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EVALUATION OF GaAs FETs FOR CRYOGENIC READOUT

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Abstract

Low-frequency, low-noise, low-power cryogenic electronics to read out photodetectors is being investigated for the star-tracking telescope of the Gravity Probe B spacecraft. We report our initial findings from evaluating more than 20 types of GaAs FETs, both commercial and non-commercial, for this application. Most exhibit useable dc characteristics at cryogenic temperatures, although gate leakage and hysteretic effects (presumably due to charge trapping) could be troublesome. Low-frequency noise (based primarily on grounded-gate measurements) at 4 K is "1/f-like", and for the quietest GaAs FETs appears to be at least as low as the lowest noise values reported for Si MOSFETs at 4 K. Further investigation is needed in several areas.

1. INTRODUCTION

We are investigating cryogenic readout electronics for the Gravity Probe B experiment, which will test relativity theory by measuring minute precessions of gyroscopes in a spacecraft orbiting the Earth.[1-5] The heart of this spacecraft is an assembly comprising the precision superconducting gyroscopes and a star-tracking telescope, all cooled to approximately 2 K. The telescope will provide an extremely precise reference direction for determining the gyroscope precessions.

One readout approach being investigated for the telescope is based on visible-range semiconductor photodetectors operating in the 2 K environment. As is common practice, we wish to co-locate electronics with the photodetectors in the cryogenic environment for buffer preamplification, signal sampling, and possibly mutiplexing.

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2. DEVICE REQUIREMENTS & OPTIONS

Requirements

An essential component of such cryogenic electronics for detector readout or similar applications is a suitable active device. Desirable characteristics of such a device include

(1) ability to operate (as an amplifier or switch) at cryogenic temperatures (for this application liquid-helium temperatures),

(2) ability to operate with low power dissipation,

(3) very low noise at low frequencies (down to 1 Hz),

(4) high input impedance (high R, low C),

(5) electrical stability and freedom from anomalies, and

(6) reasonable availability and cost.

Long-term stability is particularly important for Gravity Probe B, because of the need to maintain a precise reference direction over a ≈1 year mission,

Options

Based on the work of previous investigators, we have considered four classes of semiconductor devices which could meet the above requirements to varying degrees:

(1) The **Si JFET** has been used extensively for detector preamplification; it exhibits the lowest noise and stable operation at cryogenic temperatures, but is useable only down to about 30 K (Si freezout temperature). Si JFETs have been used with detectors operating below 30 K by thermally isolating the JFET and operating it at a higher temperature (say 60 K), as in the Infrared Astronomical Satellite (IRAS)[6]; however, this entails mechanical and thermal complications.

(2) The **Si MOSFET** has been used extensively at liquid-helium temperatures, primarily for readout of large detector arrays.[7] Fabrication technology for conventional Si MOSFETs is well developed and many types of commercial devices are available; however, when these are operated at temperatures below Si freezout they frequently exhibit high noise levels and other anomalies.[8-11] These drawbacks may be overcome with specially designed and fabricated Si MOSFETs,[7] but their availability is limited.

(3) The **Ge JFET** was used in the past, and gave good results at liquid-helium temperatures. However, results are reported for a single device type, whose manufacture was discontinued about 20 years ago.[12] At present there is no established manufacturing base for Ge FETs.

(4) The **GaAs MESFET** has been used at liquid-helium temperatures with good results, particularly for higher-frequency applications (>~100 Mhz).[13] There is an established fabrication technology, and commercial devices and foundries are available, although less so than for Si. Noise appears to be low, although information relevant to our application is scarce, and much of it applies to devices which are no longer available.

Considering these four alternatives, and the particular requirements of Gravity Probe B, we decided to investigate two device classes: Si MOSFETs, which represent a relatively established approach; and GaAs MESFETs, as a promising but relatively unexplored approach. Two GaAs JFETs were also measured. Our preliminary findings concerning GaAs FETs are presented in this paper, although this initial evaluation leaves many issues unresolved.

3. GaAs FETs

The aim of this initial survey of GaAs FETs was to obtain a general idea of basic functionality and low-frequency noise----in particular at low power (~10 μW) and liquid-helium temperatures----for available devices and foundry processes. As a rapid means of getting started, we obtained a number of "off-the-shelf" commercial GaAs FETs, and test devices that had been made by GaAs integrated-circuit fabricators.

All GaAs FETs considered in this paper are MESFETs except for two JFETs from Aerojet; all are n-channel, depletion-mode. We do not consider enhancement-mode GaAs MESFETs to be good candidates for photodetector readout because of the high gate current associated with forward biasing the Schottky diode.

Commercial FETs

Although there are many microwave GaAs MESFETs available commercially, with gate length about 1 μm and less, we concentrated on relatively long gate, low-frequency types (dual-gate UHF MESFETs). Theory, and experience of previous investigators,[14-16] indicate that longer-gate GaAs FETs exhibit lower noise at low frequencies.

The commercial FETs that we investigated are listed in Table Ia. All except two of these are dual gate; for all measurements reported here on dual-gate FETs the two gates were connected together to simulate a longer gate as suggested by previous investigators,[15-17] and the devices were then measured as if they were single-gate.

"Foundry" FETs

We obtained GaAs test chips (used for process control) and custom FETs from three fabricators, and also custom GaAs MESFETs made through MOSIS for another project,[b] as listed in Table Ib. These GaAs FETs, referred to as "foundry" FETs in this paper, were all single gate, with gate lengths ranging from 1 μm to 88 μm.

4. EXPERIMENTAL EVALUATION

We have made dc measurements at 300 K, 77 K and 4 K; and noise measurements at 300 K and 4 K. The cold measurements were made by direct immersion of the FET into liquid nitrogen or liquid helium. For the foundry MESFETs, the GaAs die were directly exposed to the liquid cryogen; when measuring such exposed devices, light was excluded.

During all our measurements we found no device failures or changes that could be attributed to temperature cycling. This is in accord with previously reported experience with many types of transistors and integrated circuits cycled to cryogenic temperatures. Thus, these GaAs FETs appear sufficiently mechanically robust for cryogenic use.

Most of the GaAs FETs we have evaluated are capable of operating to hundreds of MHz or higher. Consequently they are susceptible to unwanted radio-frequency oscillation in the presence of minute amounts of stray inductance and capacitance in low-frequency circuits; furthermore, this tendency to oscillate can be aggravated by cooling. As a preventive measure, miniature chip resistors were usually connected in series with the FET terminals for both dc and noise measurements.

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[b] MOSIS is a "multi-project" semiconductor fabrication service. These particular GaAs MESFETs were also made by Vitesse; for details, see F. S. Shoucair "High-Temperature Electrical Characteristics of GaAs MESFETs (25°C-400°C)" to appear in *IEEE Trans. on Electron Devices*, 1992.

Table Ia - Commercial GaAs MESFETs Evaluated

Manufacturer	Type	Gate[a] dimensions L_{G1}/L_{G2} x W (μm)	Package[b]	Number measured	
				DC	Noise
Motorola	MRF966	1.2/1.6 x 470	Macro-X, 317-01	1	0
NEC, JA	NE25137-D	1/1 x 400	Micro-X	1	1
	3SK177-U71	" "	SOT-143	1	1
	NE25337-D	1/1 x 800	Micro-X	1	1
	3SK206-U79/U78	" "	SOT-143	1/1	1/1
	NE72084-D	S: 1 x 400	Micro-X, ceramic	1	1
Plessey	P35-1101-1	S: 4 x 300	TO-18, metal	2	1
Sanyo	3SK189-4	1.5/2.5 x 400	SOT-143	1	1
Siemens	CF739		SOT-143	1	1
Sony	3SK164	4[c] x 600	SOT-143	2	1
	3SK165	4[c] x 300	SOT-143	1	1
	3SK166	4[c] x 1200	SOT-143	1	1
	SGM2004M	4[c] x 400	SOT-143	3	1
	SGM2006M	4[c] x 600	SOT-143	1	1
Telefunken	CF300B		Macro-X	2	1
	CF930C		SOT-143	1	0

[a] All are dual gate except as noted by S; widths of gate 1 and gate 2 are the same.
[b] All packages are plastic except as noted.
[c] Estimate for $L_{G1} + L_{G2}$, actual lengths not available.

