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X-BAND NOISE PERFORMANCE OF COMMERCIALLY-AVAILABLE GaAs FET's AT ROOM AND CRYOGENIC TEMPERATURES

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I. Introduction

This report presents the results of noise parameters measurements of a number of commercially-available GaAs FET's at the frequency of ~ 8.4 GHz, both at room and cryogenic temperatures. This work has been undertaken in order to:

1) supplement the previous study [1] with results for transistors which have become available only recently, and
2) test the repeatability of noise performance at cryogenic temperatures for the transistors of the same type.

The method of measurement as described in [1] and [2] has been used. In addition to noise measurement, some d.c. measurements were also performed to allow for better comparisons between different FET's and, as well, between FET's and HEMT's.

The sample transistors of the following types have been fully evaluated: MGF1412 (Mitsubishi), NE75083 and NE04583 (NEC), FSC10FA (Fujitsu), and H503-HEMT (Dexel-Gould). The measured data on sample transistors include: noise parameters for several values of drain current at 297K and 12.5K, drain I_{ds}-V_{ds} characteristics and g_m (I_{ds}) characteristic at 297K and 12.5K, and also cool-down data for a single-stage amplifier. The repeatability of cryogenic performance for several transistors of the same type was also checked.

Several other FET's, namely MGF1405 (Mitsubishi), NE71083 (NEC) and 2SK575 (Sony) were also tested for their cryogenic performance, but not fully evaluated.

The results of the measurements are described in Section II of this report. Section III is devoted to a discussion of experimental results and comparisons between different FET's and between FET's and HEMT's, while Section IV contains main conclusions.

II. Results

A. MGF1412 (Mitsubishi)

This transistor has long been considered to be the best choice for cryogenic applications. It has been specified by the manufacturer as a .7 μm gate length device with 400 μm gate width, and .8 dB (59K) and 1.7 dB (139K) noise figure at 4 GHz and 8 GHz, respectively [4]. This specification remained almost unchanged for the past several years [5]. Our present measurement closely confirms this claim; in fact, this transistor usually performs better: T_{min} = 59K at 4.8 GHz [3] and T_{min} = 125K at 8.5 GHz have been measured. It should be noted, however, that 1980 results of Weinreb and Brookes for the same transistor [6], [7], [8] were not as good: T_{min} between 80 and 110K were observed at room temperature at 5 GHz. The same authors measured the minimum noise temperatures between 20K and 30K at 5 GHz for MGF1412's cooled to 20K. The typical values measured recently at the ambient temperature of 12K are much better: 10K at 4.8 GHz [3] and 20K at 8.4 GHz. Obviously this transistor has been greatly improved since its introduction on the market.

The typical noise and d.c. data for the MGF1412-08 transistor are given in Table I and Figures 1 and 2. A large increase in transconductance g_m (about 50%) upon cryogenic cooling is typical for these transistors, though for all the other FET's tested the transconductance changes very little or not at all.

Recent results indicate fairly good repeatability of cryogenic noise performance for the transistors from a single lot - there has been, however, evidence to the contrary in the past [1], [8]. The cryogenic noise performance may vary quite significantly for different lots - the observed range of minimum noise temperature at T_a = 12.5K and frequency of $f \cong 8.4$ GHz was 18-26K.

B. MGF1405 (Mitsubishi)

The MGF1405 transistors, while having superior room temperature performance to that of MGF1412's, are usually useless for cryogenic applications because of parasitic oscillations. They frequently exhibit oscillations at the frequencies above 30 GHz when cooled to 12K, and there is little one can do to "tame" it with the outside circuit. It is very unlikely that these parasitic oscillations are caused by a large increase in transconductance upon cooling, as HEMT structures with .3 μm gates and transconductance approaching 200 mS at cryogenic temperatures were successfully tested in the same mount without similar problems. The oscillations, therefore, seem to be inherent to the packaged device itself and are of an unknown nature. Most likely, they are caused by the Gunn type instabilities in GaAs.

It should be noted that the MGF1404 FET, predecessor to MGF1405, also exhibited instabilities upon cooling.

TABLE I. Noise parameters of MGF1412 (3YAK8) FET at the frequency f ≈ 8.4 GHz.

T_a = 297K

I_{ds} mA	V_{ds} V	T_{min} K	R_{gopt} Ω	X_{gopt} Ω	g_n mS	Ass. Gain dB
5	3	116	11.1	42.1	13.7	8.1
10	3	122	13.4	39.6	11.5	9.0
15	3	136	15.3	37.1	9.9	9.4

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
5	4.5	20.0	5.1	40.9	4.7	11.3
10	4.5	20.1	7.1	38.7	3.7	12.3
15	4.5	22.0	8.4	37.5	3.5	13.0

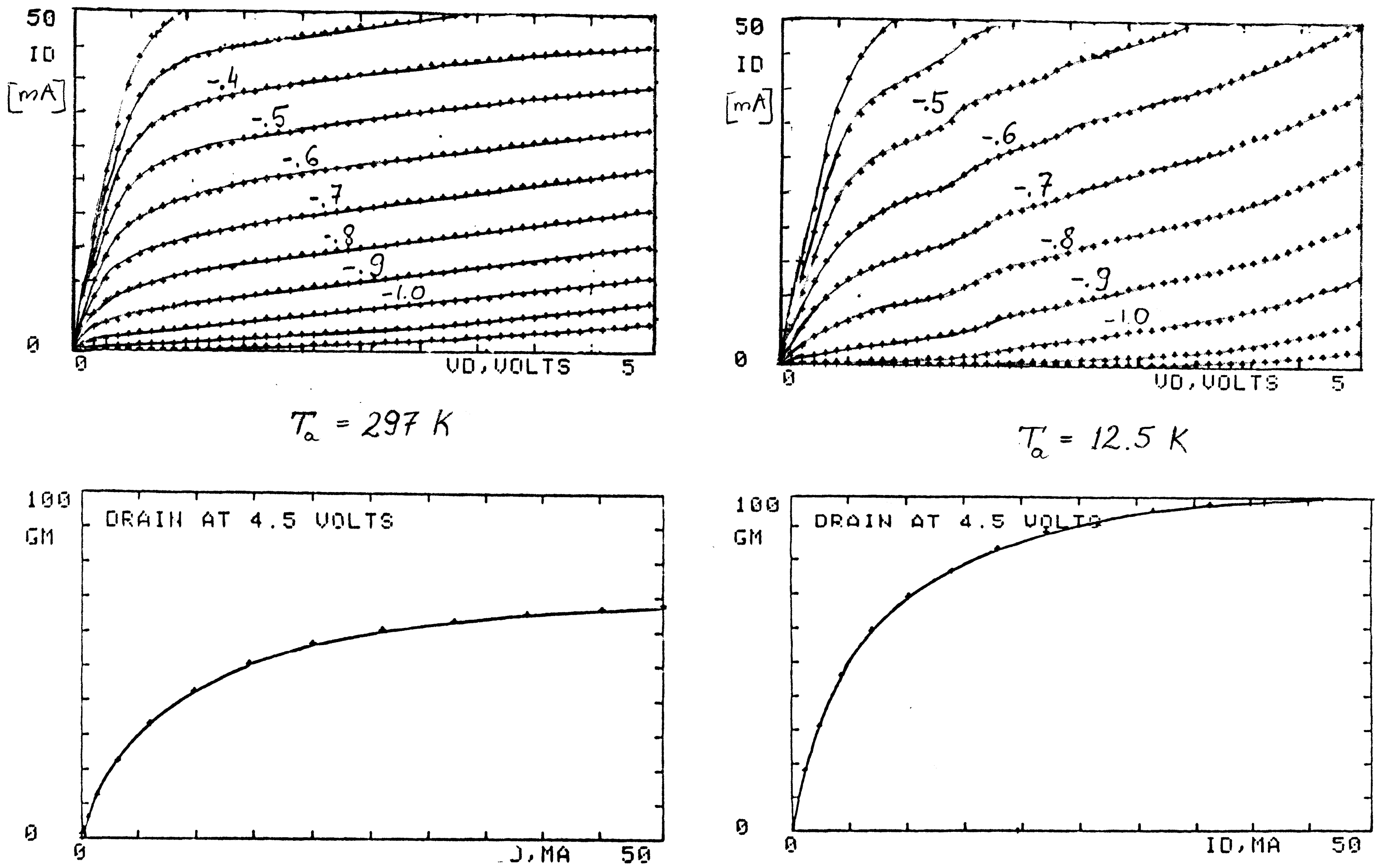

Fig. 1. Typical d.c. characteristics of MGF1412 (3YAK8) FET at 297K and 12.5K.

