Noise Parameters of FET's: Measurement, Modeling and Use in Amplifier Design

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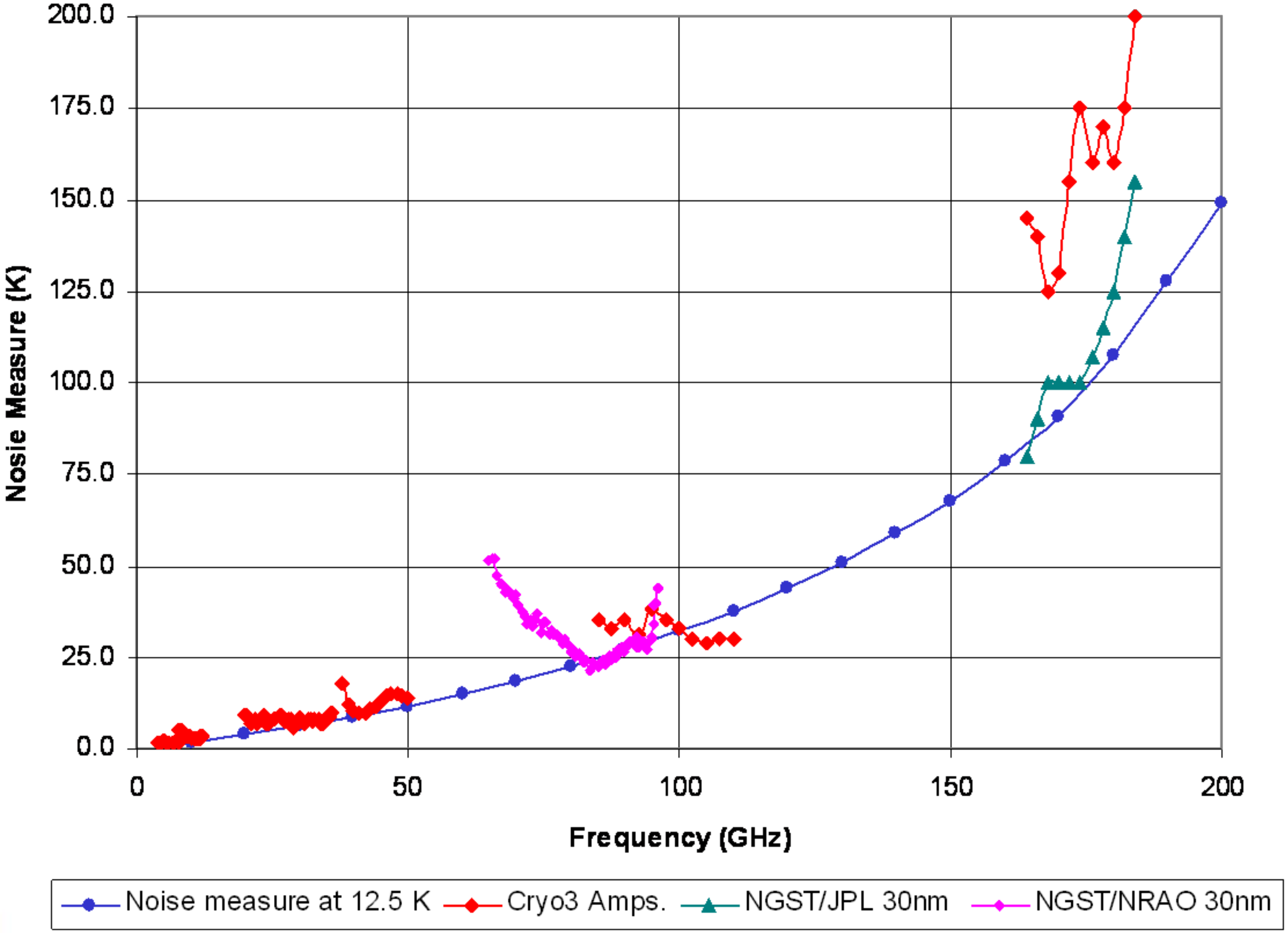
Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

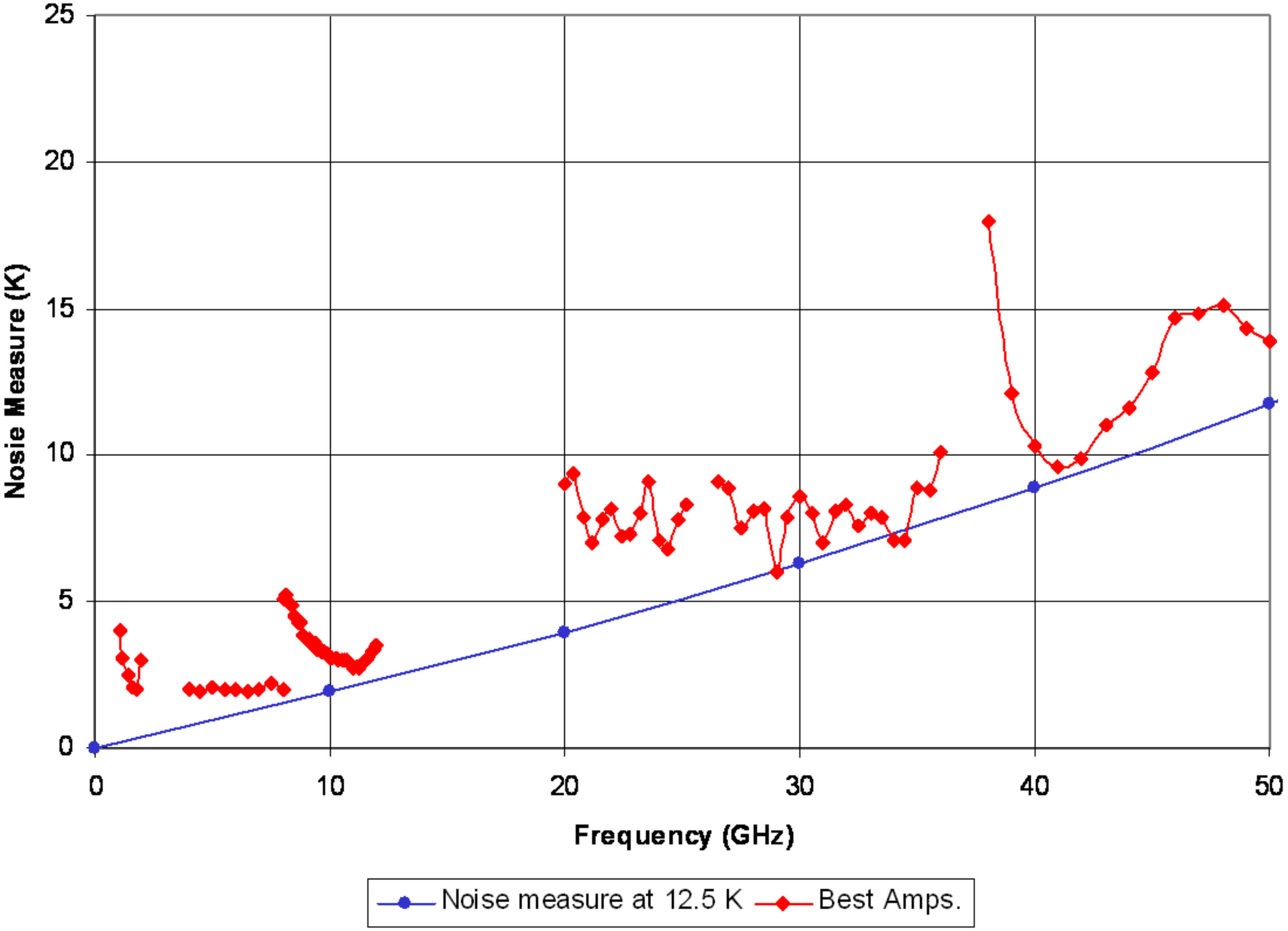
Outline

- State-of-the-art
- Noise temperature measurement methods employed at CDL
- Review of the sources of error
- Some properties of signal and noise models of FETs
- Method of measurement of noise parameters at cryogenic temperatures
- Optimal noise bias of a FET – lessons for future improvements
- Effects observed but not understood
- Final observations

M_{min} Prediction (1991) and State of the Art (2009)