Table Ib - "Foundry" GaAs JFETs and MESFETs Evaluated

Manufacturer	Description	Gate dimensions L x W (μm)	Number measured	
			DC	Noise
Aerojet	Custom JFETs	48, 88 x 200	0	2
Microwave Technology	"Fat" MESFETs	60 x 90	2	3
Vitesse/MOSIS	Custom MESFETs	2 - 16 x 50	3	15
Vitesse	Process control monitor MESFETs	1 - 3 x 10	3	3

5. DC CHARACTERISTICS

To determine basic functionality at cryogenic temperatures, three types of measurements were made of dc characteristics: (1) conductance, (2) transconductance, and (3) gate current. All measurements were made with a Hewlett Packard 4145B Semiconductor Parameter Analyzer. For these measurements we kept the drain-source voltage, V_{ds}, below 1 V----to avoid high-field effects and anomalies, because we are interested in operating at low power, and in expectation of lower noise.

Conductance

Figures 1 and 2 are typical examples of drain current, I_d, versus drain-source voltage, V_{ds}, with gate-source voltage, V_{gs}, as a parameter. These figures exhibit several effects typically observed at cryogenic temperatures for most of the commercial GaAs MESFETs: straightening of the curves, shift of gate threshold voltage, and slight turn-on "kink" at 4 K and low I_d. The foundry FETs generally exhibited excellent characteristics at 77 K and 4 K, as illustrated in Figure 3. Our findings are similar to previous observations of dc characteristics,[15,18-22] which demonstrate that GaAs MESFETs work well down to liquid-helium temperatures.

Many of the commercial GaAs MESFETs exhibited hysteresis, as shown in Figure 2, for example. The amount of hysteresis differed among the different FETs and could be present at 77 K, 4 K, or both temperatures (even at room temperature for a few FETs); there was a weak correlation between the amount of hysteresis at 77 K and 4 K. We could not attribute this hysteresis to simple heating effects, and presume that it is a manifestation of charge trapping. Another effect attributed to charge trapping is the recently reported cryogenic *collapse* phenomenon,[23] in which the I_d-vs-V_{ds} curves take on an "inverted" curvature, and shift with respect to V_{gs}. We observed this phenomenon, but have not studied it.

Transconductance

Figure 4 illustrates I_d versus V_{gs}, with V_{ds} as a parameter for the same two commercial FETs as in Figures 1 and 2 and the foundry FETs in Figure 3. At a given V_{ds} and I_d in our measurement range, for the commercial GaAs MESFETs transconductance could either increase or decrease slightly upon cooling; for the foundry FETs it usually increased slightly.

As Figures 4 illustrates, at low temperatures the curves shift towards higher V_{gs}, about half a volt. Such shifts with temperature can be influenced by several effects including charge trapping and an orientation-dependent piezoelectric effect.[24] We have made no attempt to interpret this shift because of the complexity of the underlying effects and lack of knowledge of the geometry and fabrication details for many of the FETs.

Gate current

Figure 5 shows typical results for gate current, I_g, versus voltage, V_g (source and drain connected), for the same GaAs MESFETs as in Figures 1-4. As shown, I_g depends strongly on gate bias, and decreases a couple of orders of magnitude at 77 K and 4 K compared to 300 K, as expected for reverse-biased diode leakage. At cryogenic temperatures and low gate bias the current drops below that measurable with this experimental arrangement (~10 pA), and another technique was used to estimate the gate current as described in the next section.

For many of the GaAs FETs measured, gate current may be too high for applications where extremely high input impedance is required, such as for photodetectors (one exception is the Plessey P35-1101, for which gate current at 77 K and 4 K and V_g to –4 V was below that measurable). Because of the strong dependence on gate bias, it is advantageous to use FETs that operate with a gate bias near zero.

Substrate effect/backgating

The packaging arrangement for the foundry FETs enabled a voltage to be applied to the substrate, and thus allowed observation of backgating. For a substrate-source voltage varied between –3 V and +3 V, we found the substrate effect at 4 K greatly reduced or absent relative to 300 K. This probably resulted from substrate freeze-out; however, since the FETs were attached with Ag epoxy it is also possible that this resulted from the epoxy becoming non-conductive at 4 K.