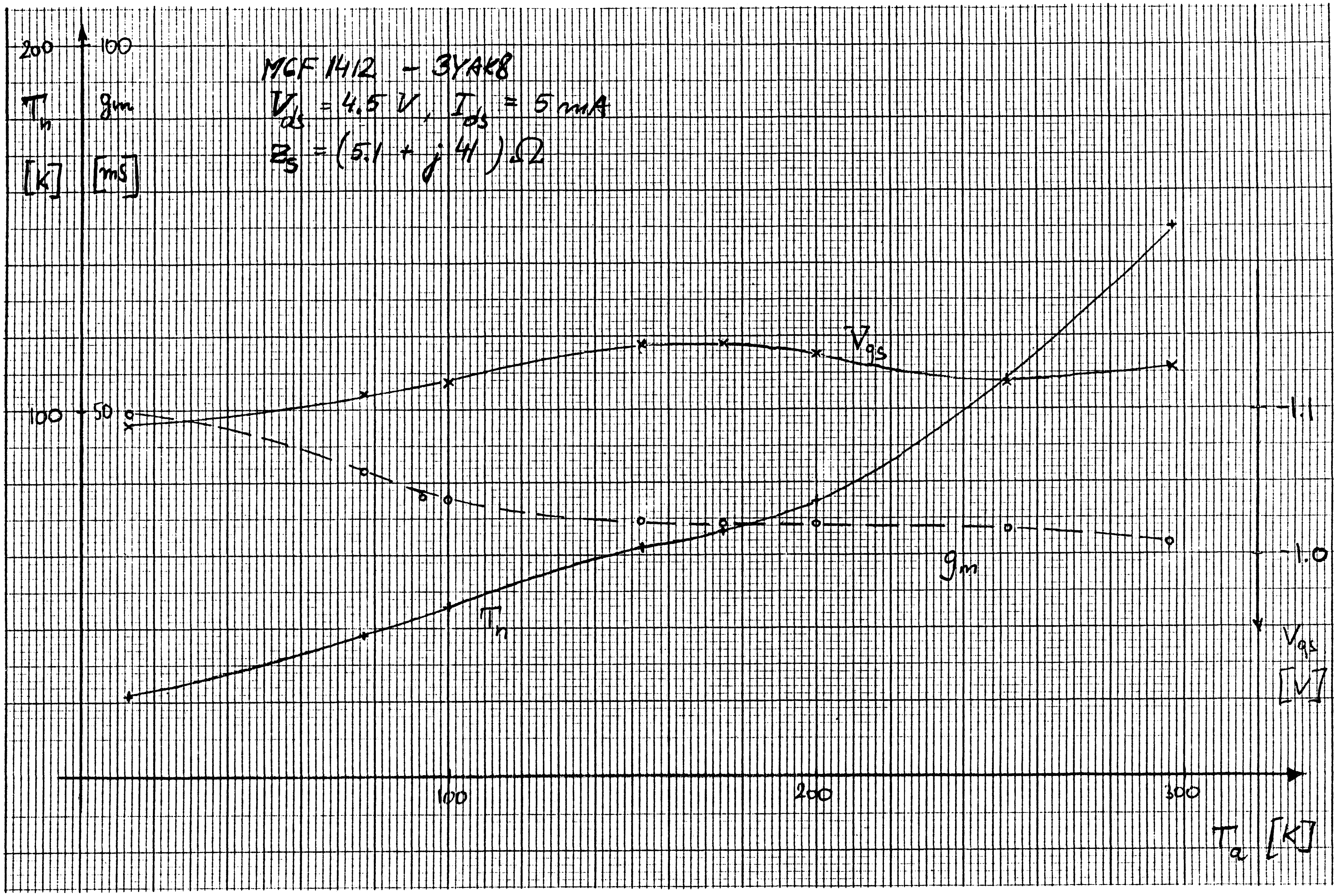

Fig. 2. The cooling curve of the 8.4 GHz, single-stage MGF1412 (3YAK8) amplifier with the source impedance optimal for cryogenic noise performance.

C. NE75083 (NEC)

This FET was introduced on the market in late 1984 and withdrawn from the market in 1985. It was advertised as "super low noise FET" with .3 μm gate length and a room temperature noise figure of .4 dB (30K) and 1.0 dB (75K) at 4 GHz and 8 GHz, respectively. Early samples of this FET (lot 72A) came close to the manufacturer's claim. The minimum noise temperatures of 52K (.72 dB) [3] and 89K (1.16 dB) were measured at the frequencies of 4.8 GHz and 8.5 GHz, respectively. The FET samples from the lot 72A also exhibited excellent cryogenic noise performance. The minimum noise temperature of 9K [9] and 10K [3] were measured at the frequency f = 4.8 GHz. Also 14.6K [9] and 14.2K (this report) were measured at the frequency f ≅ 8.4 GHz. Very close agreement between independent measurements (in fact, much better than estimated accuracy of X-band measurement ± 1.5K) builds confidence in these results. These samples, therefore, demonstrate the attainable limit of cryogenic performance in conventional FET technology, if a combination of factors is right for cryogenic applications. The X-band noise data and d.c. data for the 72A lot transistor are given in Table II and Figures 3 and 4.

Unfortunately, subsequent testing of a number of other NE75083 transistors from different lots has shown much worse cryogenic performance (T_{min} = 18-23K), though their room temperature performance was very similar to that of lot 72A transistors. Very good repeatability of the noise temperature of the order of ± 1K for the FET's from the same lot was observed. The example of d.c. characteristics for the lot 4Y-13 transistors, for which the typical noise temperature was T_{min} = 22-23K, is shown in Figure 5.

Two differences can be observed between the d.c. characteristics of FET's from lots 72A and 4Y13: the smaller value of g_m and worse pinch-off characteristics for the lot 4Y13 in comparison with lot 72A. Both differences can be qualitatively explained by different crystal quality and/or electrical characteristics of the interface region between the semi-insulating buffer layer and active layer. The importance of the quality of the interface for low noise room temperature operation has been known [5], [8], [10]. It appears from this example that the cryogenic noise performance is much more sensitive to characteristics of the interface region than the room temperature performance.

TABLE II. Noise parameters of NE75083 (72A) FET at the frequency f ≈ 8.4 GHz.

T_a = 297K

I_{ds} mA	V_{ds} V	T_{min} K	R_{gopt} Ω	X_{gopt} Ω	g_n mS	Ass. Gain dB
5	3	90	7.2	32.5	10.8	8.6
10	3	89	9.4	32	8.4	9.7
15	3	95	10.7	31.5	8.3	10.5

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	3	14.3	2.3	33	8.6	8.0
5	3	14.2	3.2	33	6.1	9.0
10	3	15.2	4.5	32.5	4.3	11.1
15	3	17.8	5.4	32	3.9	11.4

D. NE04583 (NEC)

This FET has been recently introduced by NEC for 12/14 GHz band applications. It has .3 μm gate length, 200 μm gate width and an advertised room temperature noise figure of 1 dB (75K) and 1.4 dB (110K) at 8 and 12 GHz, respectively [11]. Our room temperature measurement closely confirms this claim: T_{min} = 80K has been measured at 8.5 GHz. The measured noise parameters of a sample FET from lot #G01-10 are given in Table III. The noise parameters at 12.5K could be measured only at V_{ds} ≤ 1.5V due to parasitic oscillation at higher drain voltages. This

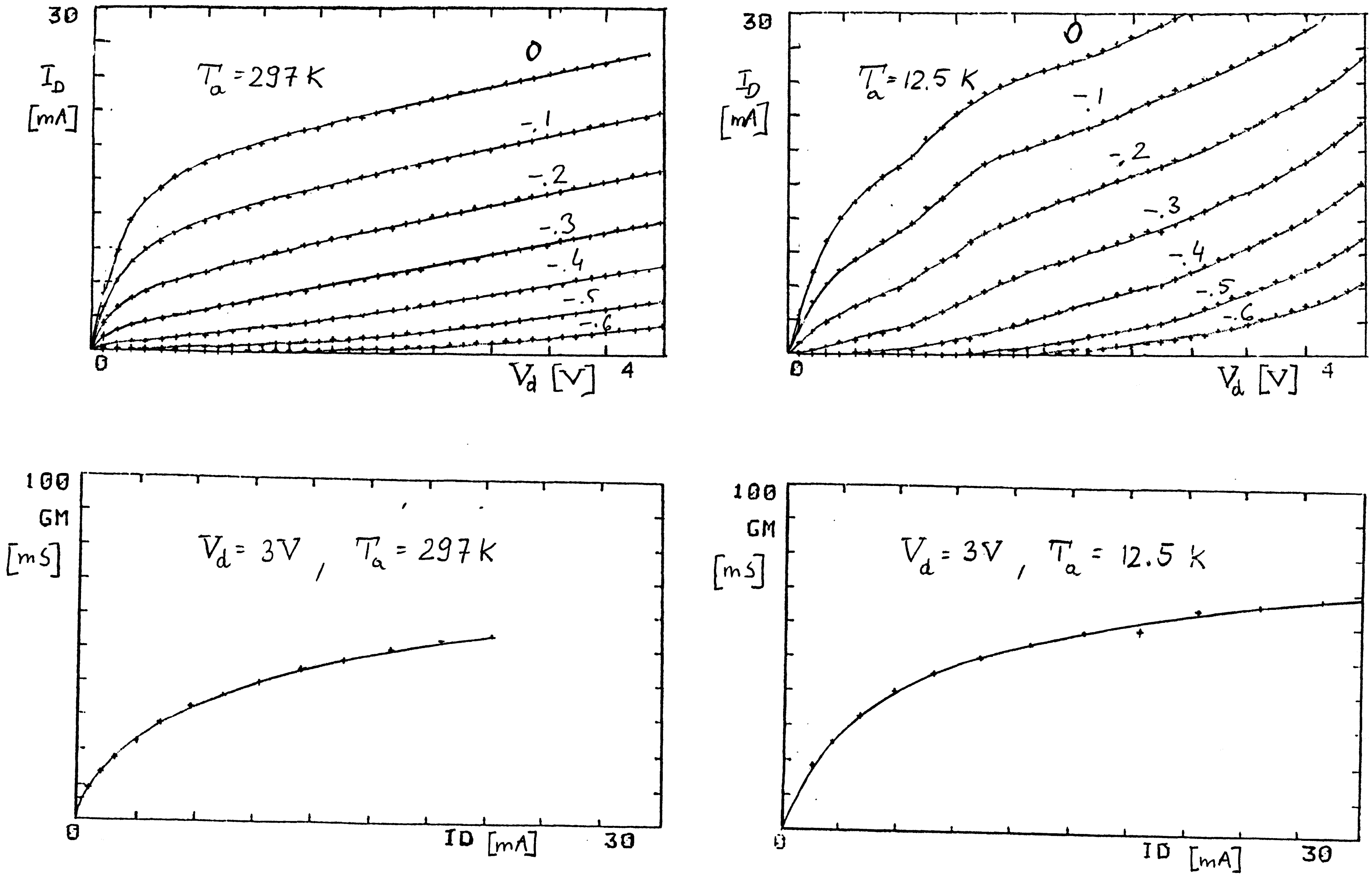

Fig. 3. Typical d.c. characteristics of NE75083 (72A) FET at 297K and 12.5K.