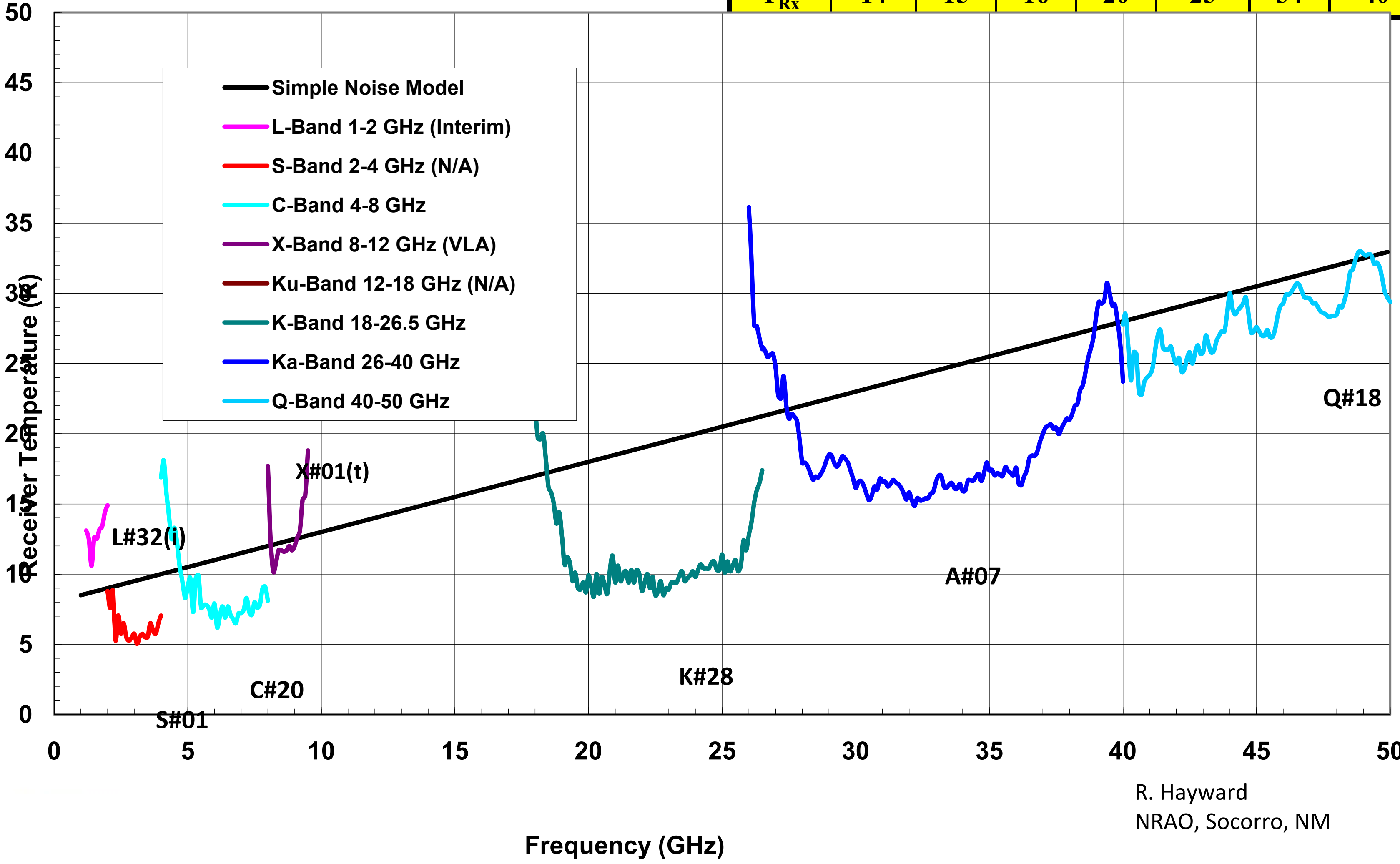
M_{min} Prediction (1991) and State of the Art (2009)



VLA/EVLA

T_{Rx} versus Frequency

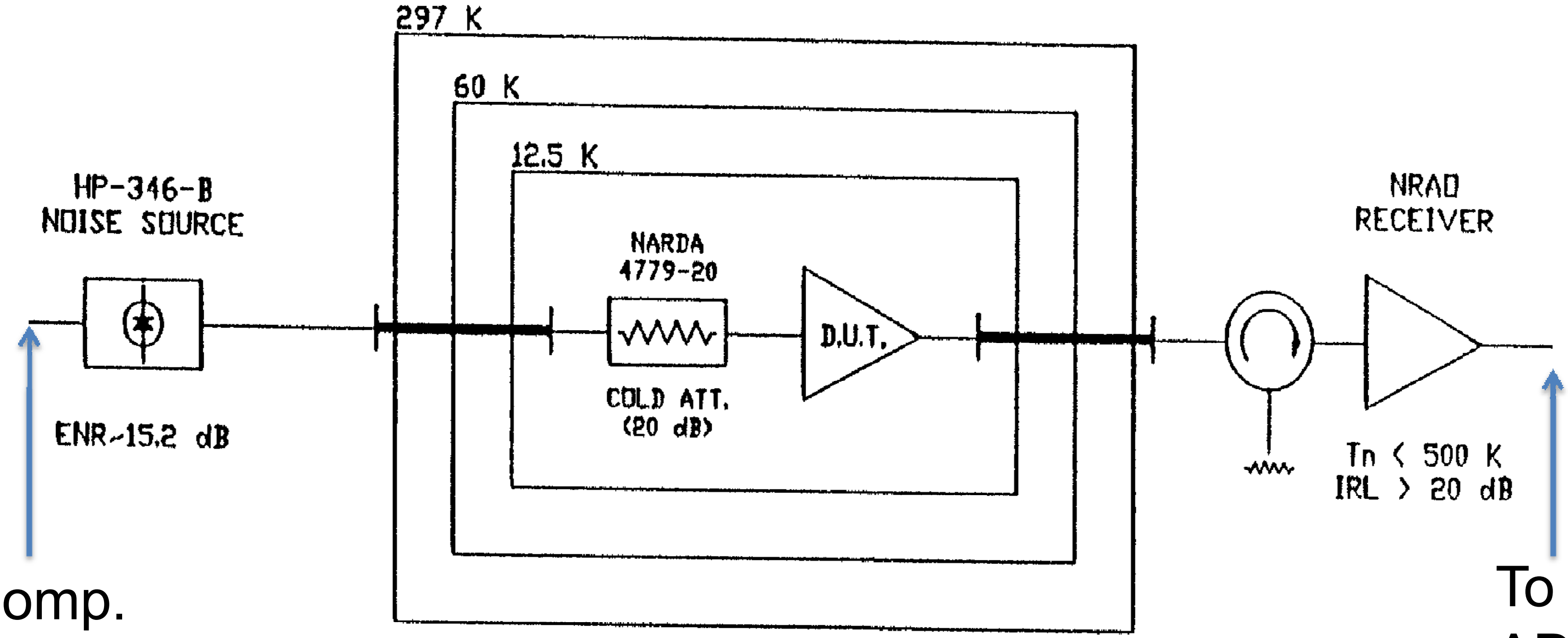
EVLA Project Book - T_{Rx} Requirements (Band Center)								
Band	**L**	**S**	**C**	**X**	**Ku**	**K**	**Ka**	**Q**
T_{Rx}	**14**	**15**	**16**	**20**	**25**	**34**	**40**	**48**



R. Hayward
NRAO, Socorro, NM

$$T_{Rx} = m \cdot F + b \;;\; m = 0.5^{\circ}K/\,GHz \;;\; b = 8^{\circ}K$$

Cold Attenuator Measurement Method

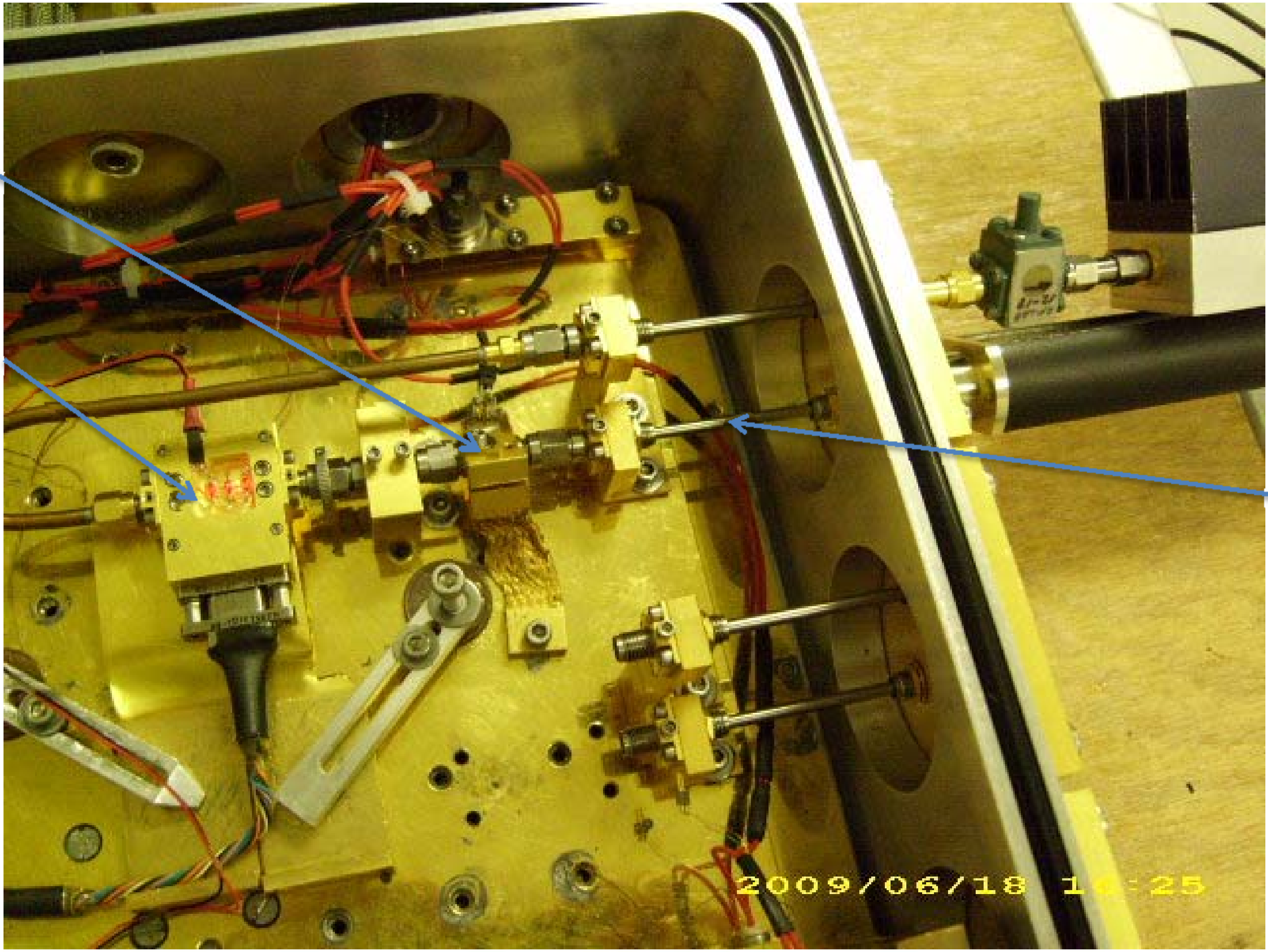


Comp. Contr.