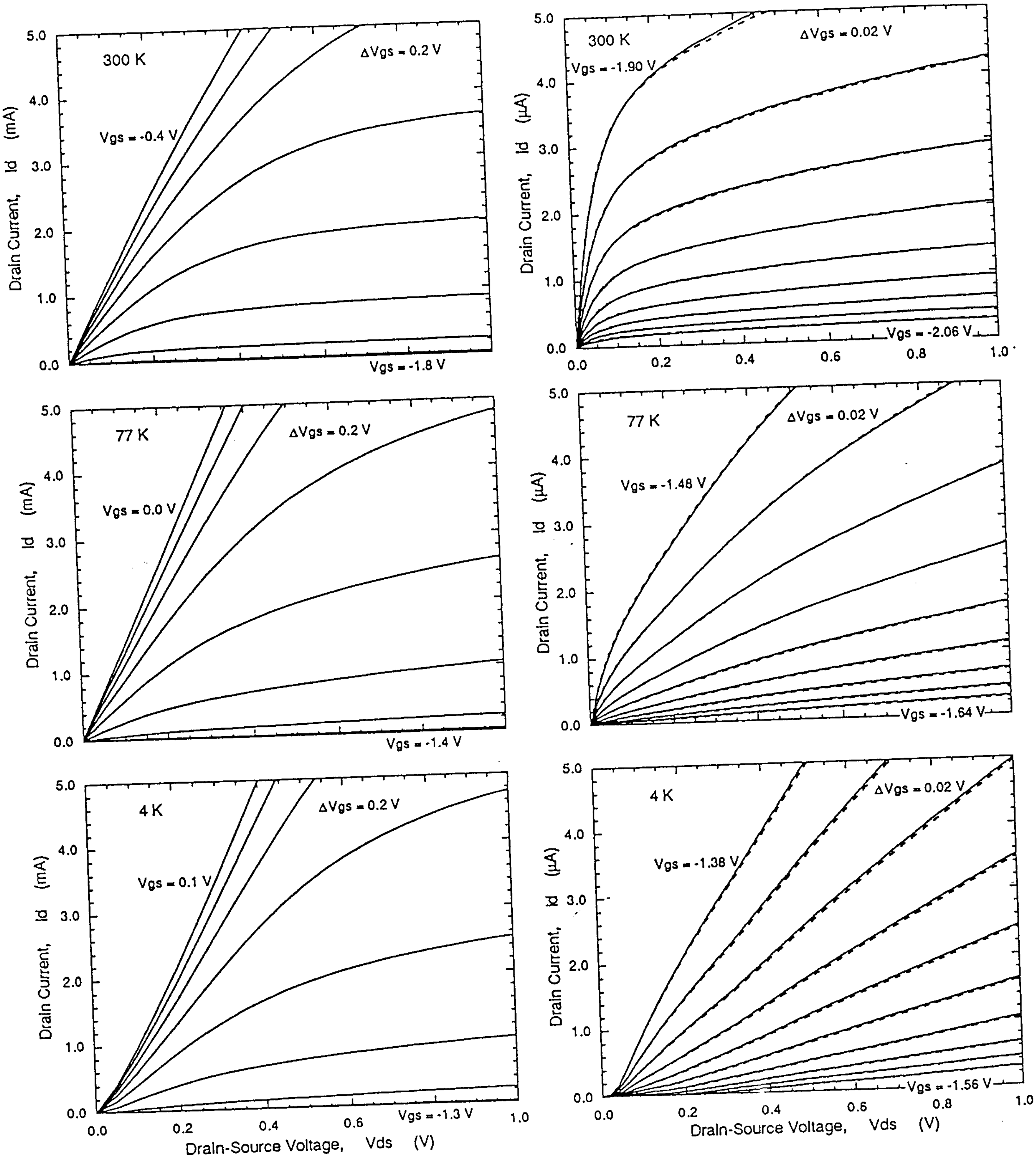

Figure 1 - Characteristics of a Sony SGM2004M GaAs MESFET. The solid curves are for forward sweep (V_{ds} and V_{gs} increasing) and the dashed curves are for reverse sweep (V_{ds} and V_{gs} decreasing). This device exhibits essentially no hysteresis.

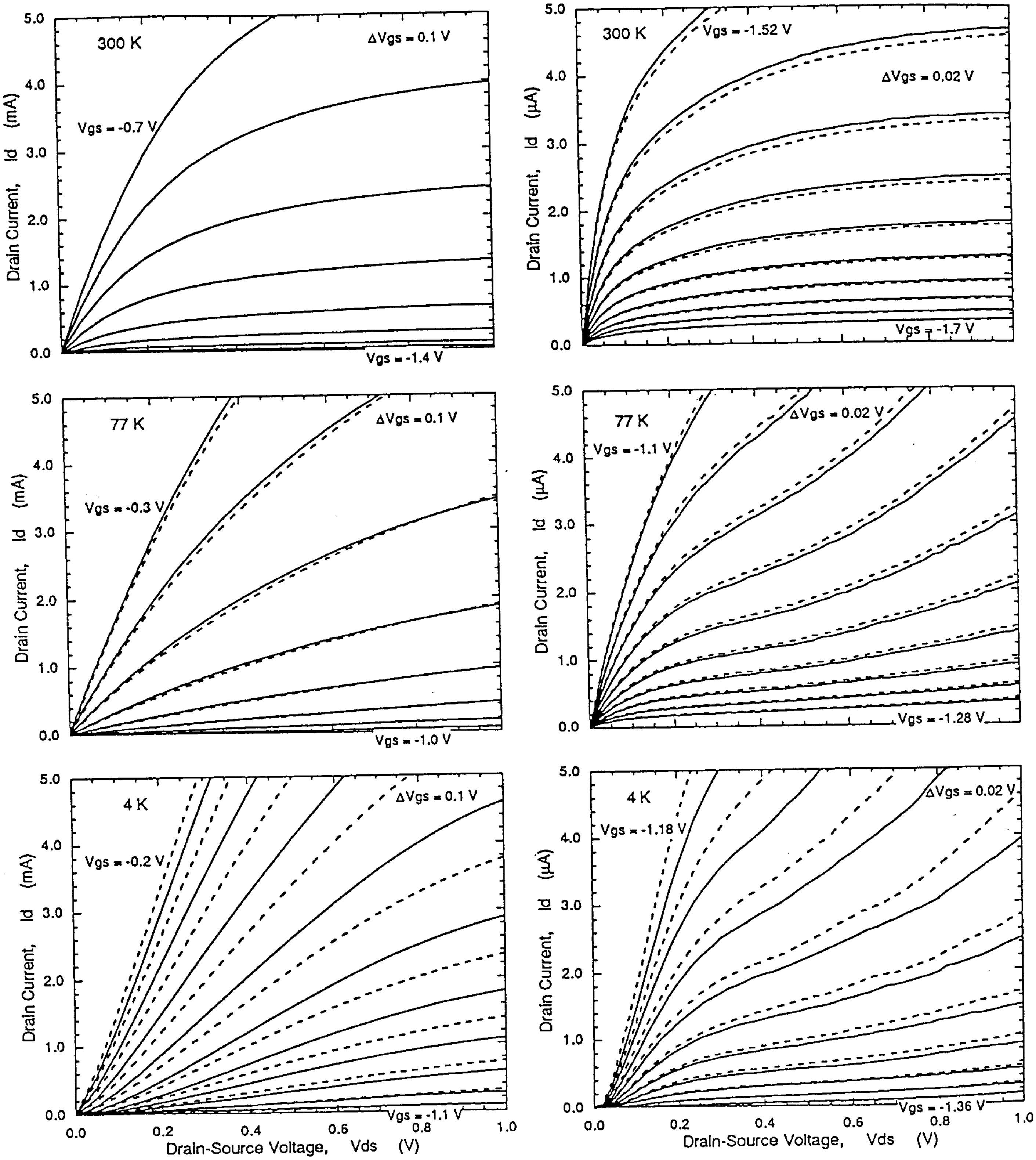

Figure 2 - Characteristics of an NEC 3SK206-U78 GaAs MESFET. This device exhibits substantial hysteresis at 4 K.