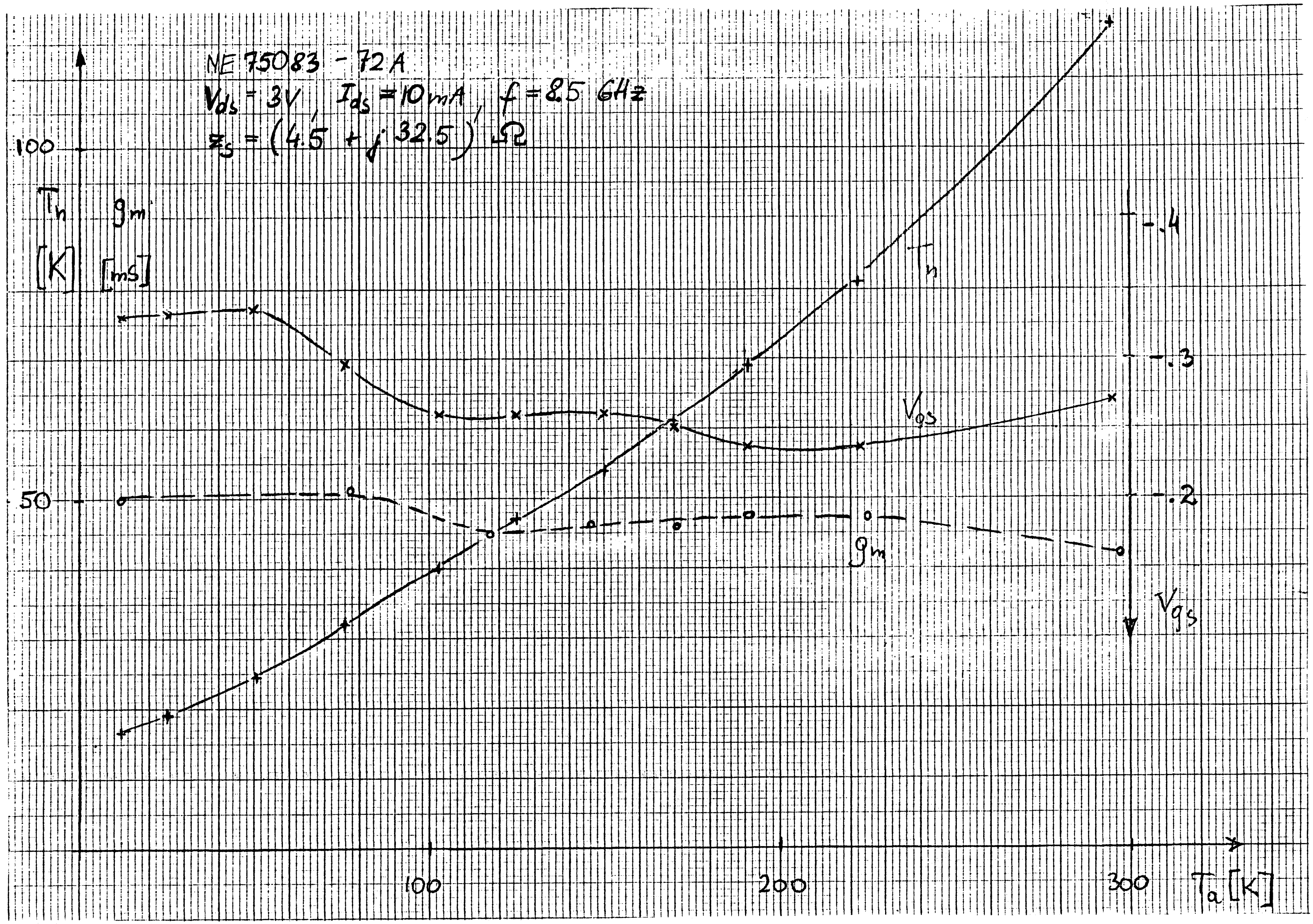

Fig. 4. The cooling curves for the 8.4 GHz, single-stage NE75083 (72A) amplifier with the source impedance optimal for cryogenic noise performance.

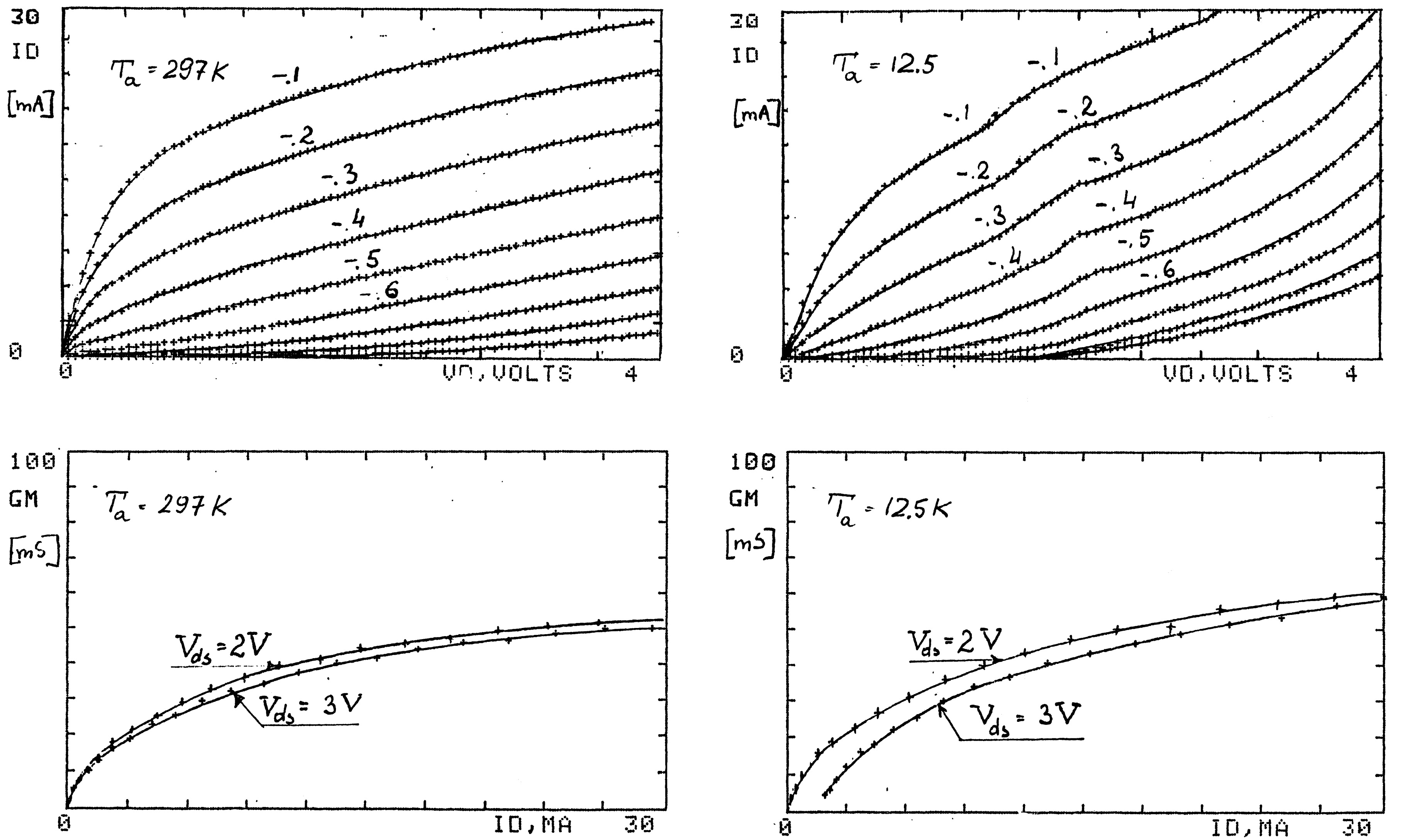

Fig. 5. Typical d.c. characteristics of NE75083 (4Y13) FET at 297K and 12.5K.

was found to be a problem for two transistors tested from this lot. The frequency of oscillation was in both cases around 60 GHz. Examples of d.c. data for the sample FET are given in Figure 6. The shaded region of the I-V characteristics indicates the presence of oscillations. The nature of the parasitic oscillations has not been determined.

TABLE III. Noise parameters of NE04583 (G01-10) FET at the frequency $f \simeq 8.4$ GHz.

T_a = 297K

I_{ds} mA	V_{ds} V	T_{min} K	R_{gopt} Ω	X_{gopt} Ω	g_n mS	Ass. Gain dB
3	3	88	5.3	42.5	18.5	7.8
5	3	80	6.5	42.3	14.6	8.6
10	3	84	8.2	42.0	12.1	10.3
15	3	93	8.9	41.5	12.2	11.2
20	3	107	9.2	41.0	13.7	11.7

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	1.5	18.5	2.9	42.5	7.0	9.9
5	1.5	19.3	3.7	42.4	6.1	11.4
10	1.5	23.6	5.7	42.1	5.9	12.3
15	1.5	28.6	6.5	41.7	6.9	13.2

E. NE71083 (NEC)

The NE71083 transistor has .3 μm gate length, ~ 300 μm gate width and an advertised room temperature noise figure of 1 dB (75K) at 8 GHz and is otherwise identical to NE67383 (.8 dB at 8 GHz) [12]. The noise temperature measured at 12.5K and 8.5 GHz for sample transistor (lot #32-4) was T_{min} = 21K, which is about the same as for NE67383 transistors [1]. However, the cryogenic d.c. characteristics, the examples of which are shown in Figure 7, exhibit quite unusual features. The

