some devices useless for cryogenic applications. Besides low-noise applications, emerging importance of cooling of HEMT's and FET's for high-speed applications makes it important at least to list the observed phenomena, even without full explanation. While certain general trends can be identified, their explanation is not possible, even qualitatively, without detailed knowledge of the device structure and processing. For obvious reasons, this information is not always easily available. This paper is, therefore, intended to provide a comprehensive view to what is observed in HEMT's and FET's at cryogenic temperatures. The first section deals with FET's, the second with HEMT's, and the third gives examples of amplifiers built with cryogenically well-behaved FET's and HEMT's.

FET's

Sample transistors of the following types have been tested at cryogenic temperatures: MGF1412, MGF1405 (Mitsubishi), NE75083, NE04583, NE71083 (NEC), FSC10FA, FSX02FA (Fujitsu), 2SK525 (Sony). While the choice of transistors is hardly balanced, it follows the past history of good cryogenic performance.

Table I presents the comparison of performance of FET's that were found most useful for cryogenic application. The data are self-explanatory, though the following comments could be useful.

The spread in minimum noise temperature between transistors from different lots is much greater than from within the same lot. In fact, in the latter case the spread may be as low as 2K. For repeatable cryogenic performance of amplifiers, it is always useful to use transistors from the same lot.

Poor cryogenic noise performance for FET's with otherwise orderly behavior can usually be traced to the poor pinch-off characteristic at the cryogenic temperatures, not necessarily noticeable at the room temperature. As an example, the comparison of room and cryogenic temperature characteristics of two NE75083 FET's having very different noise performance at cryogenic temperatures is shown in Figure 1. Note the small differences in room temperature characteristics, as opposed to large differences at 12.5K between these two transistors.

For most of the FET's, the transconductance g_m does not vary appreciably upon cooling. It usually goes up by less than 20 percent of the room temperature value or remains constant. A notable exception is the MGF1412 transistor, where an increase in transconductance as large as 50 percent of the room temperature value was observed; this is about the same as for good cryogenic HEMT's (30 to 60 percent increase [3], [4]. An example of the d.c. characteristic of the MGF1412 FET is shown in Figure 2. Together with increase in transconductance, a reduction of small-signal shunt drain resistance is observed (Figures 1 and 2).

Theoretical studies [5], [6], [7] predict linear dependence of the minimum noise temperature on the gate length, even for submicron gate devices [6], [7]. In this light, comparison of the gate dimensions (published by the manufacturer) with the noise performance of the best FET's (Table I) reveals superb quality and/or structure of Mitsubishi epitaxial GaAs from the point of view of cryogenic applications. The cryogenic d.c. data, notably $g_m = f(I_{ds})$ characteristic also support this conclusion.

Not all transistors present such an orderly behavior when cooled as those in Figures 1 and 2. Unusual distortion of the I-V characteristic (example of NE71083 is shown in Figure 3) or oscillations which are most likely caused by the Gunn type

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instabilities in GaAs (a number of MGF 1405 transistor samples) are sometimes present.

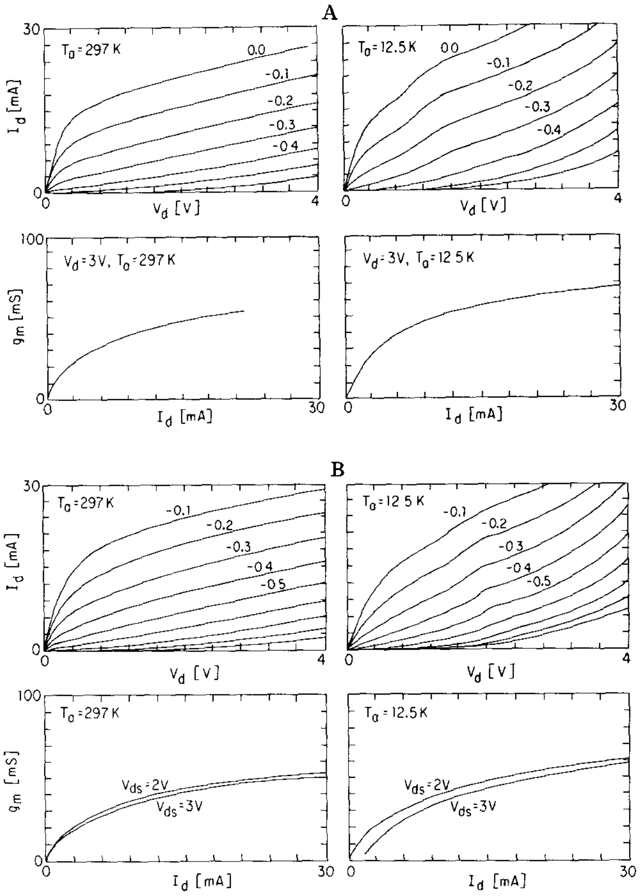

Fig. 1. The d.c. characteristic at room and cryogenic temperatures of two FET's of the same type with different cryogenic noise performance at 8.5 GHz:
A. NE75083 (72A) FET exhibiting T_{min}=15K.
B. NE75083 (4YB) FET exhibiting T_{min}=23K.