To ADC

Main source of error: Uncertainty in calibration of ENR

Cold Attenuator Noise Measurements

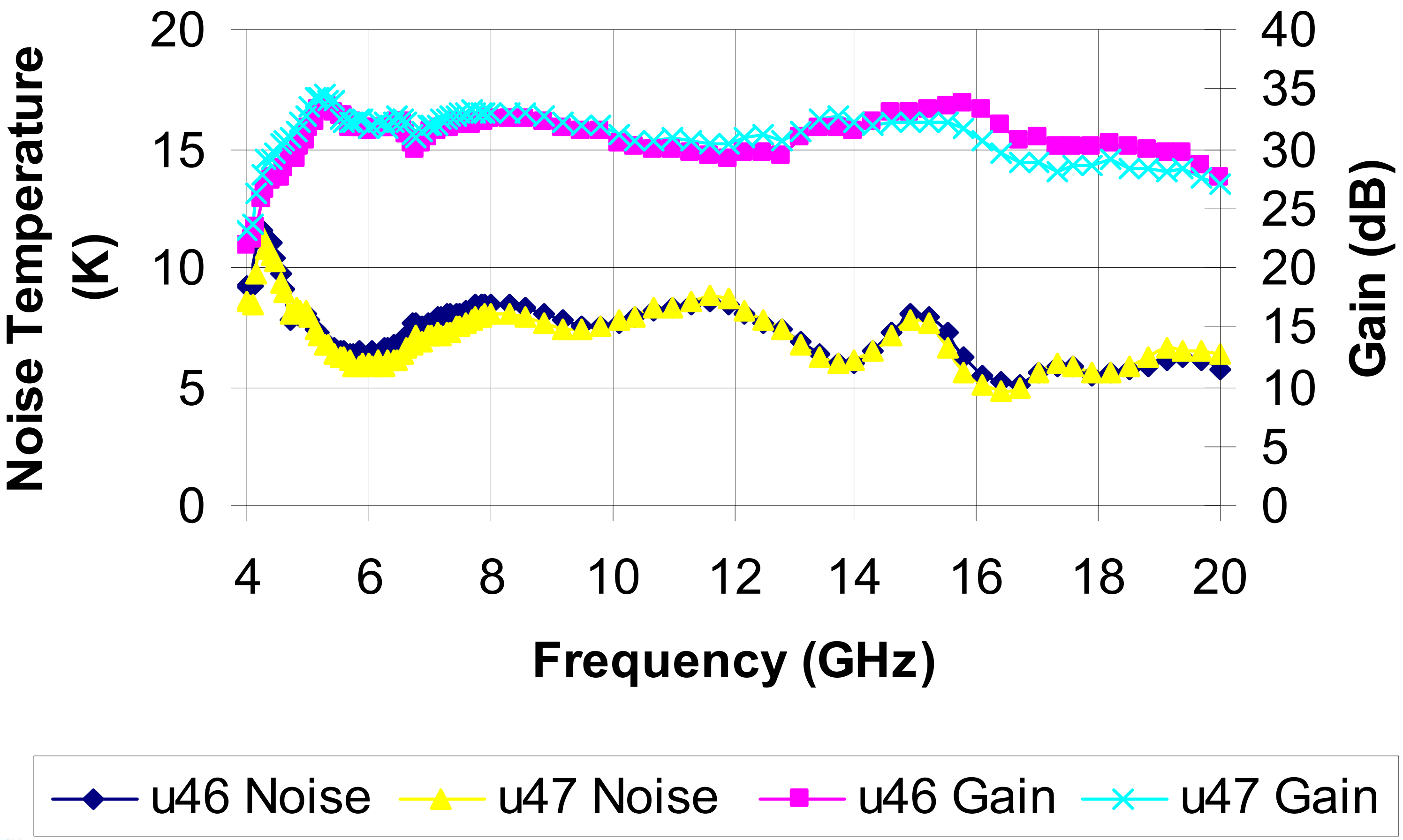


Att.

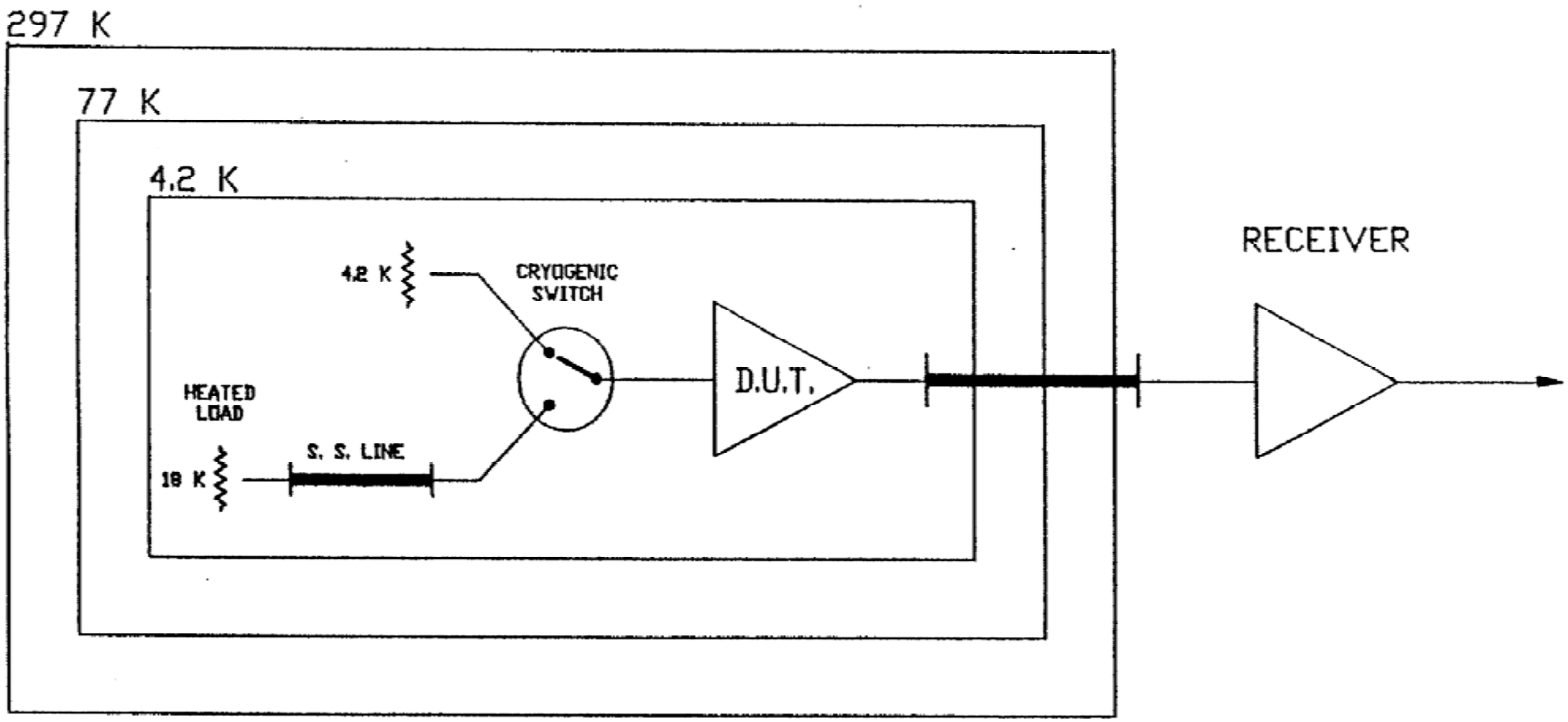
Amp.