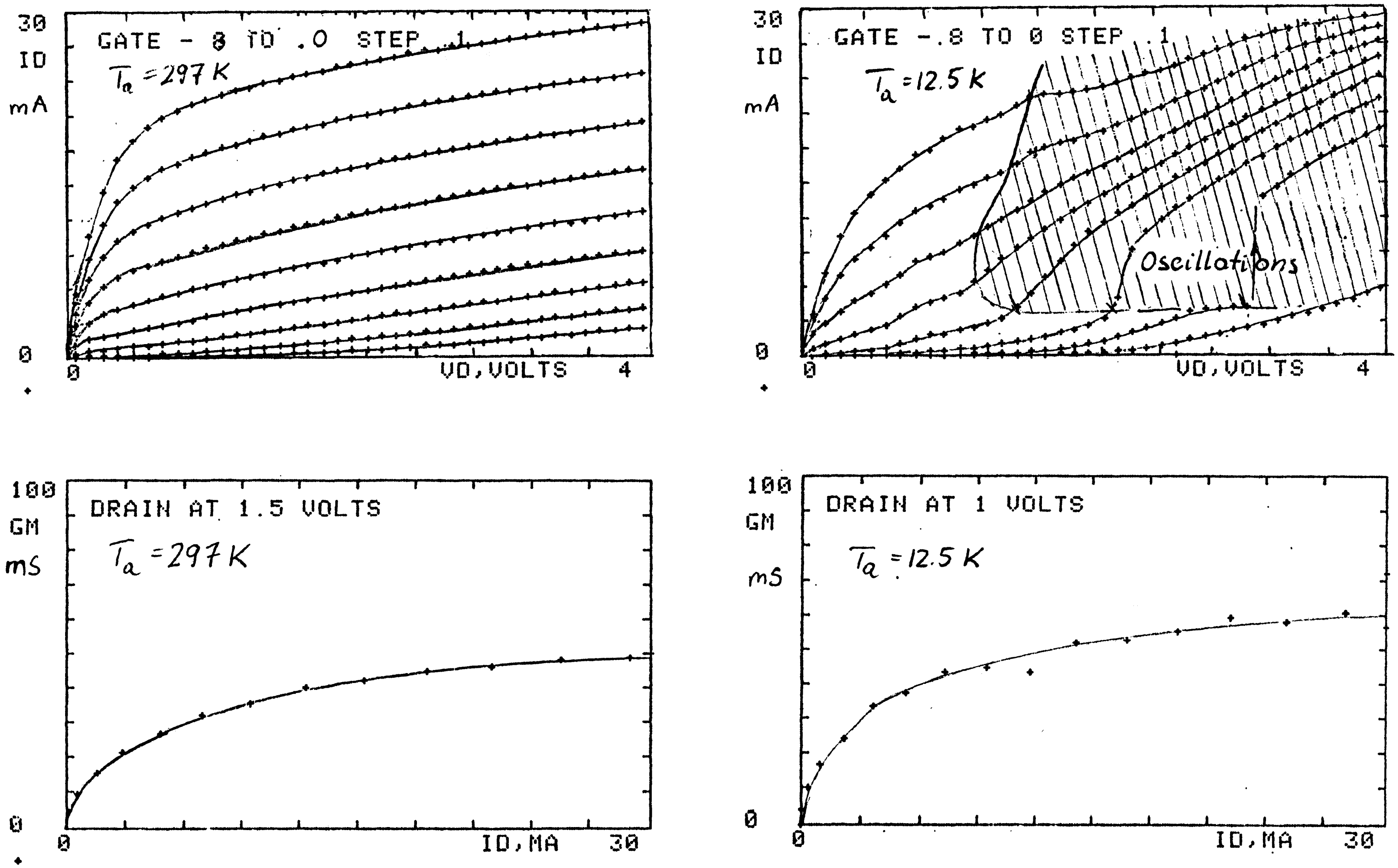

Fig. 6. Typical d.c. characteristics of NE04583 (G01-10) FET at 297K and 12.5K.

"steps" in I-V characteristics are in this case not connected with any detectable oscillations. In fact, the optimum bias for this particular transistor, yielding T_{min} = 21K, was V_{ds} = 3.5V, I_d = 5 mA, and V_{gs} = -.85V. There is no known explanation of the observed phenomenon. Surprisingly, close examination of the d.c. characteristics of the FET's with "orderly" behavior at 12.5K, like MGF1412, NE75083, or FSC10FA, reveals fine structure similar in appearance to that distinctively seen in the case of NE71083.

The parasitic oscillations of the frequencies around 60 GHz were also observed for cold NE71083 transistors.

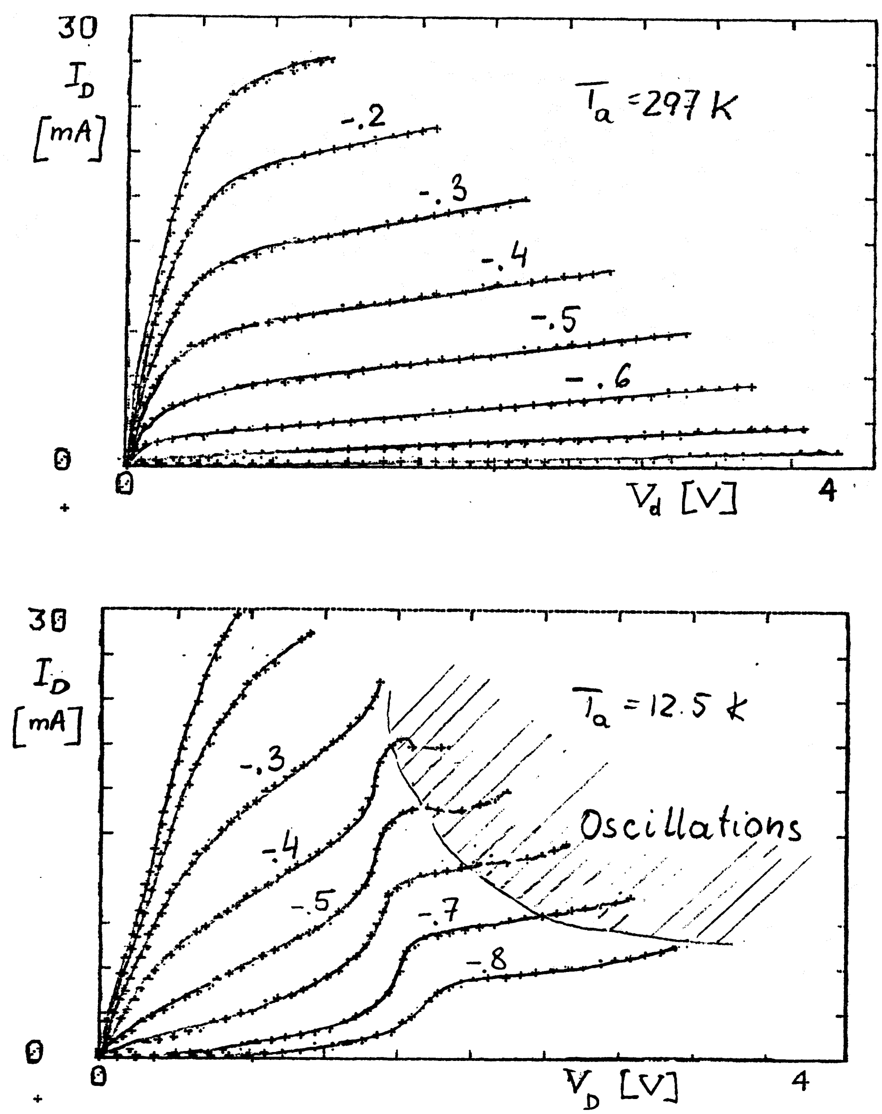

Fig. 7. The drain characteristics of NE71083 (32-4) FET at 297K and 12.5K.

F. FSC10FA (Fujitsu)

The FSC10FA FET has been designed for low-noise C-band applications and is specified as ~ .5 μm gate length and 400 μm gate width device with .6 dB (43K) and 1.6 dB (129K) noise figure at 4 GHz and 8 GHz, respectively [13]. The X-band performance is very closely confirmed by our measurements. The typical d.c. and X-band noise data for the FSC10FA transistor from lot #PT-04 are given in Table IV and Figures 8 and 9. Very good repeatability of the noise temperature for the transistor from a given lot was observed. Relatively large variations in cryogenic minimum noise temperature, 15 to 24K, were found for transistors from different lots. These variations can be linked to the quality of the interface between the buffer layer and the active layer, as it was demonstrated for NE75083 transistors. It is interesting to notice that the d.c. characteristics of NE75083 (lot #4Y13) and those of FSC10FA (lot #PT04) reveal the same qualitative behavior at cryogenic temperatures.

TABLE IV. Noise parameters of FSC10FA (PT-04) FET at the frequency f ≃ 8.4 GHz.

T_a = 297K

I_{ds} mA	V_{ds} V	T_{min} K	R_{gopt} Ω	X_{gopt} Ω	g_n mS	Ass. Gain dB
5	2.5	134	8.6	33.6	16.9	6.5
10	2.5	125	10.7	33.2	12.8	7.3
15	2.5	127	11.8	32.9	12.0	7.8

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
5	2.5	20.3	2.3	32.6	8.8	7.7
10	2.5	20.5	3.6	32.4	6.6	8.9
15	2.5	21.2	4.4	32.1	7.2	10.0