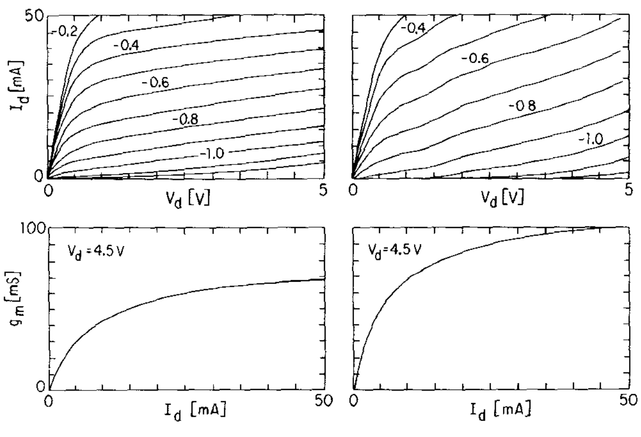

Fig. 2. Typical d.c. characteristics at room and cryogenic temperatures of MGF1412 FET (3YAK8) exhibiting T_{min} = 20K at f = 8.5 GHz and T_a = 12.5K).

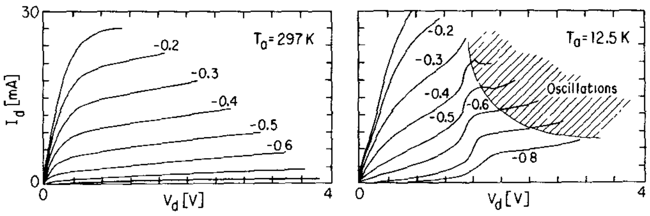

Fig. 3. Example of unusual distortion of I-V characteristics at cryogenic temperatures observed for NE71083 FET's.

HEMT's

The sample HEMT's of the following type have been tested: H-503-P70 (Gould-Dexel), JS8901-AS (Toshiba), 2SK676 (Sony), and FHR01FH (Fujitsu). A sample of their d.c. characteristics at room and cryogenic temperatures are shown in Figures 4 and 5, and comparison of their noise performance is given in Table II. All HEMT's had to be illuminated with light to be time-invariant, memory-less devices at cryogenic temperatures. With the notable exception of FHR01FH, all failed to pinch off properly at the cryogenic temperatures, exhibiting a large portion of drain current not controlled by the gate voltage. Judging from the available manufacturer information [8], [9], [10], this effect can be linked to the very high doping (2 - 3 x 10^{18} cm^{-3}) of the AlGaAs layer. Devices with moderate doping, as reported in [3], do not exhibit this effect.

For the HEMT's, the d.c. and/or noise data taken at a number of different temperatures between 297K and 12.5K reveal the same qualitative behavior and sensitivity to light as reported in [3]. This has been linked to the existence of traps but, as yet, not fully understood. The results for the sample HEMT's are shown in Figures 5 and 6. The noise parameters of Fujitsu HEMT with excellent cryogenic performances are given in Table III. The minimum noise temperatures T_{min} = 9K at 8.5 GHz and T_a = 12K are, within the measurement error, equal to the record-breaking values reported previously [3].

X-Band Amplifier Examples

A number of X-band amplifiers were constructed for radio astronomy applications, using both FET's and HEMT's with good cryogenic performance. It was found that in the process of computer-aided design of cryogenically-cooled amplifiers with well-behaved FET's, the room temperature S-parameter data and cryogenic noise parameter data can be used with accuracy sufficient for practical applications. The change in amplifier gain upon cooling can be accounted for by the changes in transconductance and small signal drain resistance (compare Figures 1 and 2). The example of computer-predicted and measured cryogenic performance of all FET (NE75083), three-stage, 10.7 GHz amplifiers is shown in Figure 7. An example of three-stage, 8.4 GHz amplifier performance with a FHR01FH in the first stage and MGF1412's in following stages is shown in Figure 8. The noise temperature of 11K (.16 dB) at 8.5 GHz is probably the best yet reported for cryogenically-cooled, multi-stage amplifiers at this frequency.