SS air line

Noise and Gain of 5-20 GHz Amplifier at T_a=15 K



Hot-Cold Load Measurement Method



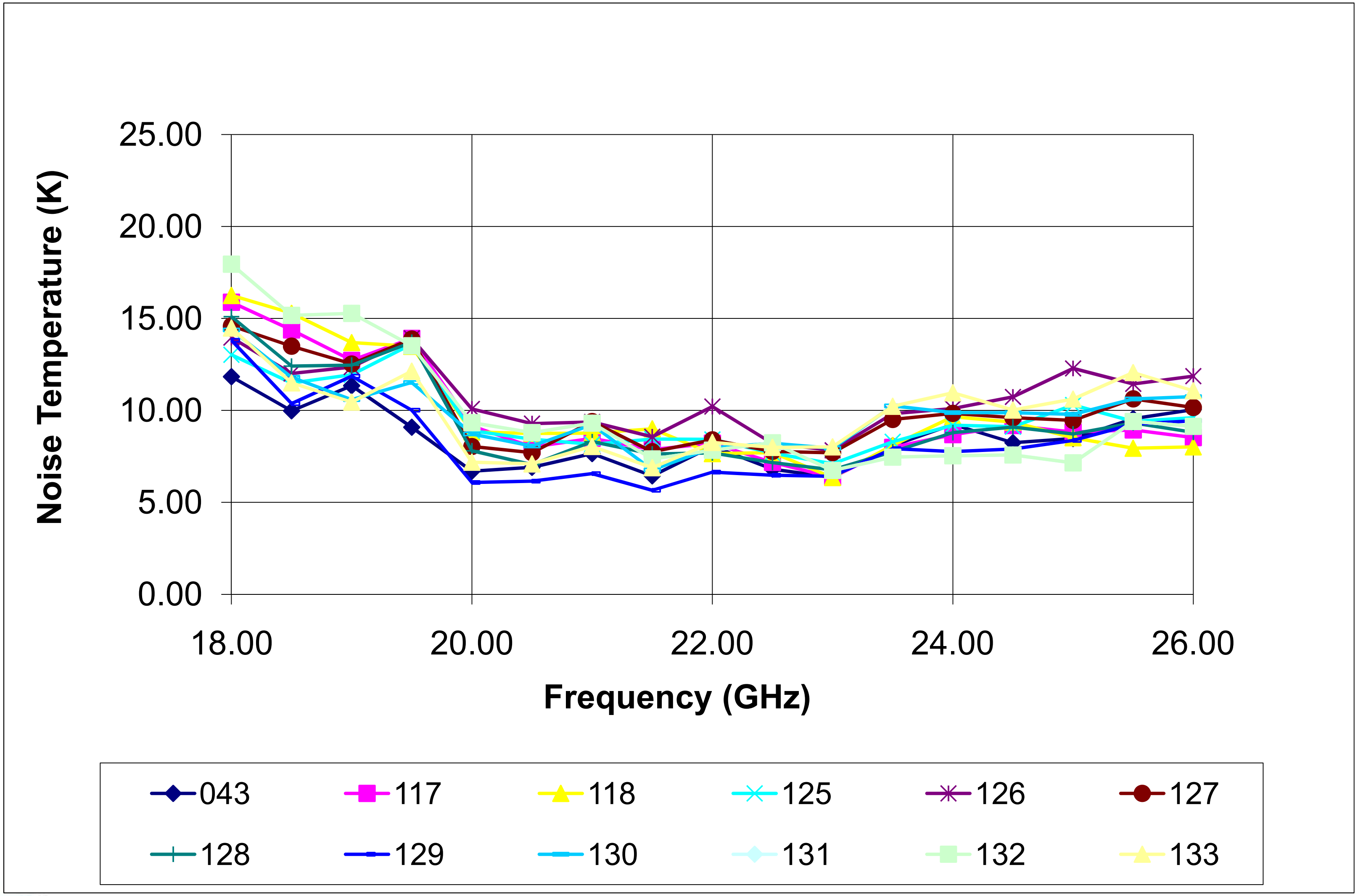
Sources of error:

1) Uncertainty in calibration of T_h

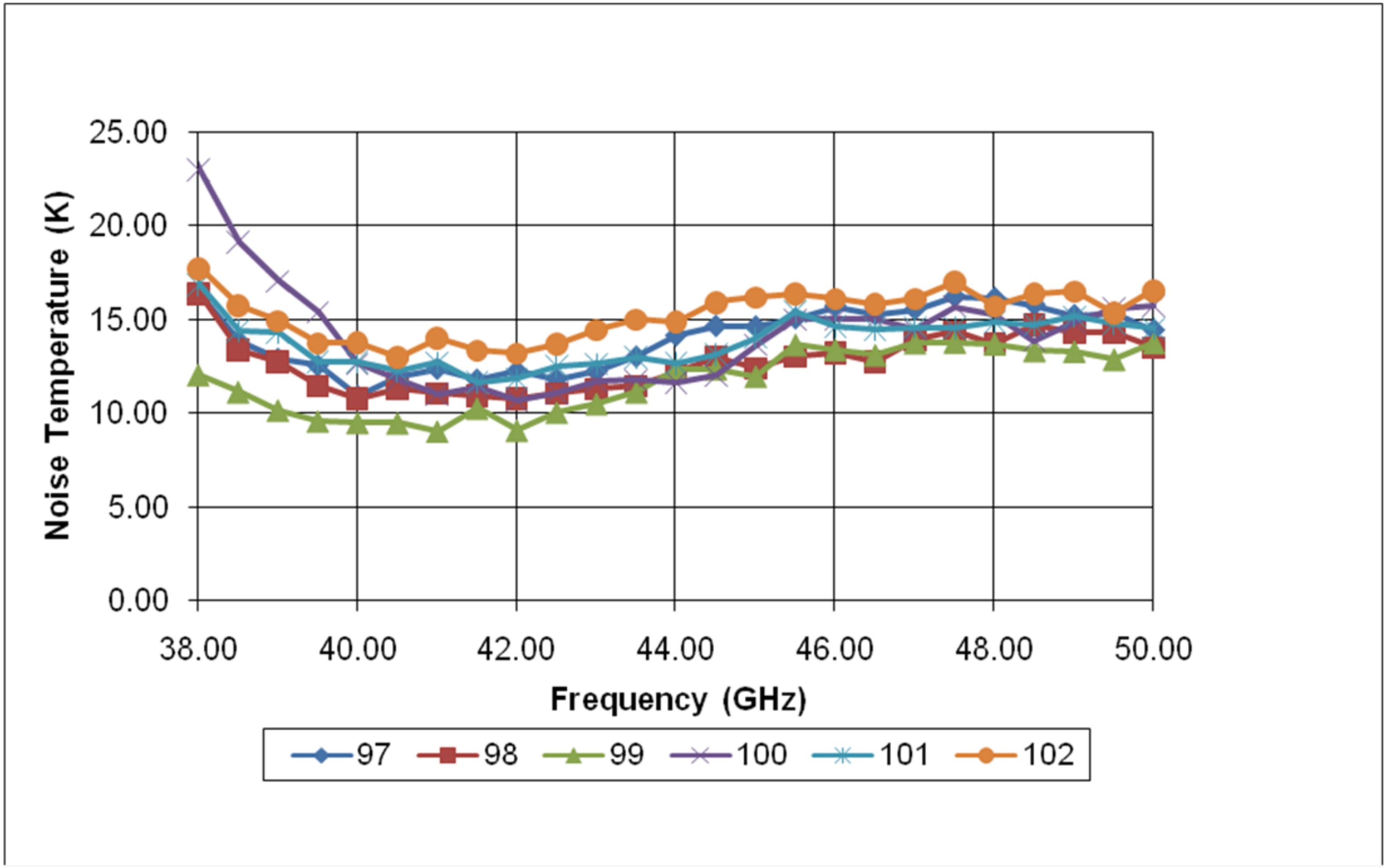
2) Change in impedance of “hot” and “cold” state

Noise Measurements of Waveguide Amplifiers

GBT K-Band Array Amplifiers at 19 K



Noise Performance of Q-Band Amplifiers



Sources of Error

- Uncertainty in calibration of T_h and T_c
- Change in impedance of “hot” and “cold” state
- Receiver nonlinearity
- Receiver calibration
- Receiver stability
- Finite integration time for a given IF bandwidth

Common Noise Representations of 2-Ports

$$T_n = T_{min} + T_o \frac{g_n}{R_g}\left|Z_g - Z_{opt}\right|^2 = T_{min} + NT_o \frac{\left|Z_g - Z_{opt}\right|^2}{R_g R_{opt}}$$

$$T_n = T_{min} + 4NT_o \frac{\left|\Gamma_g - \Gamma_{opt}\right|^2}{\left(1 - \left|\Gamma_{opt}\right|^2\right)\left(1 - \left|\Gamma_g\right|^2\right)}$$