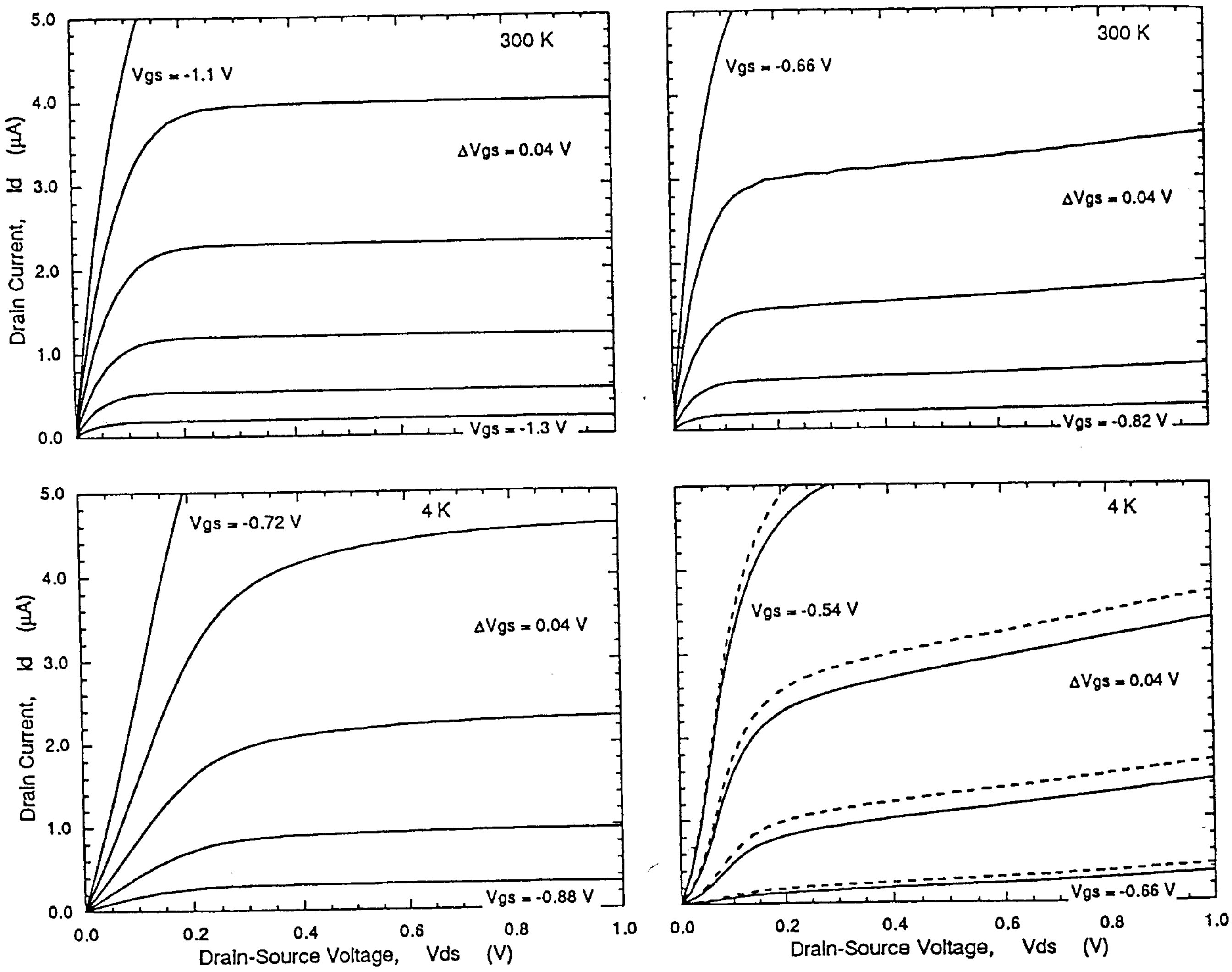

Figure 3 - Characteristics for two "foundry" GaAs MESFETs: Microwave Technology (left) and Vitesse/MOSIS, 16 µm gate length (right). The solid and dashed curves have the same meaning as in Figure 1.

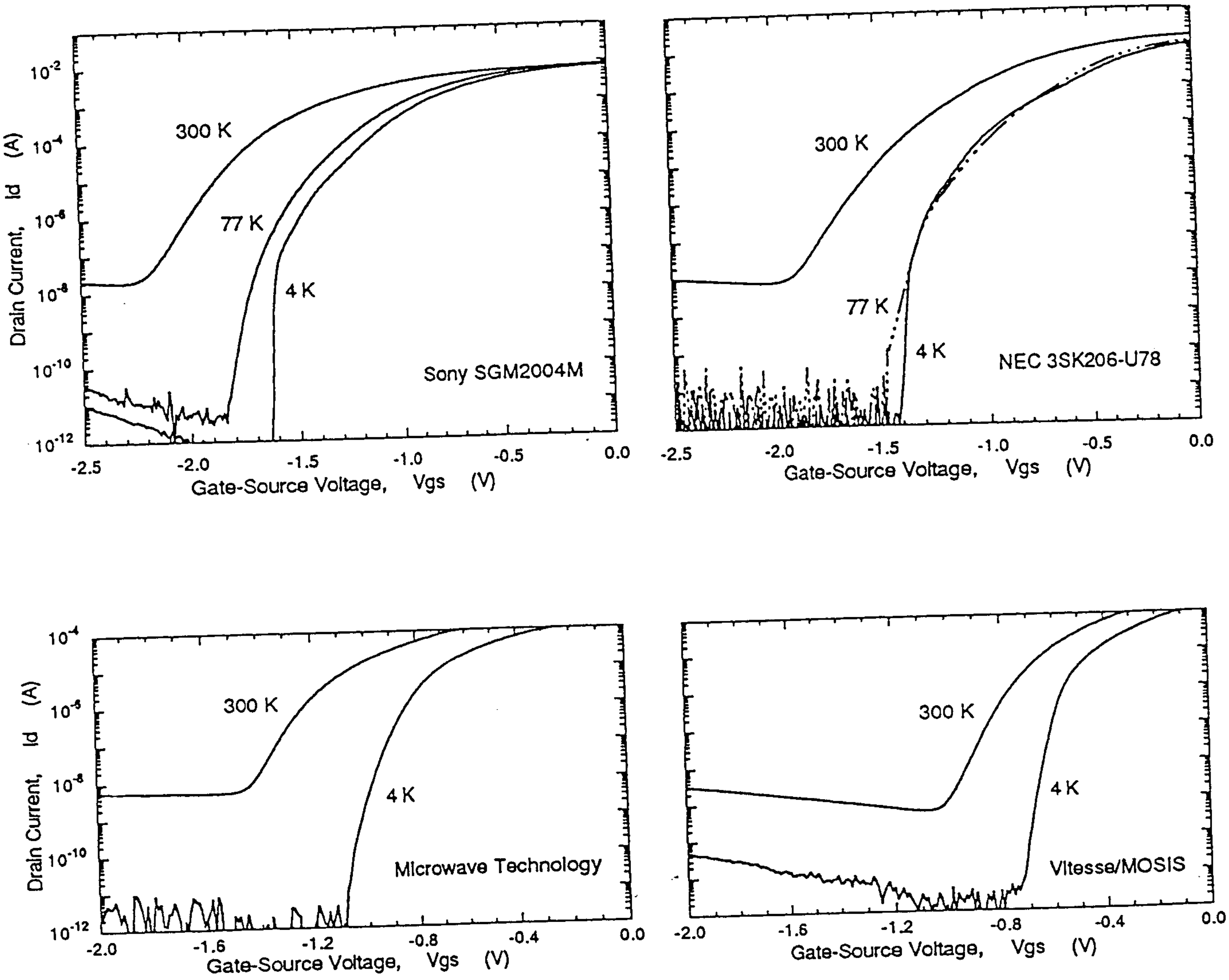

Figure 4 - Transconductance characteristics for the same two commercial GaAs MESFETs as in Figures 1 and 2 (top), and for the same two foundry GaAs MESFETs as in Figure 3 (bottom). For all curves $V_{ds} = 0.6$ V.