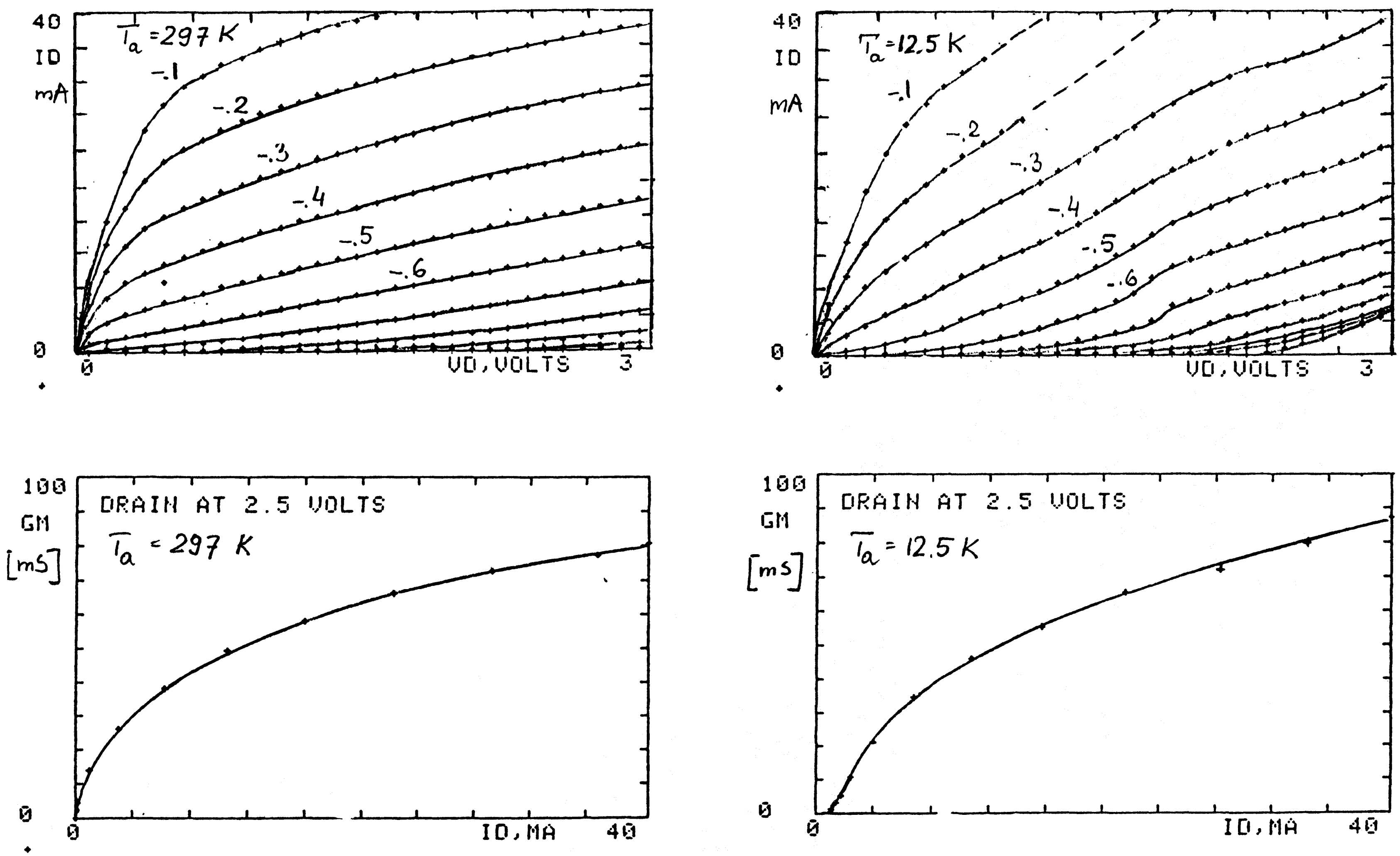

Fig. 8. Typical d.c. characteristics of FSC10FA (PT-04) FET at 297K and 12.5K.

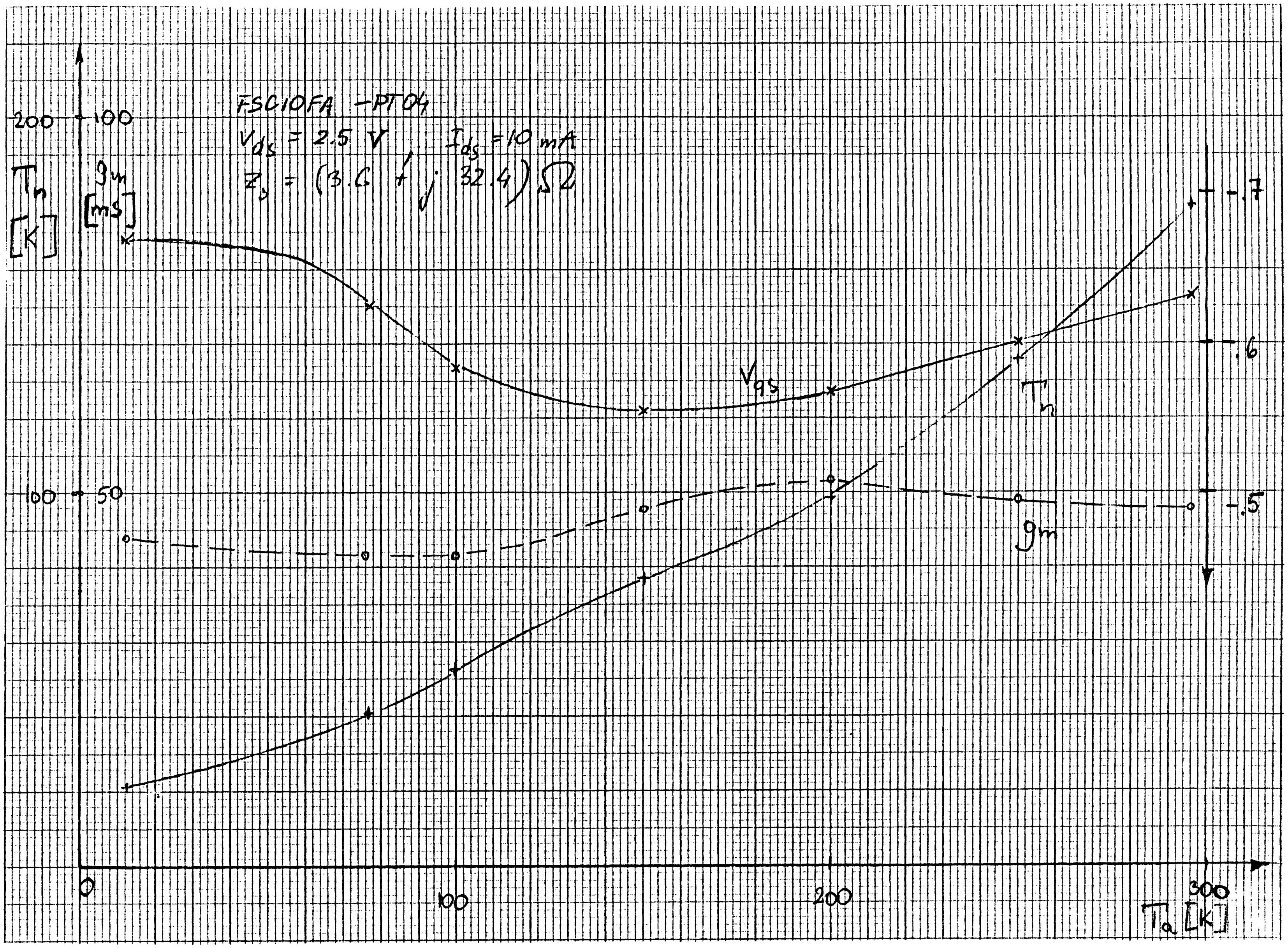

Fig. 9. The cooling curves for the 8.4 GHz, single-stage FSC10FA amplifier with the source impedance optimal for cryogenic noise performance.

G. <u>2SK575 (Sony)</u>

The 2SK575 is recommended by the manufacturer for 12 GHz low noise applications and has typical noise figure 1.4 dB (110K) at 12 GHz [14]. Our measurement on sample transistor from lot #YY925 yielded $T_{min} \cong 85K$ at 8.5 GHz, which closely confirms manufacturer's data. In fact, it was the second best room temperature FET tested during this work (80K was measured for NE04583). However, the cryogenic testing of the sample FET yielded only $T_{min} = 23K$. The d.c. characteristics of this FET, which are shown in Figure 10, revealed poor pinch-off and g_m compression at 12.5K. This observation agrees with those previously made for NE75083 and FSC10FA transistors concerning the importance of the quality of buffer-active layer interface for cryogenic performance. It is possible that the devices from other lots would have performed much better at the cryogenic temperatures.

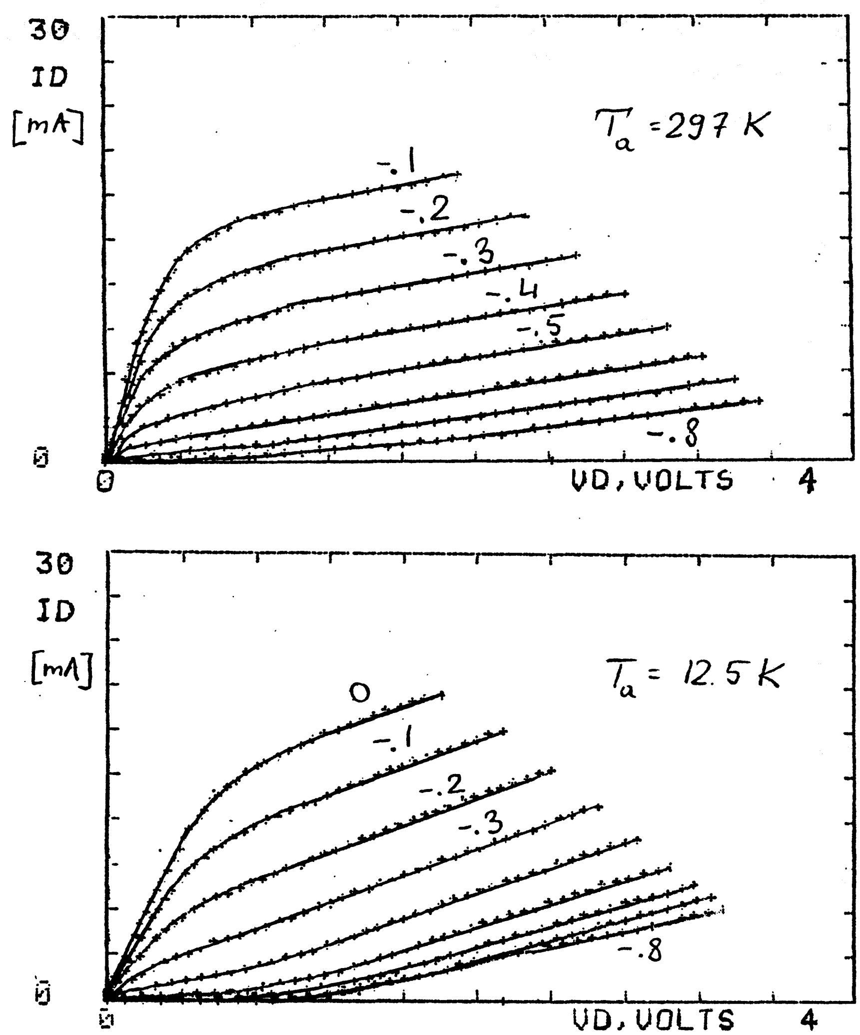

Fig. 10. The drain characteristic of the 2SK575 (YY925) FET at 297K and 12.5K.