where $\Gamma_{opt} = \frac{Z_{opt} - Z_o}{Z_{opt} + Z_o}$ $N = R_{opt} g_n$

For All Linear Noisy Two-Ports: $T_{min} \leq 4NT_o$

Other Properties of Noise Parameters

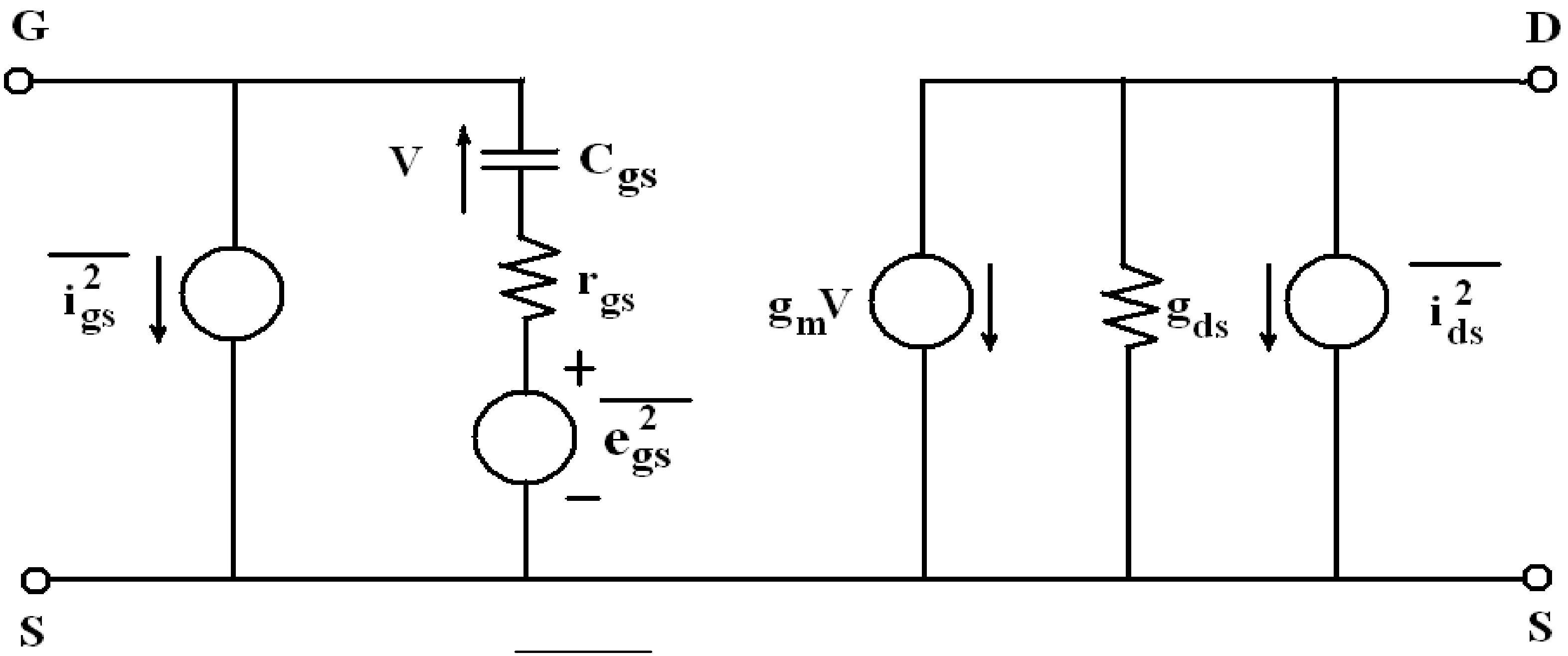
$$T_{min} = T_0 \{2N + \mathrm{Re}\left(\rho \sqrt{R_n g_n}\right)\} \ .$$

Hence, $$1 \leq \frac{4NT_0}{T_{min}} \leq 2$$

if and only if Re(ρ) ≥ 0 and correlation matrix is Hermitian and non-negative definite.

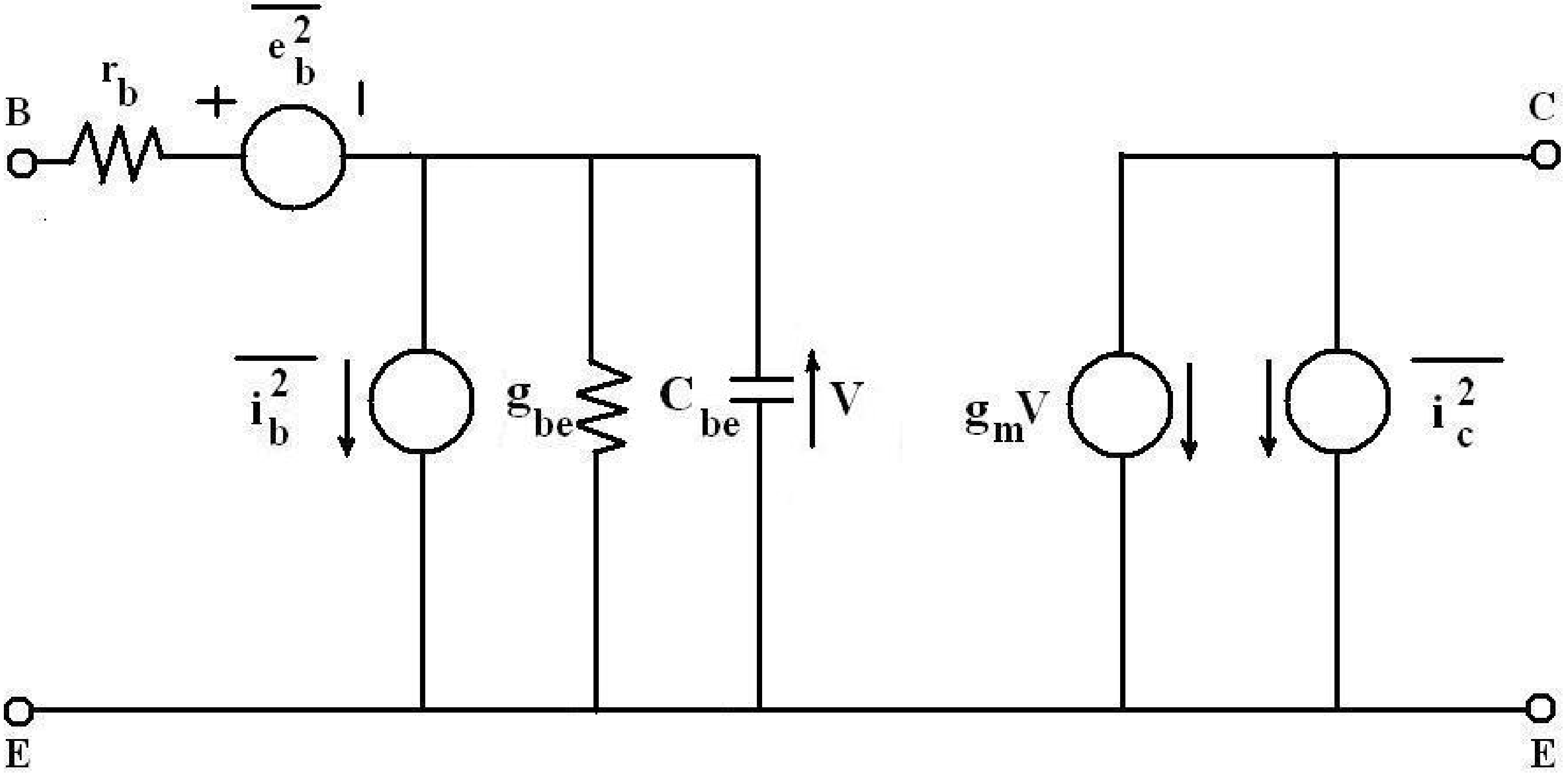
It holds for generally accepted noise equivalent circuits of both FETs and HBTs.