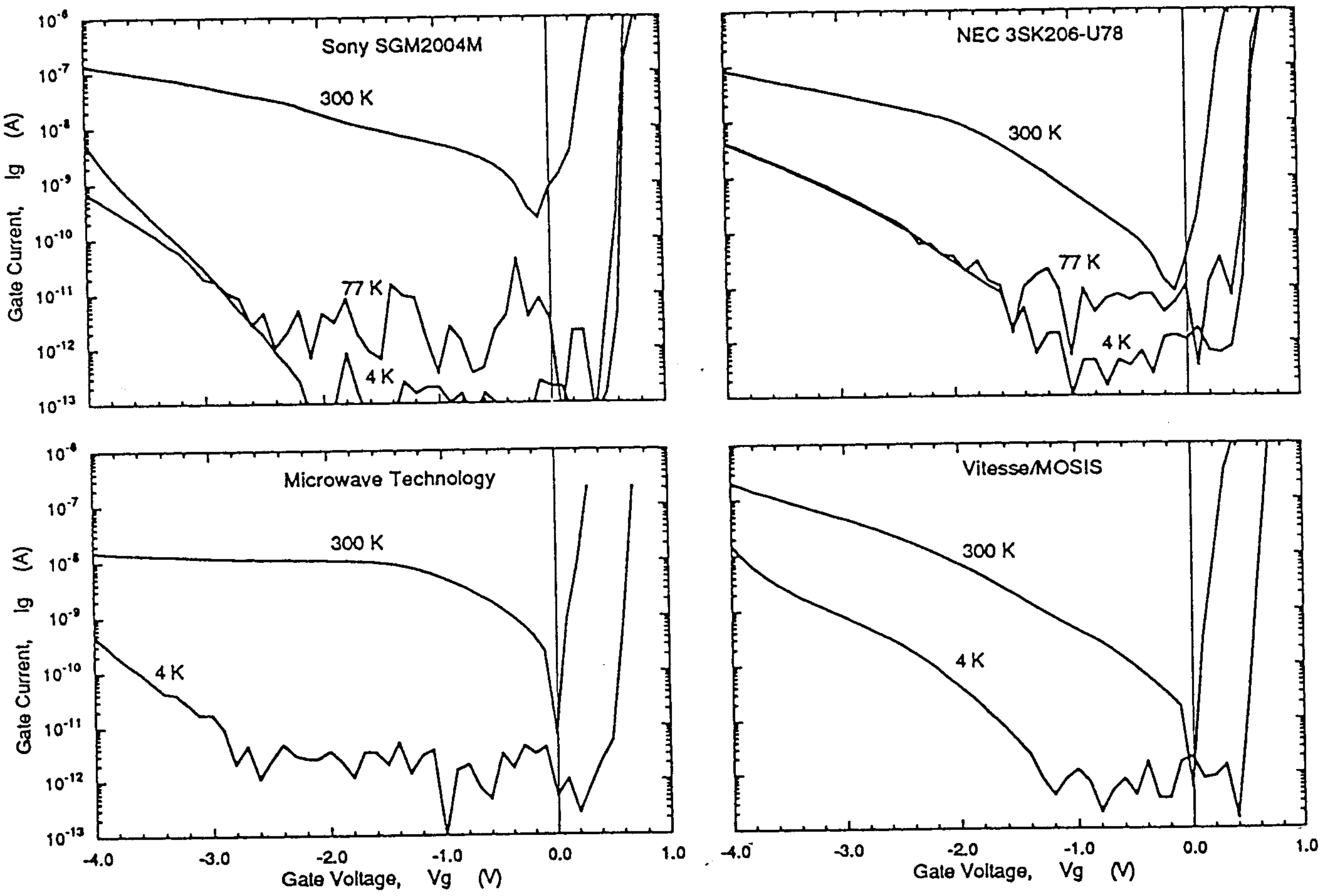

Figure 5 - Gate current as a function of gate-source/drain voltage (source and drain connected) for the same two commercial GaAs MESFETs as in Figures 1 and 2 (top), and for the same two foundry GaAs MESFETs as in Figure 3 (bottom). For all curves $V_{ds} = 0.6$ V.

6. LOW-FREQUENCY NOISE

Noise in a FET is commonly represented by two noise generators at the gate: a series noise voltage generator and a parallel noise current generator. For applications where the input device has a low impedance the noise current can be ignored. However, for our application the FET will be connected to a photodetector, which is expected to have very high resistance at cryogenic temperatures, so that in the relevant frequency range, ≈1 Hz to ≈10 kHz, the input impedance will be determined by the combined capacitance of the detector and FET preamplifier (~1 pF). In this situation both noise voltage and noise current need to be considered. We first made grounded-gate measurements to determine noise voltage and to guide selection of FETs for further measurements; this was followed by measurements of open-circuit (floating-gate) noise on two FETs.

Experimental Arrangement

Noise voltage for most of the GaAs FETs listed earlier has been measured at 300 K and 4 K, using a simple amplifier circuit (Figure 6) with the FET in a grounded-source configuration. A CMOS operational amplifier with a feedback resistor R_F acts as a transimpedance amplifier, maintaining V_{ds} at 0.6 V and driving the spectrum analyzer. The output is fed directly to a Hewlett Packard 35660A Dynamic Signal Analyzer. V_{gs} is adjusted so that the output dc level remains within a few tenths of a volt of zero, thus $I_d \approx (V_B - 0.6\ \mathrm{V})/R_F$. Noise measurements were made at $I_d \approx 200\ \mu\mathrm{A}$ and $20\ \mu\mathrm{A}$, using $R_F = 60\ \mathrm{k\Omega}$ and $590\ \mathrm{k\Omega}$ respectively. The frequency range was 1 Hz to 12 kHz (measured in two spans). The FET probe and circuitry are shielded and battery powered; the noise measurements were made in an electrically noisy laboratory environment.

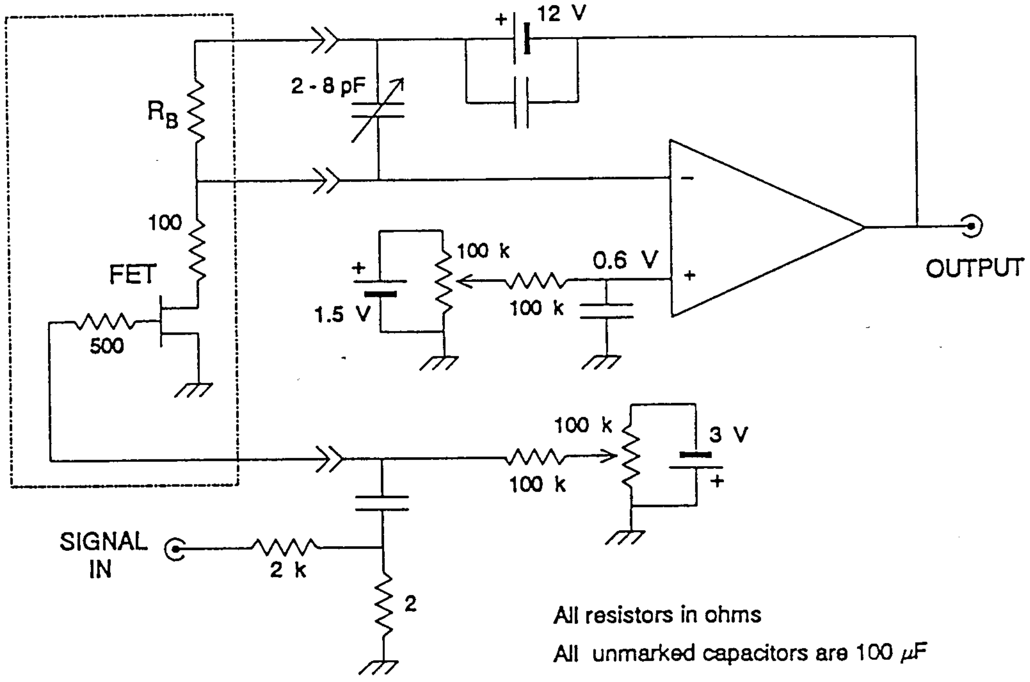

Figure 6 - Noise measurement circuit; for 4 K measurements, parts within the dashed line are immersed in liquid helium. The operational amplifier is a Texas Instruments TLC2201BCP, CMOS. The 100-Ω and 500-Ω resistors are connected directly at the FET leads to prevent radio-frequency oscillations. "Signal In" is used for determining gain; input level is 1 Vrms or 0.1 Vrms. $R_F = 60\ \mathrm{k\Omega}$ for $I_d = 200\ \mu\mathrm{A}$; $590\ \mathrm{k\Omega}$ for $20\ \mu\mathrm{A}$.

The HP 35660A is also used to measure the gain of the amplifier. For the various GaAs FETs and drain currents, gain ranged between approximately 20 and 250. However, for a given FET and drain current, gain was constant over frequency to well within the accuracy needed for these noise measurements. Measured noise voltages have been divided by the gain, so that all noise data reported in this paper are referred to the gate of the FET. Values of transconductance, g_m, given in the Tables have been calculated from $g_m = \mathrm{Gain}/R_F$.