H. H-503-P70 (Gould)

The H-503 transistor is the first commercially-available high electron mobility transistor [15]. It has .5 μm gate length, 280 μm gate width and the room temperature noise figure of .4 dB (30K) and .8 (59K) at 4 GHz and 8 GHz, respectively. Our room temperature measurement on two samples from lot #R07A taken at 8.4 GHz gave T_{min} = 95K, which is considerably more than the manufacturer's claim. The minimum noise temperature at 12.5K was T_{min} = 25K which is more than typical FET. The HEMT had to be illuminated to remain time invariant, memory-less device at the cryogenic temperatures. The drain characteristics, g_m (I_{ds}) characteristics and $T_n = f(T_a)$ characteristics of a single-stage amplifier for the H503 HEMT are shown in Figures 11, 12 and 13, respectively. The following phenomena, peculiar to HEMT's and attributed to the existence of traps in the doped AlGaAs layer [16], were also observed in this HEMT:

- the presence of a "camel-hump" on the $T_n = f(T_a)$ characteristic around T_a = 175K, and
- the distinctive change in the slope of I-V characteristics in the saturation region around T_a = 175K.

The Gould HEMT also shows a presence of a shunting current gradually increasing upon cooling. The same effect was observed in this laboratory for other HEMT's having high doping of the AlGaAs layer (2 x 10^{18} cm^{-3}). In short, the H503-HEMT shows all the ills of cryogenically cooled HEMT's but none of the possible virtues.

III. Discussion and Comparison with HEMT's

The summary of X-band performance of different FET's, which could be used for cryogenic applications, is presented in Table V, while a more detailed comparison of best GaAs FET's is given in Table VI. The data are self-explanatory, though the following comments could be useful.

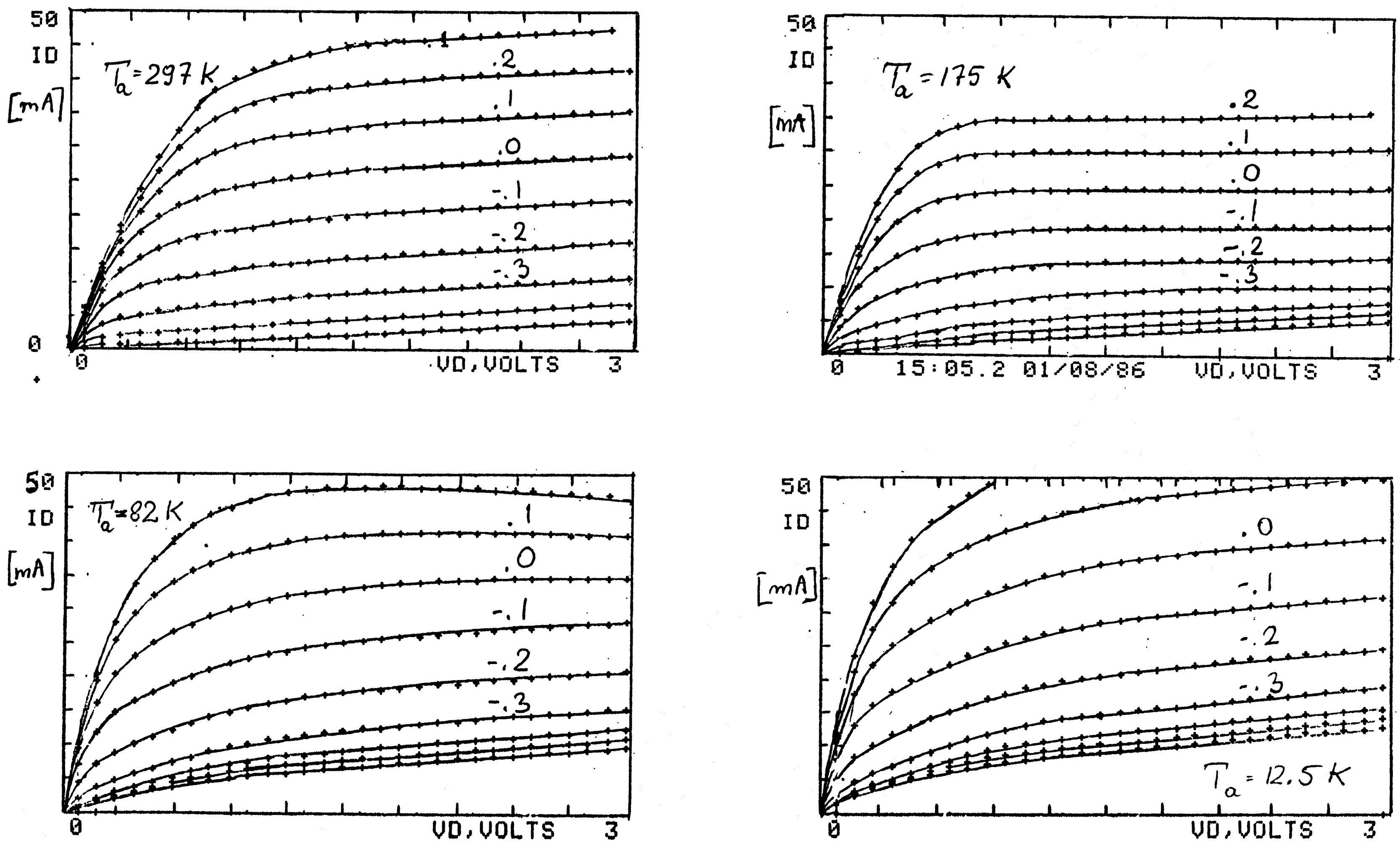

Fig. 11. Typical drain characteristic of the H503-P70 (R07A) HEMT at 297K, 175K, 82K and 12.5K.

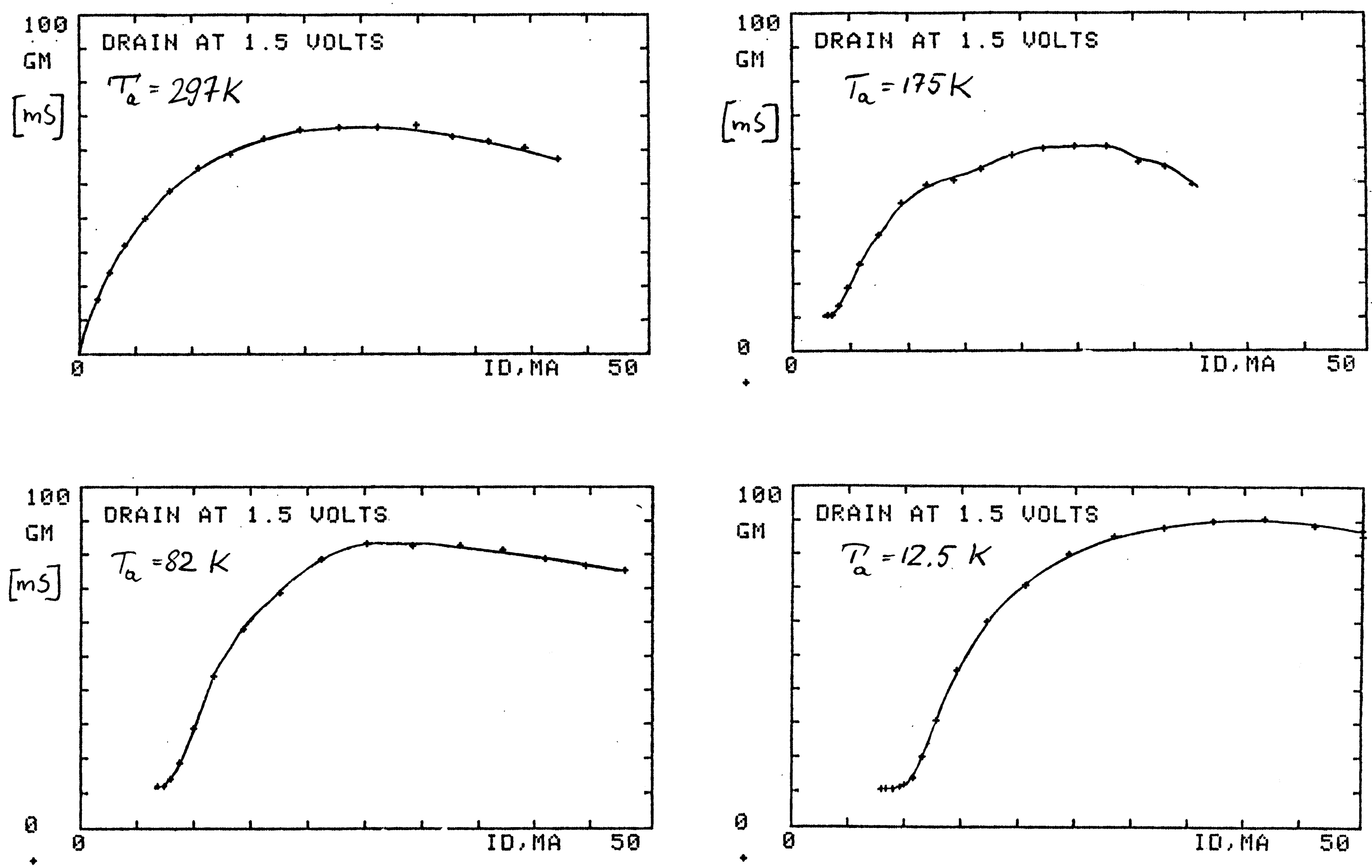

Fig. 12. Typical g_m (I_d) characteristic of the H503-P70 (R07A) HEMT at 297K, 175K, 82K and 12.5K.