Simplest Noise Equivalent Circuit of a FET

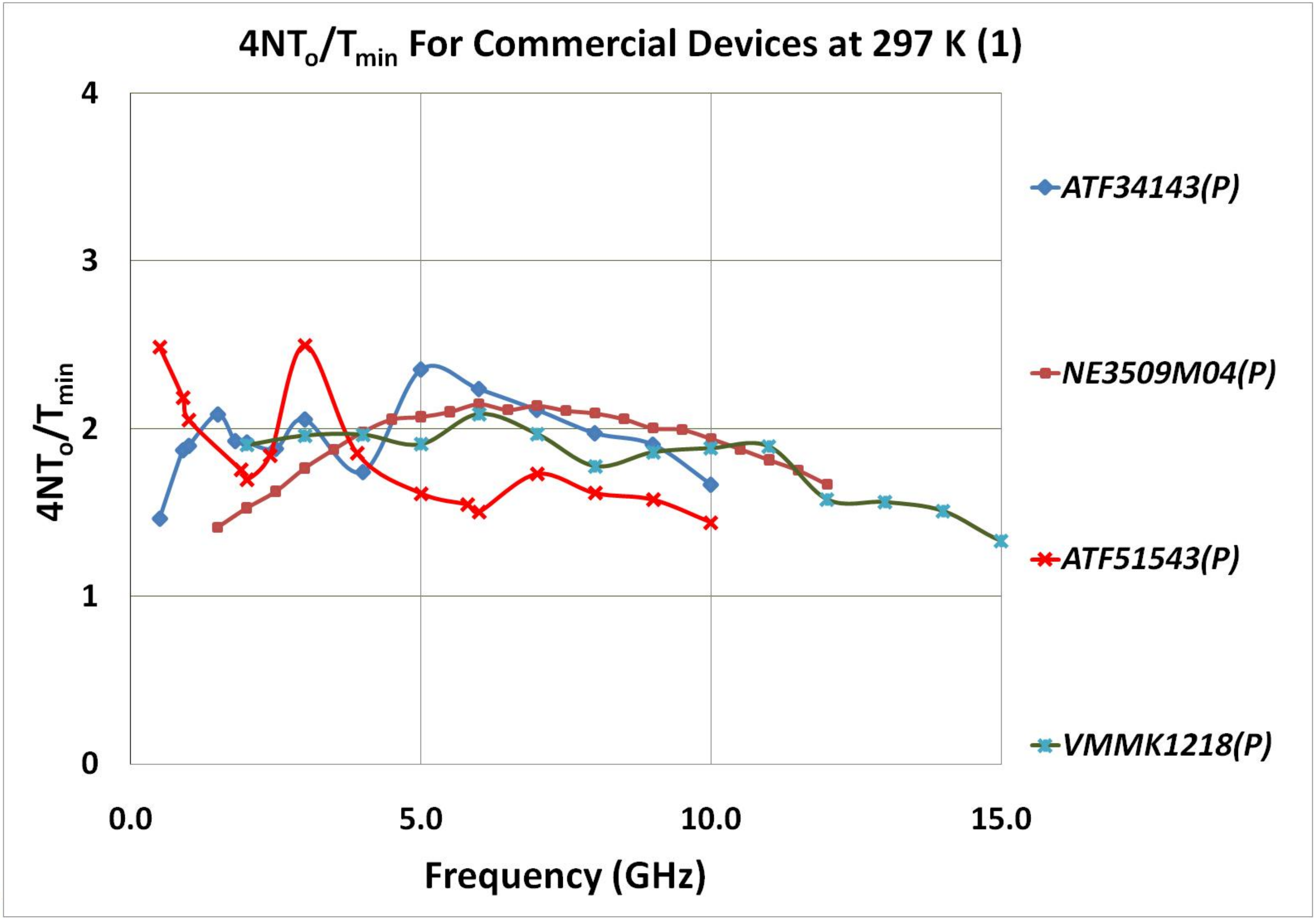


$$\overline{i_{gs}^2} = 2qI_{gs}\Delta f \qquad \overline{e_{gs}^2} = 4T_g r_{gs}\Delta f \qquad \overline{i_{ds}^2} = 4kT_d g_{ds}\Delta f$$

Simplest Noise Equivalent Circuit of Intrinsic BT

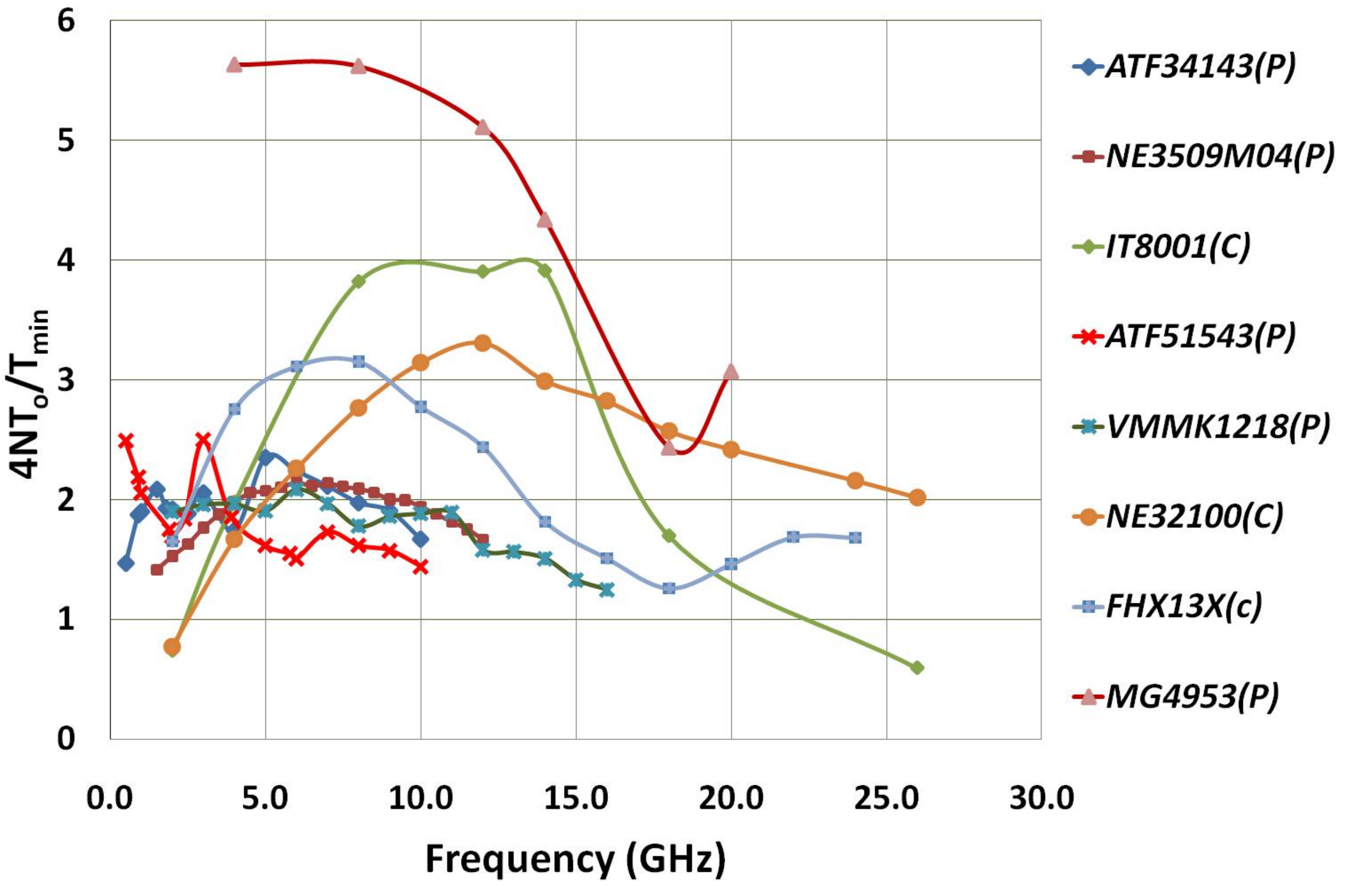


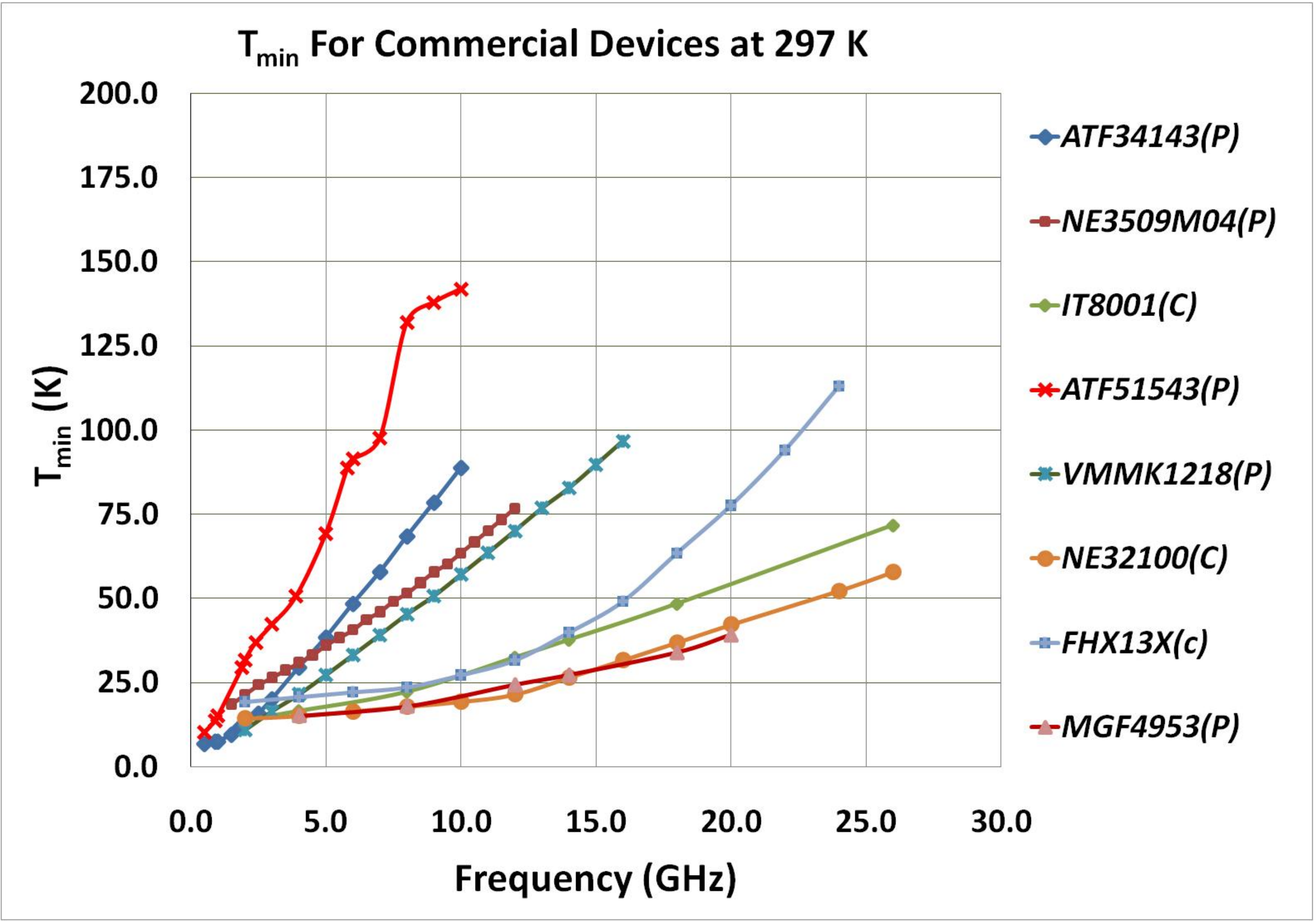
$$\overline{i_b^2} = 2\,qI_{gs}\Delta f \qquad \overline{e_b^2} = 4\,kT_d\, r_b\,\Delta f \qquad \overline{i_c^2} = 2\,qI_c\Delta f$$