Noise Results

Spectra for two GaAs MESFETs (Figure 7) illustrate typical characteristics. Typically, the noise voltage, e_n, decreases about one order of magnitude at 4 K compared to 300 K, in accord with previous reports.[15-18,25,26] It usually follows approximately a $1/f^{1/2}$ dependence at 4 K, with an occasional "bulge" for some FETs, characteristic of prominent generation-recombination noise components.[27] As expected, there was no evidence of a transition to white noise, which is probably in the MHz range.[27]

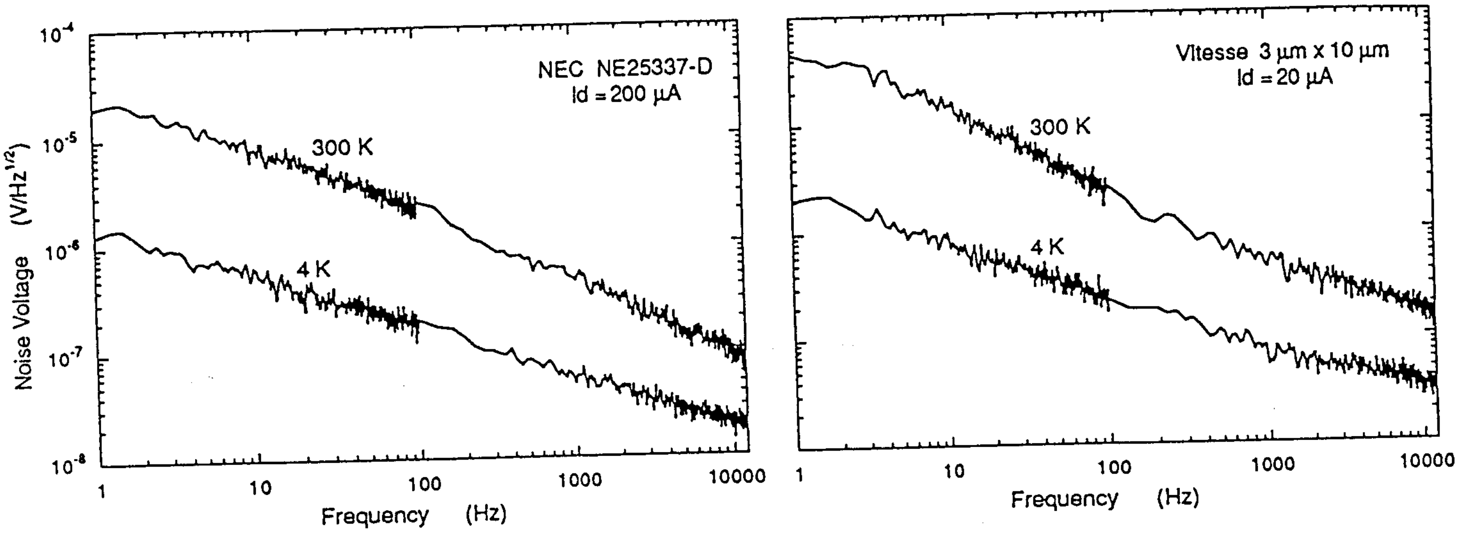

Figure 7 - Noise spectra for a commercial (left) and a foundry GaAs MESFET (right). For all graphs $V_{ds} = 0.6$ V. Measurements were made in two frequency spans: 1 Hz - 101 Hz and 100 Hz - 12 kHz.

To characterize noise voltage, we use the coefficient A_f, where $e_n^2 \equiv A_f/f$. This noise-voltage coefficient, and the transconductance, g_m, are summarized for the lowest-noise commercial FETs in Table IIa, and for the foundry FETs in Table IIb. All data are for a 4 K environment (direct immersion in liquid helium) and $V_{ds} = 0.6$ V. Measured frequency range is 1 Hz to 12 kHz.

A_f for the commercial FETs varied over a wide range---from 0.25×10^{-12} to 1×10^{-10} V^2; several exhibit noise voltage corresponding to A_f less than 10^{-12} V^2 ($e_n < 1$ µV at 1 Hz). Our results for the Plessey P35-1101 are similar to those previously reported for higher frequencies.[18,25,28,29] The lowest noise voltage previously reported for commercial GaAs MESFETs is $A_f \approx 4 \times 10^{-14}$ V^2 for the Sony 3SK164.[15,16,c] Likewise, we find that among the commercial GaAs FETs the lowest noise voltage is exhibited by the 3SK164, although our result is $A_f \approx 25 \times 10^{-14}$ V^2. Unfortunately, this transistor is no longer available; its replacement, the SGM2006, exhibits higher noise.[19]

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[c] Camin and co-workers have also measured $A_f = 2.3 \times 10^{-14}$ for the NEC NE41137. The low values of noise for the 3SK164 and NE41137 were measured on early manufacturing lots, they find that recent lots exhibit higher noise. [Private communication].

TABLE IIa - Noise voltage for commercial GaAs MESFETs exhibiting the lowest noise; $I_d = 200\ \mu A$, $V_{ds} = 0.6$ V (Power = 120 µW).

Manufacturer	Type	g_m (mS)	A_f (10^{-12} V^2)
NEC	NE25337-D	1.4	3
	3SK206-U79	2.6	3
Plessey	P35-1101	1.9	0.6
Sanyo	3SK189-4	1.2	3
Siemens	CF739	2.7	~1
Sony	3SK164	2.0	0.25
	3SK165	2.7	0.5
	3SK166	1.4	~2
	SGM2004	1.8	~3
	SGM2006	1.2	~4

TABLE IIb - Noise voltage for foundry GaAs FETs; $I_d = 20\ \mu A$, $V_{ds} = 0.6$ V (Power = 12 µW).

Manufacturer	W_g (µm)	L_g (µm)	g_m (mS)	A_f (10^{-12} V^2)
Aerojet (JFET)	200	88	0.12	0.02
		48	0.17	0.03
Microwave Technology	90	60	0.13	0.06
			0.13	0.08
			0.11	0.05
Vitesse/MOSIS	50	2	0.44	~50
		4	0.31	5
		8	0.23	~2
		16	0.17	0.3
		2	0.48	4
		4	0.34	0.7
		8	0.25	0.3
		16	0.18	0.16
		2	0.43	~8
		4	0.30	~6
		8	0.22	0.4
		16	0.17	0.16
Vitesse	10	3	0.23	~4
		1.2	0.41	14
		3	0.22	6

The foundry FETs exhibit lower noise, corresponding to A_f as low as 2×10^{-14} V^2. The Vitesse/MOSIS chips include sets of FETs which have a progression of gate lengths from 2 µm to 16 µm, for which the dependence of g_m and A_f on gate length is plotted in Figures 8. There is a clear decrease of g_m with increasing gate length. Noise voltage also tends to decrease, although there is considerable scatter in the data and the dependence is closer to $1/L^2$ rather than the expected $1/L$.[29]