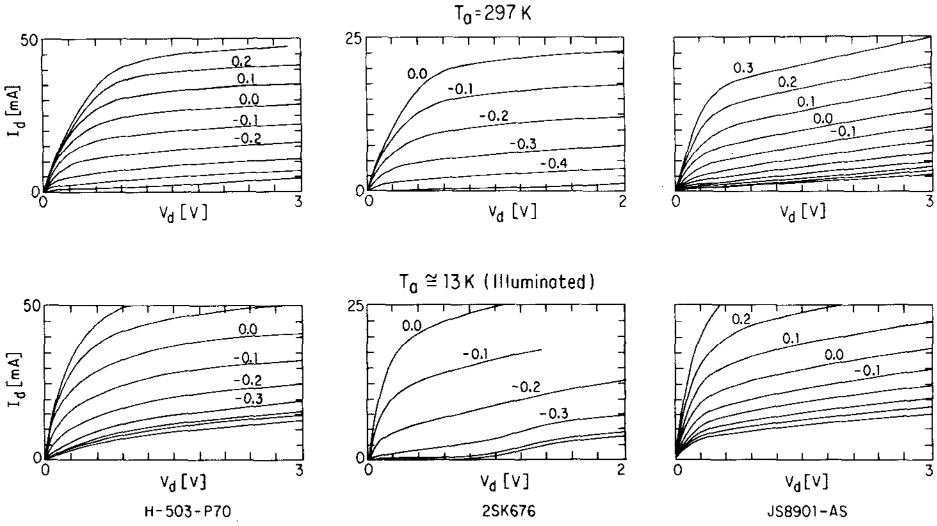

Fig. 4. Examples of room and cryogenic temperature charcteristics of commercially available HEMT's. All were taken with light illumination.

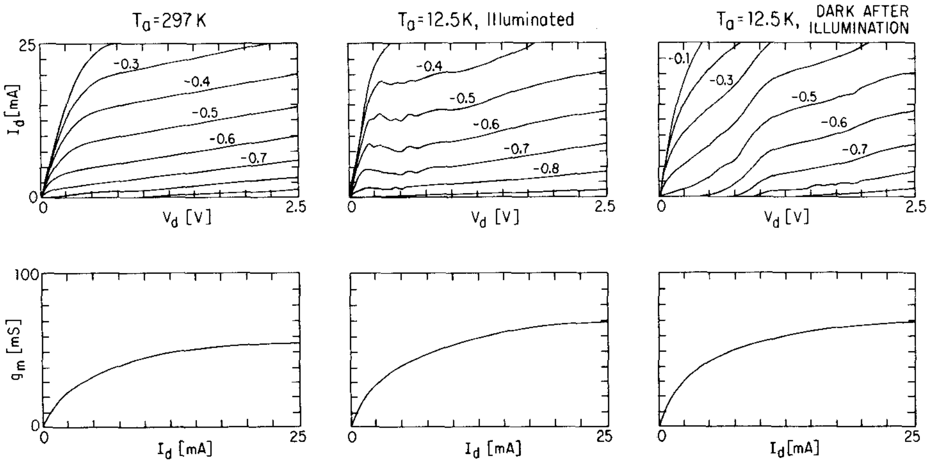

Fig. 5. The d.c. characteristic of FHR01FH HEMT with excellent cryogenic noise performance and the effect of light illumination. Note large influence of light at small drain voltages.