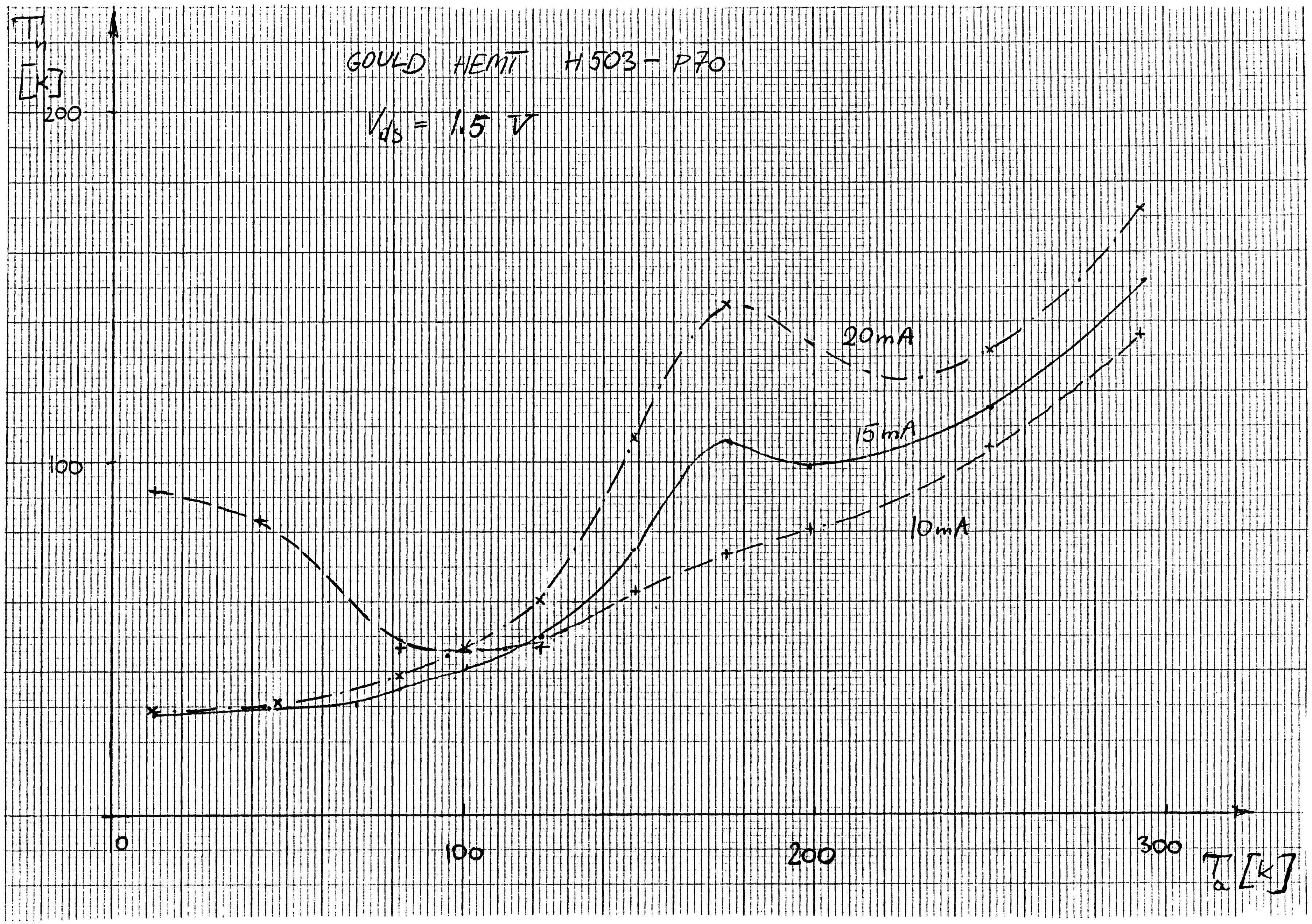

Fig. 13. The cooling curves for the 8.4 GHz, single-stage H503-P70 amplifier with the source impedance optimal for cryogenic noise performance.

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.

For most of the transistors, 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 the increase in transconductance as large as 50 percent of room temperature value was observed, which is about the same as for good cryogenic HEMT's (30 to 60 percent increase [16], [17]).

Theoretical studies [18], [19], [20] predict linear dependence of the minimum noise temprature on the gate length, even for submicron gate devices [19], [20]. In this light, comparison of the gate dimensions (published by the manufacturer) with the noise performance of the best FET's (Table VI) 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.

Finally, it is very instructive to compare the measured performance of FET's with those of HEMT's. Experimental GE HEMT's with .25 μm gate length and 300 μm gate with were chosen for comparison [16], [21], [22]. The comparison of best FET's and best HEMT's measurements in our lab is given in Table VII and VIII for room and cryogenic temperatures, respectively. The results of d.c. measurements for sample HEMT at different temperatures are given in Figures 14 and 15. The cooling curves of a single-stage amplifier with the same HEMT are given in Figure

16. These data allow direct comparison with commercial devices described in Section II.

The best HEMT's exhibit the minimum noise temperature about twice as small as best FET's, both at room and cryogenic temperatures. Also, the noise parameter, N, invariant under lossless transformation of the input and to a first approximation independent of gate width, is about two times smaller for HEMT's than for FET's. This makes the noise temperature of HEMT amplifiers much less sensitive to the input mismatch. The value of the optimum source resistance is usually larger for HEMT's than for FET's, but it can be greatly altered by the device and/or package parasitics. This is demonstrated by the noise parameters of two HEMT's from the same wafer, but differently processed, given in Table VIII. Though the values of the optimum source impedance are very different for these two samples, the values of T_{min} and N are very similar.

IV. Summary

The X-band noise performance and d.c. characteristics at room and cryogenic temperatures for a number of commercially-available FET's have been examined and compared with best experimental HEMT's. No theory is at present available to explain cryogenic performance of both FET's and HEMT's. However, based on experimental evidence several conclusions may be reached.

The noise performance and d.c. characteristic of cryogenic FET's and HEMT's may not be predicted from room temperature data. In fact, in some FET's there exists an instability of unknown nature rendering the device useless for cryogenic applications. The good cryogenic noise performance of FET's and HEMT's may be expected from the devices showing sharp pinch-off characteristic at cryogenic temperatures. The typical minimum noise temperature of cryogenic FET's at $f \approx 8.4$ GHz is 20K, although single devices have demonstrated great potential for

TABLE V. Summary of noise performance of GaAs FET's at 8.4 GHz and 12.5K.

TYPE	T_{min} [K] TYPICAL	RANGE OF T_{min} [K] MIN	RANGE OF T_{min} [K] MAX	ASSOC. GAIN [dB] TYPICAL	NUMBER OF DEVS. TESTED	COMMENTS
MGF1412	20	18	26	12	9	
FSC10FA	20	15	24	9	8	
NE 75083	20	15	23	11	8	PRODUCTION HAS BEEN DISCONTINUED
NE 04583	20	?	?	11	2	PRONE TO OSCILLATIONS
NE 67383	24	22	25	11	3	
NE 71083	24	?	?	11	1	PRONE TO OSCILLATIONS
2SK575	23	?	?	11	1	
GE-HEMT WAFER #54	9	7.5	13	14.5	11	RESULTS FOR GOOD PINCH-OFF DEVICES

TABLE VI. Noise performance comparison of best GaAs FET's at 8.4 GHz and 12.5K.

TYPE	GATE		BIAS		NOISE PARAMETERS OF SAMPLE FET				RANGE OF T_{min} [K]		ASSOC. GAIN
	L μm	W μm	V_{ds} V	I_{ds} mA	T_{min} K	R_{opt} Ω	X_{opt} Ω	g_m mS	MIN	MAX	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

* NE 75083 PRODUCTION HAS BEEN DISCONTINUED

TABLE VII. Comparison of noise parameters of sample FET and HEMT at T_a = 297K and f = 8.4 GHz.

DEVICE	I_{ds}	V_{ds}	T_{min}	R_{opt}	X_{opt}	g_n	G_{AS}	$4NT_o$
	mA	V	K	Ω	Ω	mS	dB	K
GE-HEMT, #546 .25μm, 300μm	15	1.5	43	8.7	44	5.6	12.9	57
NE04583, G01-10 .3 μm, 200μm	5	3	80	6.5	42	14.6	8.6	110

TABLE VIII. Comparison of noise parameters of sample FET's and HEMT's at T_a = 12.5K and f = 8.4 GHz.

DEVICE	I_{ds}	V_{ds}	T_{min}	R_{opt}	X_{opt}	g_n	G_{AS}	$4NT_o$
	mA	V	K	Ω	Ω	mS	dB	K
GE-HEMT, #54 .25μm, 300μm	5	1.5	8.4	7.2	46	1.4	13.5	11.7
GE-HEMT, #546 .25μm, 300μm	5	1.5	7.4	2.5	41	3.2	14.6	9.3
NE75083, 72A .3μm, 300μm	5	3	14.2	3.2	32.5	6.1	9.0	22.6
MGF 1412, 3YAK8 .7μm, 400μm	5	4.5	20	5.1	41	4.7	11.3	27.8