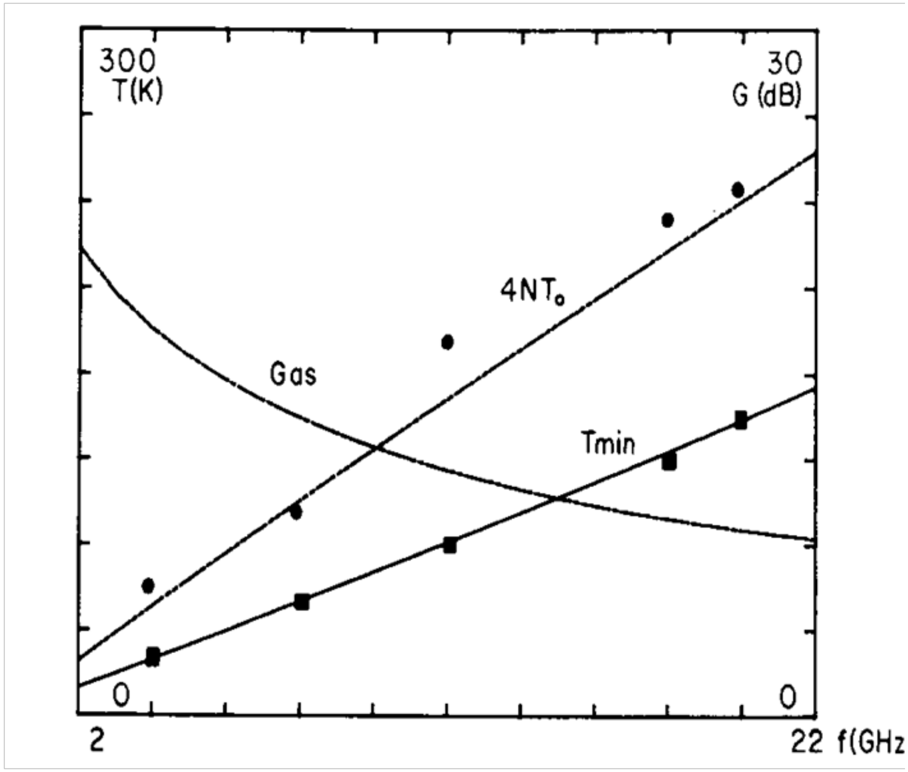
$4NT_o/T_{min}$ For Commercial Devices at 297 K (1)
4
3
2
1
0
$4NT_o/T_{min}$
0.0
5.0
10.0
15.0
Frequency (GHz)
ATF34143(P)
NE3509M04(P)
ATF51543(P)
VMMK1218(P)

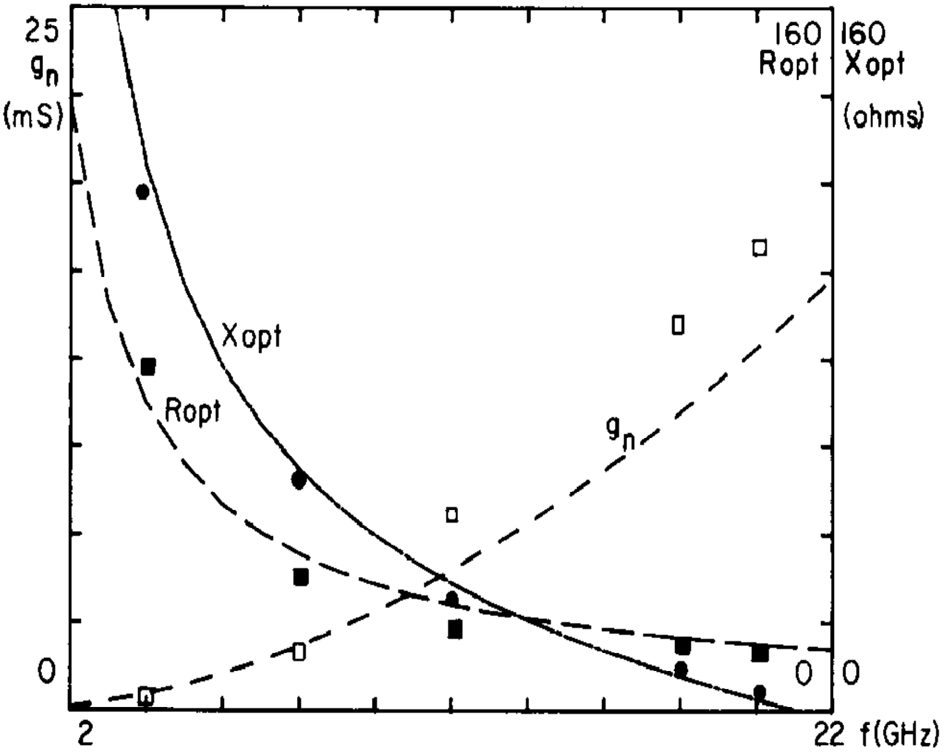
$4NT_o/T_{min}$ For Commercial Devices at 297 K (2)




T_{min} For Commercial Devices at 297 K
T_{min} (K)
200.0
175.0
150.0
125.0
100.0
75.0
50.0
25.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Frequency (GHz)
ATF34143(P)
NE3509M04(P)
IT8001(C)
ATF51543(P)
VMMK1218(P)
NE32100(C)
FHX13X(c)
MGF4953(P)

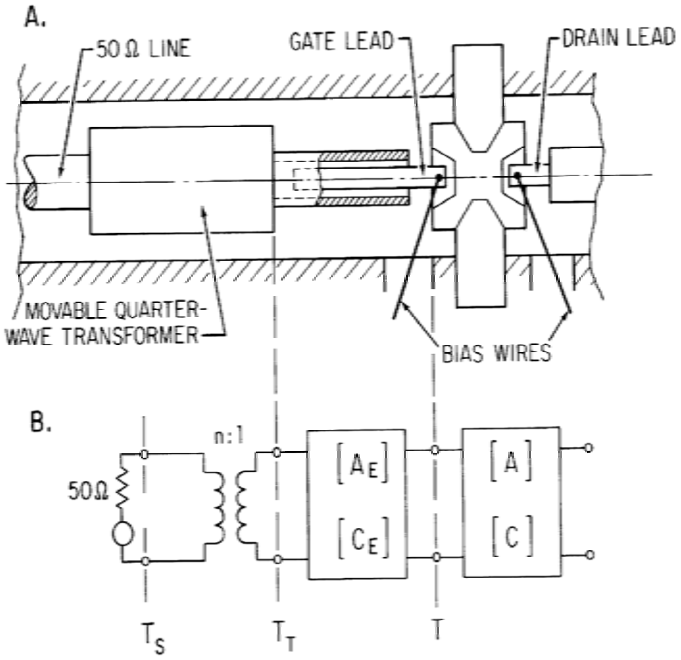
Noise Parameters of FHR01X HEMT Chip(1989)

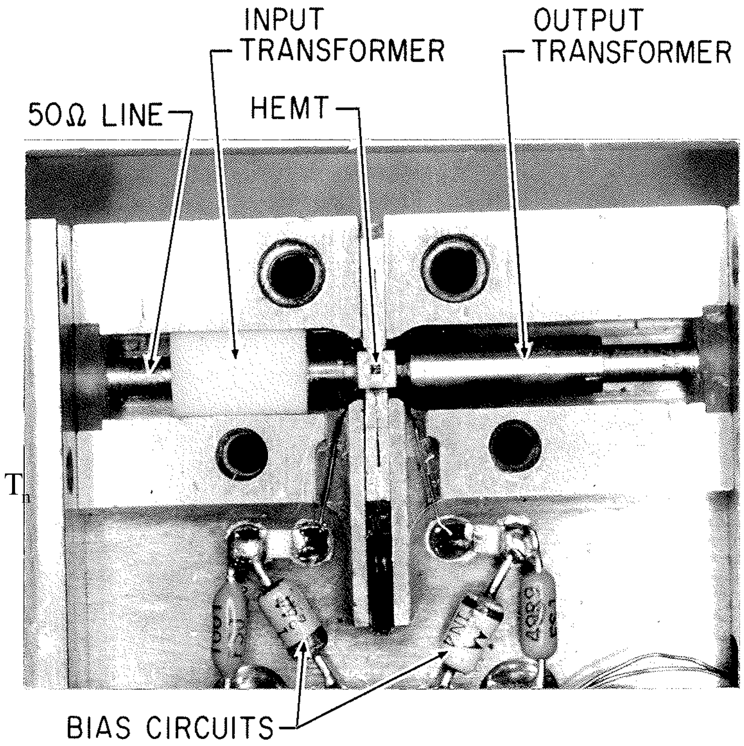




It was easier to measure devices accurately 20 years ago!!!