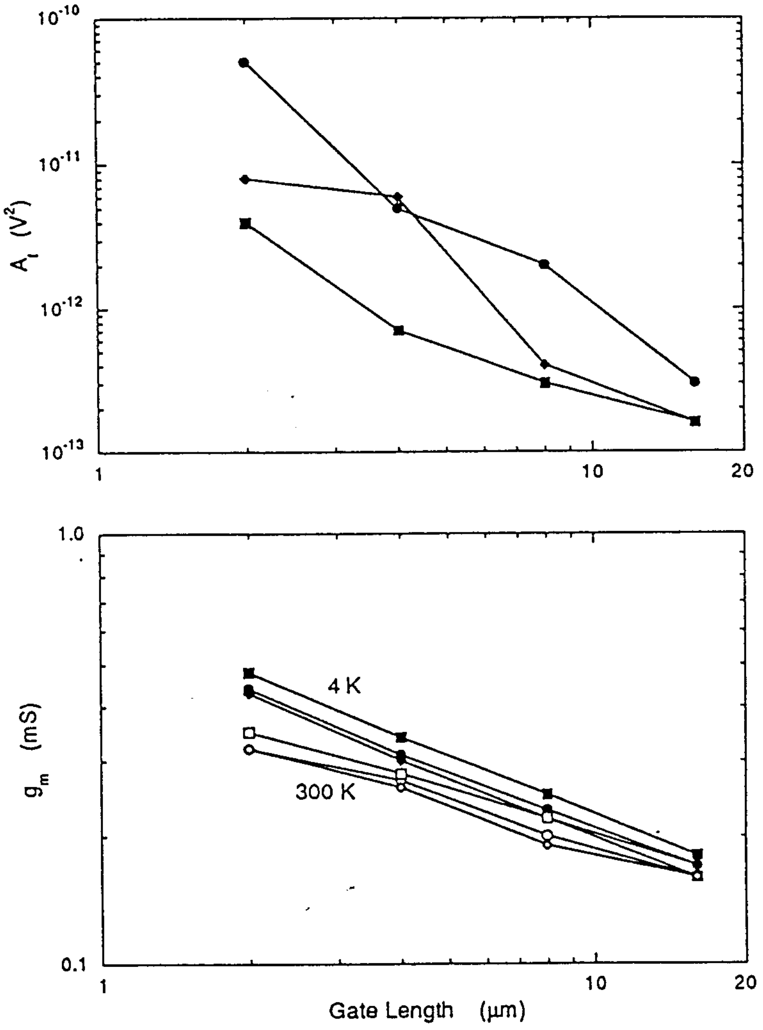

Figure 8 - Noise voltage coefficient at 4 K and transconductance as a function of gate length for Vitesse/MOSIS GaAs MESFETs. $I_d = 20$ µA, $V_{ds} = 0.6$ V. Sets of FETs on the same chip are connected by a line.

Since the gate area and input capacitance vary considerably among the FETs measured, A_f for the foundry FETs has been plotted as a function of gate area in Figure 9. Data from previous measurements at or near liquid-helium temperatures are also included for a custom GaAs MESFETs made at Hughes[26] and GaAs JFETs made at Aerojet.[30] Our results are similar, except for one large-area JFET.

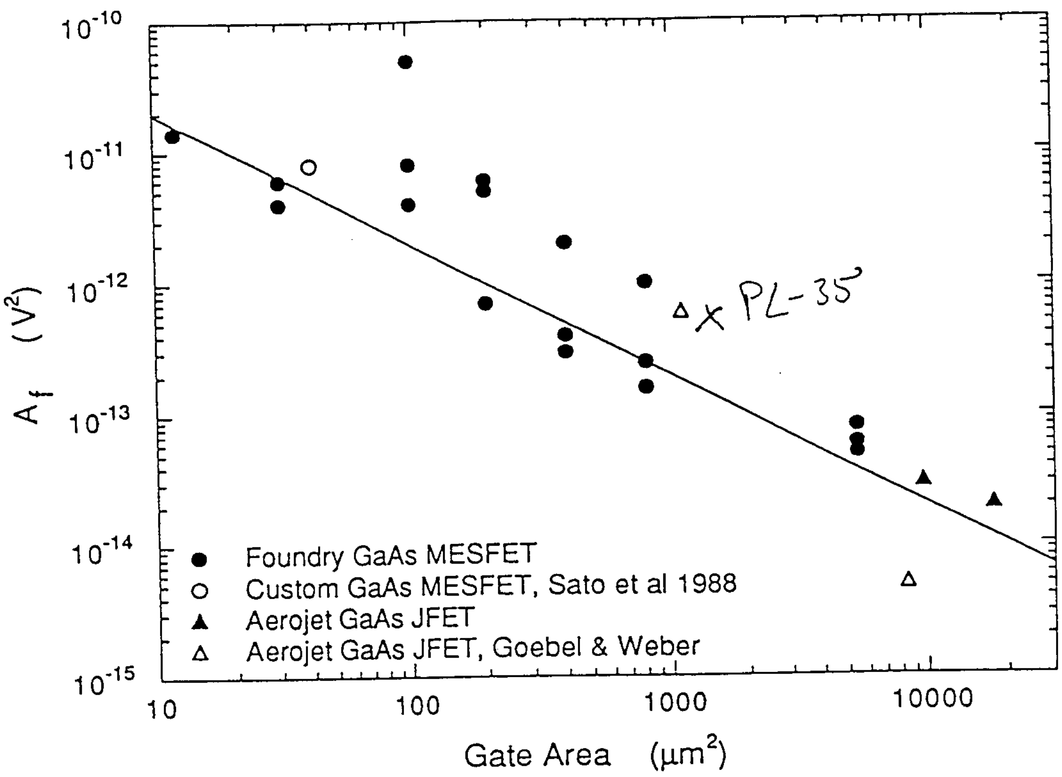

Figure 9 - Comparison of noise voltage coefficient as a function of gate area (filled symbols are data of Table IIb). The data points follow roughly the line of slope −1 which indicates "equal merit" (constant A_f x gate area), corresponding to about 3×10^{-25} Joule.

Substrate effect

For the noise data presented in this paper the FET's substrate was set to the same voltage as the source, whenever there was a substrate contact available. For eight of the foundry FETs, noise was also measured at 4 K for a substrate voltage of +3 V and for −3 V relative to the source. No clear tendency could be seen in the results. For about half the FETs the difference in the noise spectrum was slight or absent. This is consistent with the substrate effect being weak or absent in the dc measurements, as mentioned earlier. However, for the other FETs, the noise level increased or decreased by as much as a factor of 2, but was not correlated with the substrate voltage and also depended on its history.

Comparison

For comparison, Table III summarizes reported noise levels for Si FETs operating at cryogenic temperatures. The reported noise voltage spectra are represented by the 1/f coefficient A_f introduced above; this must be regarded as an approximation to the data, since the spectra often deviate from 1/f behavior. Moreover, because of the variety of biasing conditions and insufficient knowledge of the input capacitance, only a rough comparison is possible. However, using an estimate of ~1000 μm^2 as an equivalent gate area, the noise voltage of the GaAs FETs is as low as that of the Si MOSFETs (at ≈4 K), although both have at least two orders of magnitude higher A_f than the Si JFETs (at ≈60 K).

Table III - Noise voltages reported for Si FETs at cryogenic temperatures for comparison. Noise is referred to the gate, and is for grounded gate.

Class and Temperature	Manufacturer	Type	I_d (µA)	Power (µW)	A_f (10^{-12} V^2)	Reference
Si JFET @ ~ 60 K	Intersil	2N6483	4	6.4	0.002	31
	Siliconix	J230		100	~0.0005	6
			40	80	0.004	31
Si MOSFET @ ~ 4 K	Siliconix	3N167	~700	~3 mW	0.4	32
	Cryoelectronics	ZK111[a]		5.3	1	33
				50	0.3	"
				430	0.16	"

[a] With "night light" (infrared photon source) to stabilize MOSFETs (IRAS tests).

Open-gate Noise

In order to determine the noise level relevant to our application, "open gate" measurements were made in which the FET gate was connected to a small-value capacitor (≈1 pF) to simulate the impedance of the photodetector. The same measurement circuit described earlier (Figure 6) was used; except that the capacitor was placed in series with the gate, directly at the FET terminal. Both capacitor and FET were hermetically sealed in a metal capsule to exclude electromagnetic pickup and to avoid conduction or disturbances from helium gas or liquid.