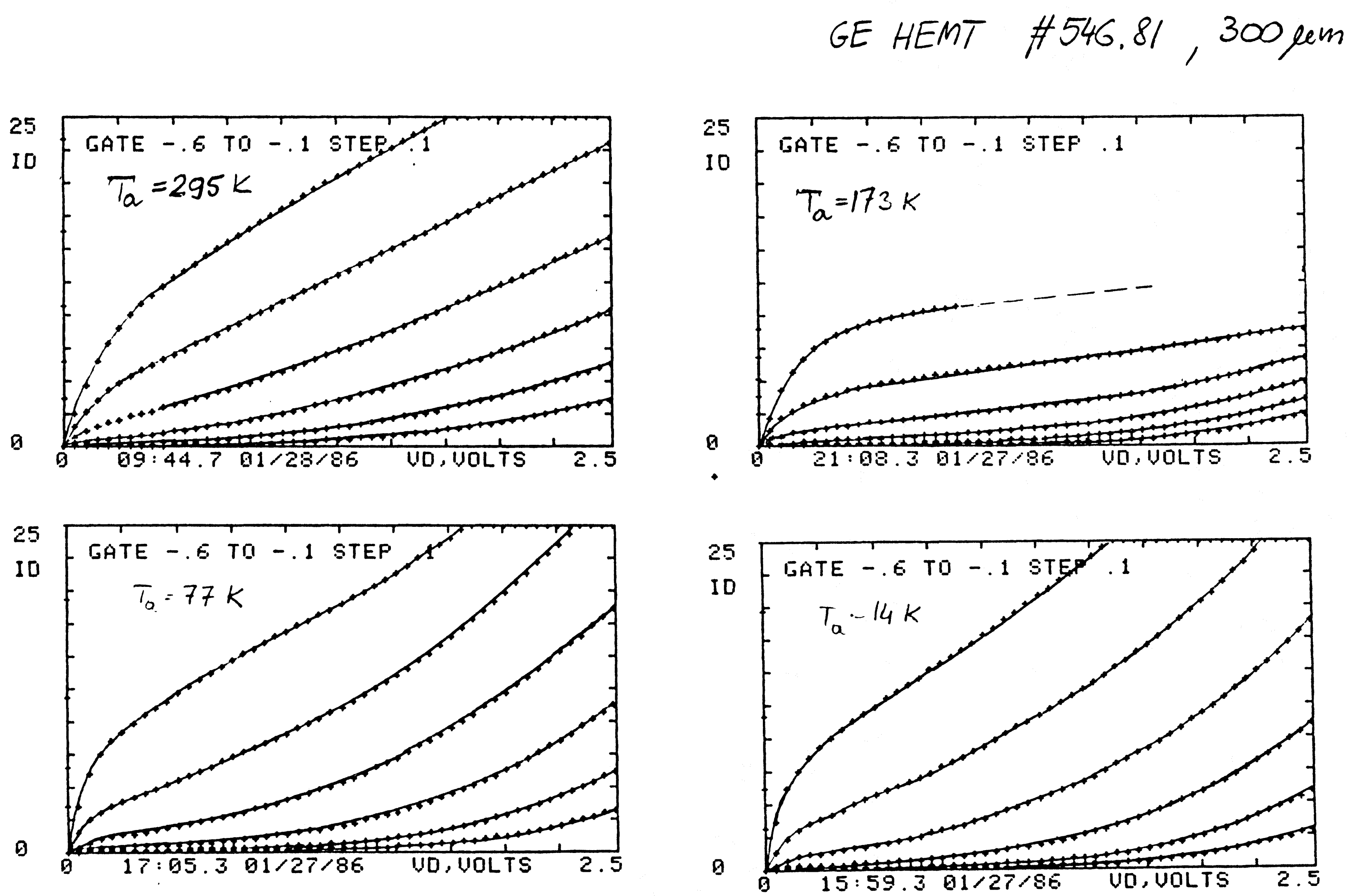

Fig. 14. The I-V characteristics of GE experimental HEMT, illuminated with red light, at different ambient temperatures.

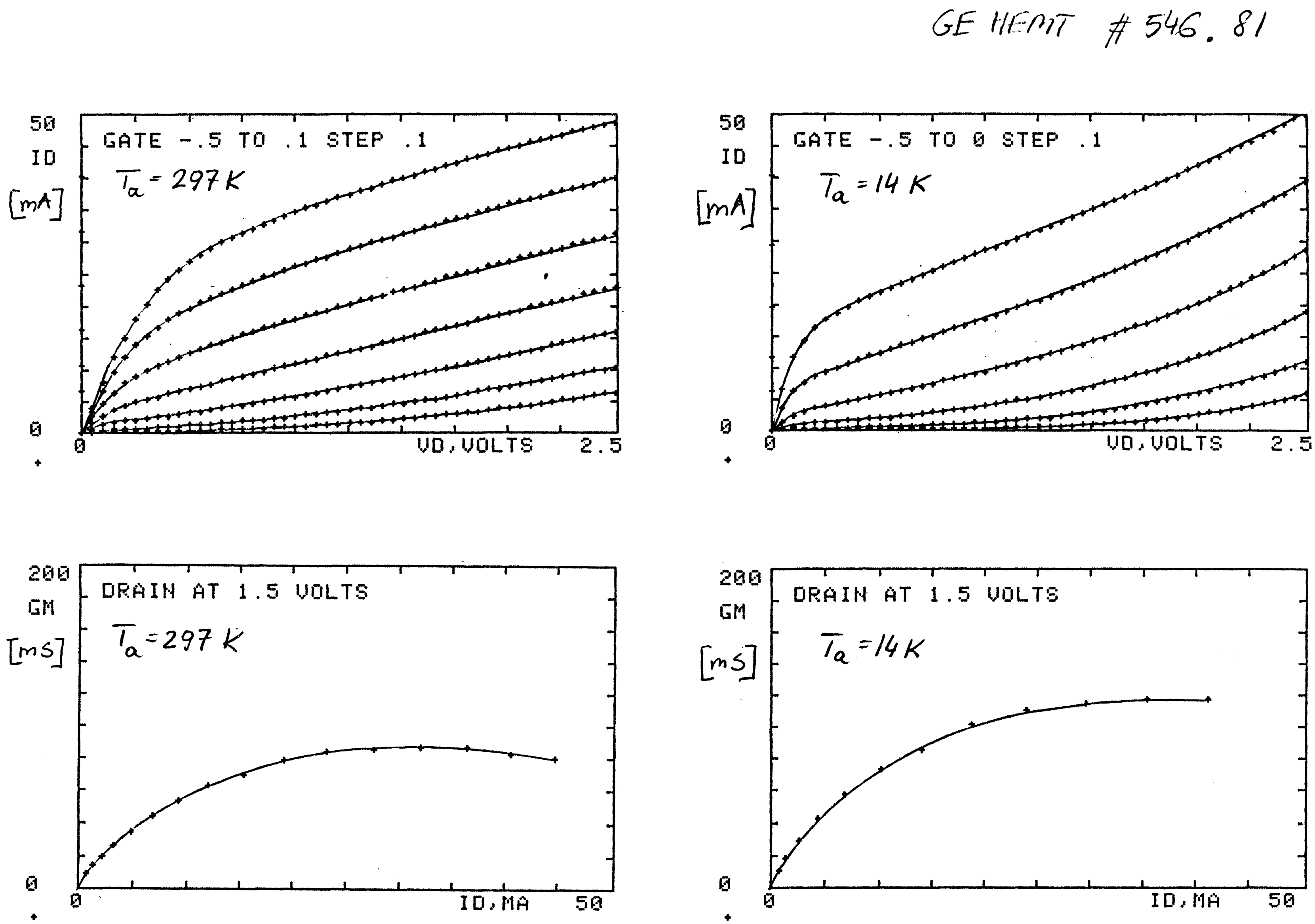

Fig. 15. The I-V characteristic and g_m (I_{ds}) characteristic for GE HEMT, illuminated with red light, at 297K and 14K.

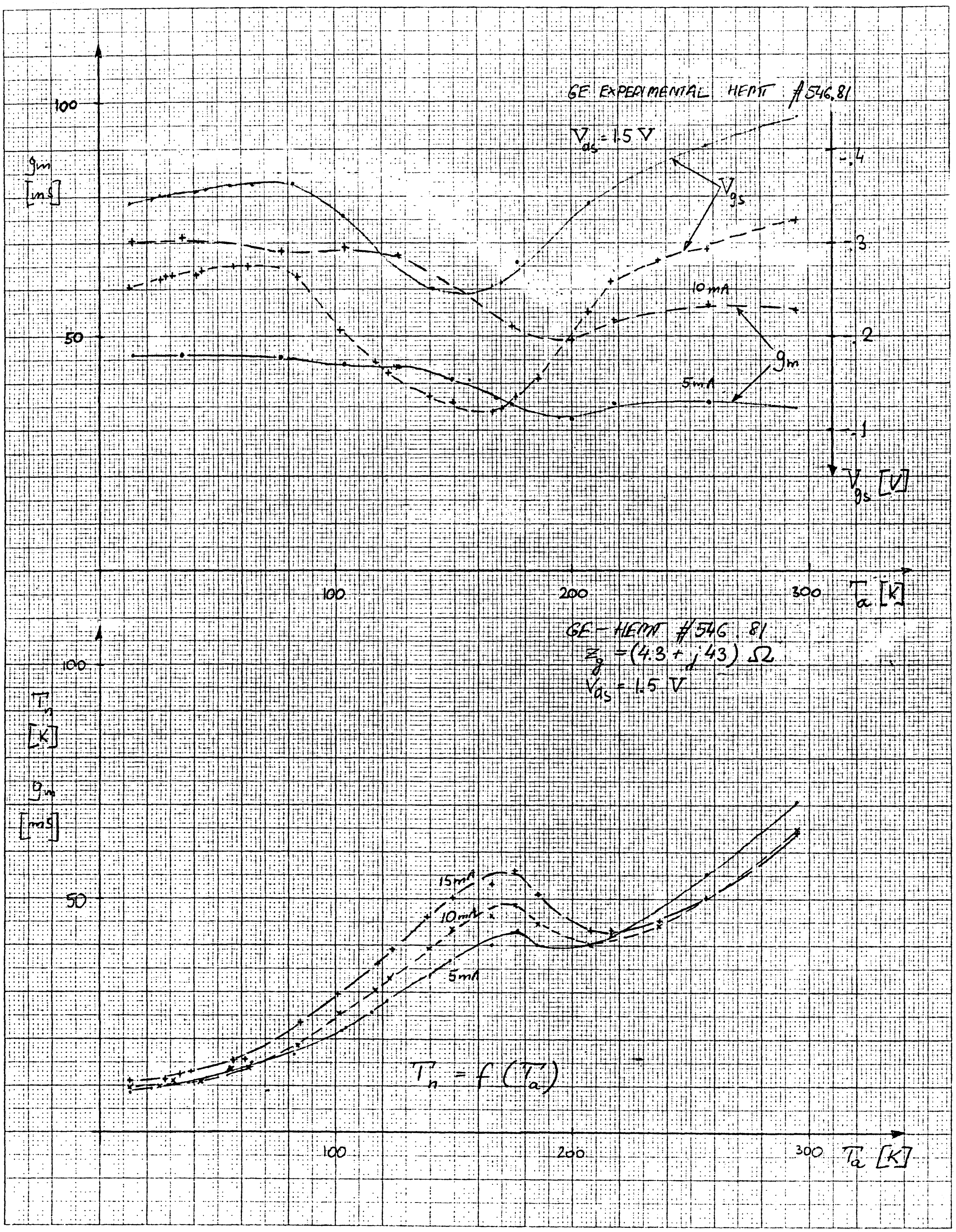

Fig. 16. The cooling curves for 8.4 GHz, single-stage GE HEMT amplifier with the source impedance optimal for cryogenic noise performance.

improvement; $T_{min} \cong 14K$ has been measured for some devices. In any case, the HEMT's offer an improvement by at least the factor of two over FET's in X-band cryogenic noise performance. Not all HEMT's, however, operate properly at cryogenic temperatures and, if they do, have good noise performance.

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