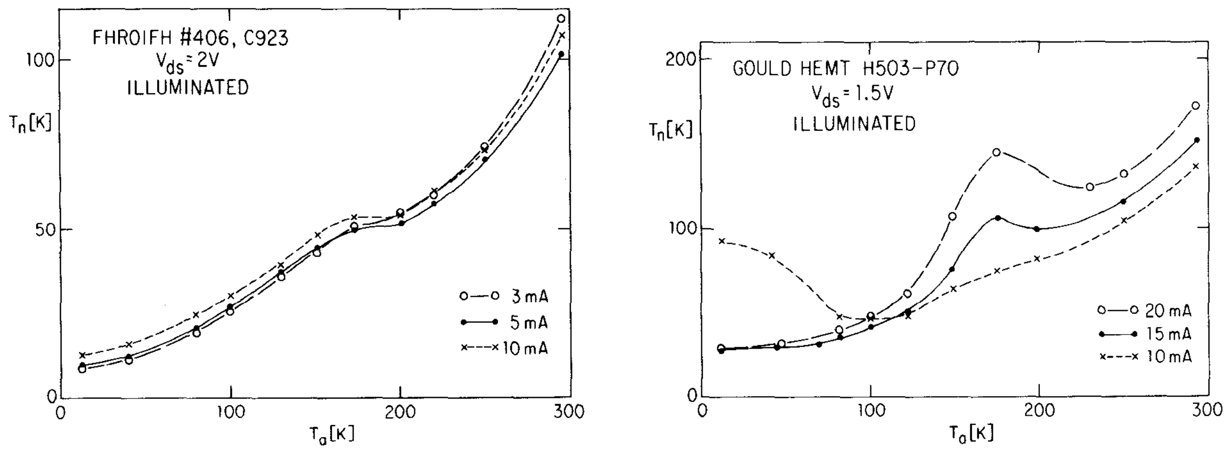

Fig. 6. The noise temperature of a single-stage FHR01FH and H-503-P70 amplifiers versus ambient temperature. Source impedance is optimal for cryogenic temperature.

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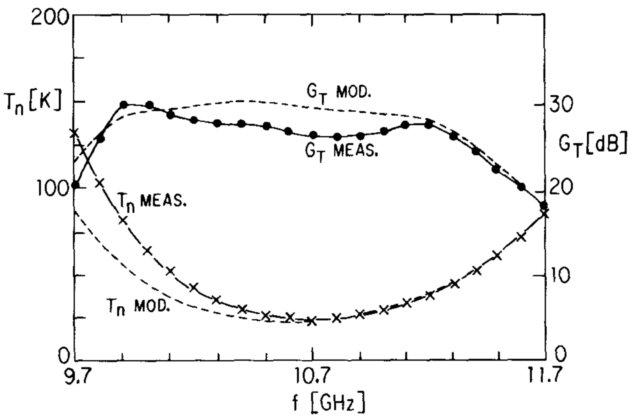

Fig. 7. Comparison of computer-predicted and measured noise temperature and gain of the 10.7 GHz, three-stage amplifier with NE75083 transistors at 12.5K. All transistors are biased at V_{ds} = 3V, I_{ds} = 10 mA. At 10.7 GHz, T_n = 26K.

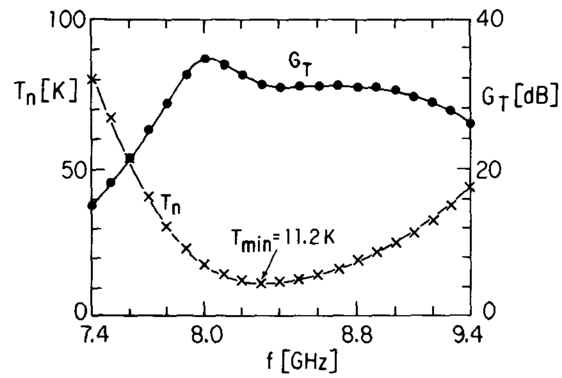

Fig. 8. Noise temperature and gain of the 8.4 GHz, three-stage amplifiers with FHR01FH in input stage and MGF 1412's in the following stages.

TABLE II. Cryogenic Noise Performance of Sample HEMT's at T_a = 12.5K, f = 8.5 GHz.

DEVICE	H503-P70	JS8901-AS	2SK676	FHR01FH
T_{min} [K]	25	27	14	9.4

TABLE I. Noise Performance Comparison of Best GaAs FET's at 8.5 GHz and 12.5K.

TYPE	GATE L μm	GATE W μm	BIAS V_{ds} V	BIAS I_{ds} mA	NOISE PARAMETERS OF SAMPLE FET T_{min} K	R_{opt} Ω	X_{opt} Ω	g_n mS	RANGE OF T_{min} [K] MIN	MAX	ASSOC. GAIN dB
MGF1412	.7	400	4.5	10	20	7.1	38	3.7	18	26	12
FSC10FA	.5	400	3	10	20	3.6	32	6.6	15	24	9
NE75083*	.3	300	3	10	15	4.5	32	4.3	15	23	11.1
FSX02FA		200	2	5	17	5.9	24	4.5			11.5

*NE75083 production has been discontinued.

TABLE III. Noise Parameters of FHR01FH HEMT at f = 8.5 GHz and T_a = 12.5K.

I_{ds} mA	V_{ds} V	T_{min} K	R_{gopt} Ω	X_{gopt} Ω	g_n mS	Ass. Gain dB
3	2	9.4	4.3	18.3	2.7	11.8
5	2	10.3	4.6	17.0	2.6	13.1
10	2	13.0	5.3	16.3	2.7	13.4
15	2	16.3	5.7	15.6	3.2	13.7