With the series capacitor added, the circuit functions only when the gate current is sufficiently low; we have found that this requirement is met with some of the FETs at liquid-helium temperature. V_{gs} is adjusted for the desired I_d as before, with the series capacitor and the gate capacitance acting as a voltage divider. The gate current can be determined from the drift, dV/dt, in the opamp output, as $I_g = dV/dt \times C \times Gain^{-1}$, where C is the total capacitance on the gate (gate + package + series capacitor).

Most of the commercial FETs tested so far were found to have gate current $>10^{-15}$ A for $I_d = 200$ µA. The only previous measurement we are aware of is on a Sony 3SK164,[16,17] for which I_g decreases exponentially down to 100 K and extrapolates to ~3 x 10^{-17} A near liquid-helium temperature. The difference could result from variations among FETs and the difference in biasing.

So far we have been able to make open-gate noise measurements on two FETs: a Plessey P35-1101 and a Microwave Technology Fat FET. Figure 10 compares their grounded-gate and open-gate noise spectra; surprisingly, the open-gate noise is not substantially different from the grounded-gate noise. Their gate current calculated from the output drift, and the predicted shot noise current are given in Table IV. Comparison to the measured noise voltage shows that for the Plessey FET the noise voltage is dominant at low frequencies, whereas for the Microwave Technology FET the noise voltage and current are comparable.

There are a few measurements of noise current in GaAs[34,35] and Si[36,37] FETs at cryogenic temperatures, but we are not aware of any experimental results for noise current in any semiconductor device at liquid-helium temperatures and for frequencies of 1 Hz - 10 kHz.

Table IV - Open-gate measurement results for two GaAs MESFETs, comparing predicted noise current with experimental results.

FET	I_g (fA) (measured)	i_n (aA/Hz$^{1/2}$) $(2eI_g)^{1/2}$	Equivalent e_n (µV) $i_n/2\pi C$ @ 1 Hz	Measured e_n (µV) @ 1 Hz
Plessey P35-1101	<~ 0.1 (measurement limit)	<6	<0.5 C ~ 2 pF	0.8
Microwave Technology	~1	~18	0.3 C ~ 10 pF	0.3

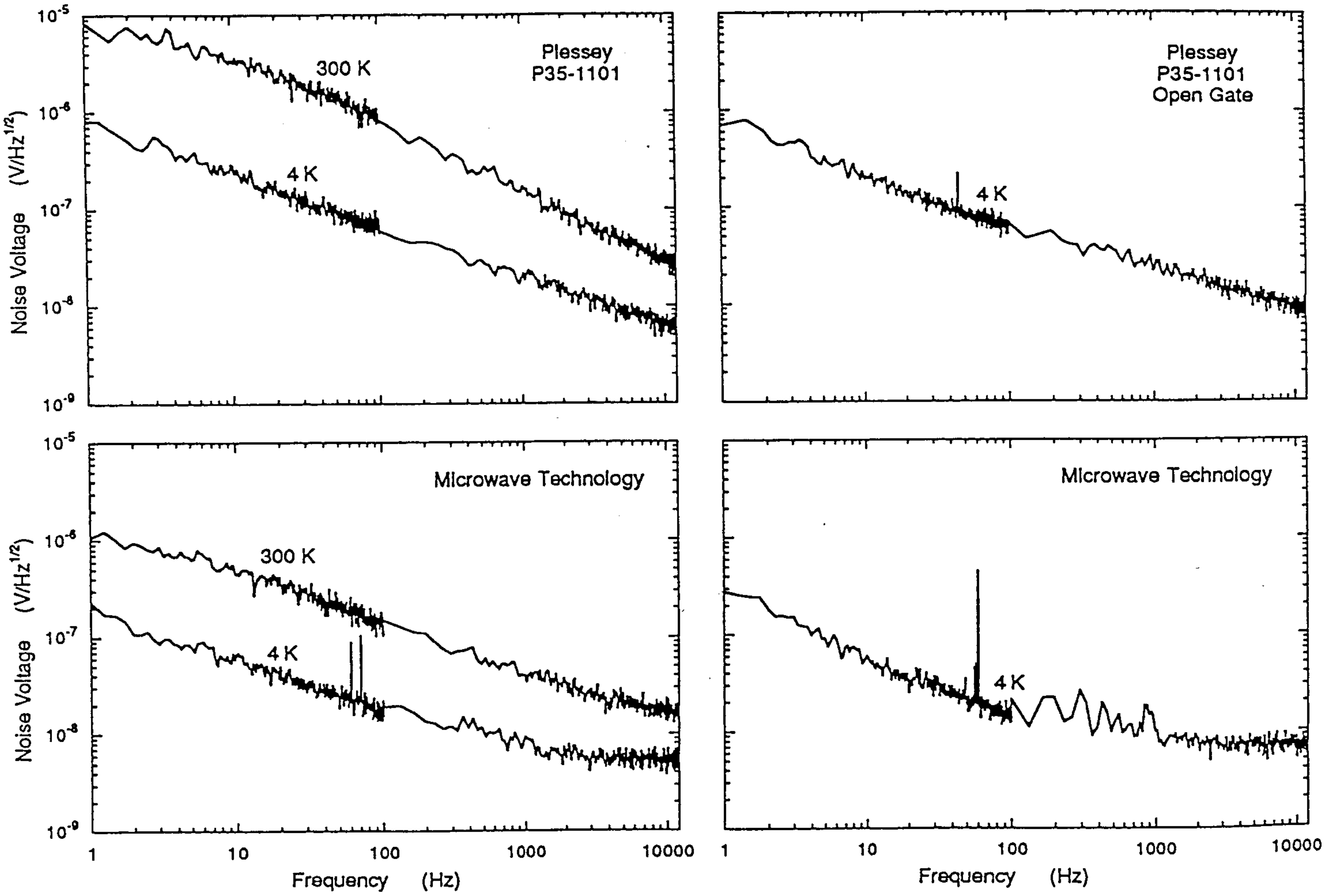

Figure 10 - Grounded-gate (left) and open-gate (right) noise spectra for two GaAs MESFETs, I_d = 200 µA, V_{ds} = 0.6 V. The noise corner in the lower graphs results from the noise floor of the measurement system.

7. SUMMARY & CONCLUSIONS

We have made an initial survey of GaAs MESFETs and JFETs, commercial and "foundry", for application in photodetector readout circuits at liquid-helium temperatures. Based on a limited number of FETs and measurements, we find that:

> Many commercial FETs and all foundry FETs exhibited useable dc characteristics at liquid-helium temperatures, down to the microwatt power level.
>
> Several GaAs FETs, both commercial and foundry, exhibited low-frequency grounded-gate noise voltage at liquid-helium temperature at least as good as the lowest reported for Si MOSFETs.
>
> Foundry FETs exhibit better dc characteristics and consistently lower noise, compared to commercial FETs. Thus, standard GaAs MESFET fabrication, available through foundries, produces GaAs FETs that are useful at liquid-helium temperatures.

There are many issues in need of further investigation, including dc anomalies attributable to charge trapping (hysteresis and collapse), substrate effects, gate leakage and capacitance, noise current, noise dependence on biasing, and mechanical stress on the die.

So far, this evaluation seems to have raised as many questions as it has answered. However, we believe that our results and those of others indicate that GaAs FETs warrant further evaluation and could be useful for low-frequency cryogenic applications, particularly for the temperature range below Si freezout (<30 K), as an alternative to Si FETs.

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