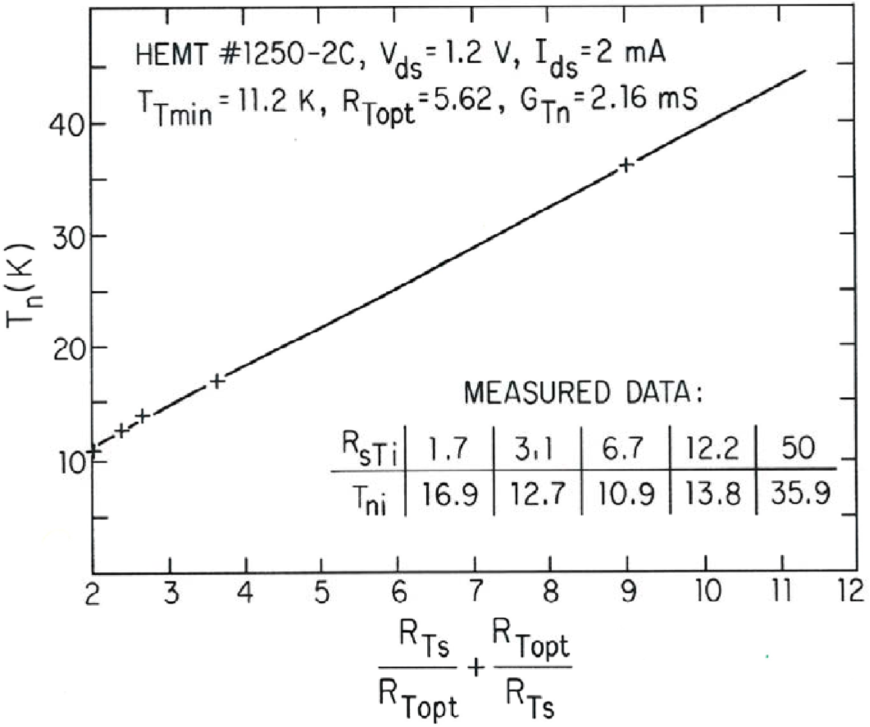
A Method of Noise Parameters Measurement (1986)





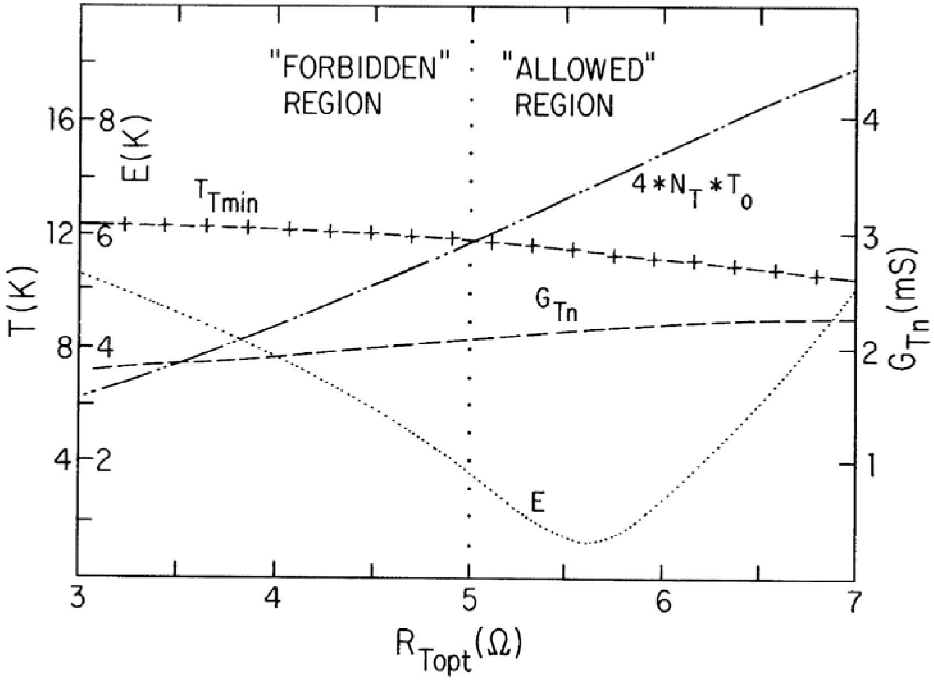
$$\frac{T_n}{T_0} = \left(\frac{T_{\min}}{T_0} - 2N \right) + N \left(\frac{R_s}{R_{opt}} + \frac{R_{opt}}{R_s} \right)$$

A Method of Noise Parameters Measurement (1986)



MEASURED DATA:

R_{sTi}	1.7	3.1	6.7	12.2	50
T_{ni}	16.9	12.7	10.9	13.8	35.9



$$E = \sqrt{\sum_{i=1}^{l} \left(T_{ni}^{m} - T_{ni}^{c}\right)^{2}}$$

Noise Parameters of FET: Approximation

For:

$$\frac{f}{f_t} << \sqrt{\frac{T_g}{T_d}\ \frac{1}{r_{gs}\ g_{ds}}}$$

$$R_{opt} \cong \frac{f_t}{f}\sqrt{\frac{r_{gs}\ T_g}{g_{ds}\ T_d}}$$

$$g_n = \left(\frac{f}{f_t}\right)^2 \frac{g_{ds}\ T_d}{T_o}$$

$$T_{min} \cong 2\,\frac{f}{f_t}\sqrt{g_{ds}\ T_d\ r_{gs}\ T_g}$$

$$\frac{4\,N T_o}{T_{min}} \cong 2$$

Broadband Matching Approximation

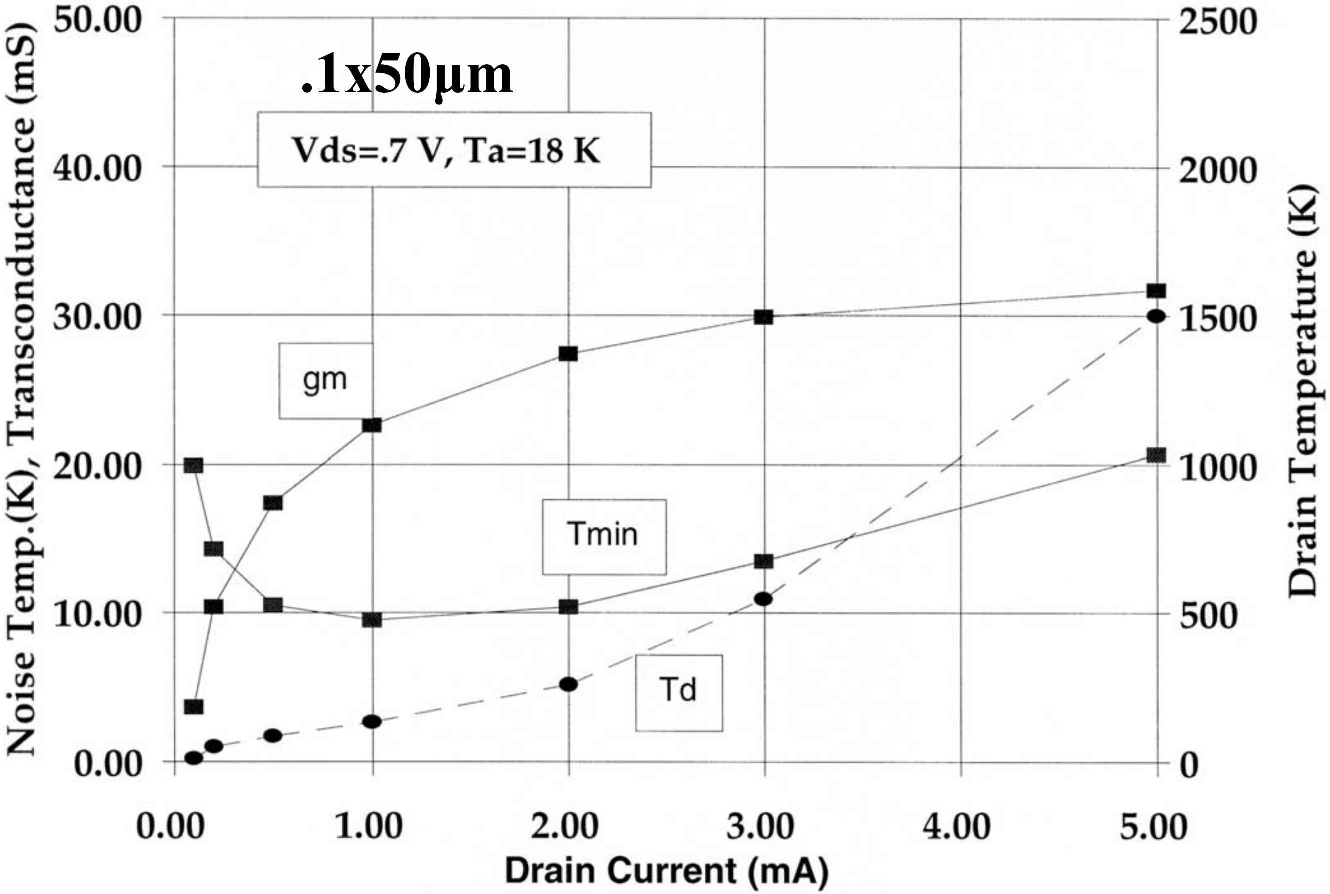
$$T_n = T_{min} + 4NT_o \frac{\left|\Gamma_g - \Gamma_{opt}\right|^2}{\left(1-\left|\Gamma_{opt}\right|^2\right)\left(1-\left|\Gamma_g\right|^2\right)}$$

At some input plane of reference A :

$$T_{min}^A = T_{min} \qquad N^A = N \qquad \Gamma_g^A = 0$$

$$T_n^A = T_{min} \frac{1+\left|\Gamma_{opt}^A\right|^2}{1-\left|\Gamma_{opt}^A\right|^2}$$

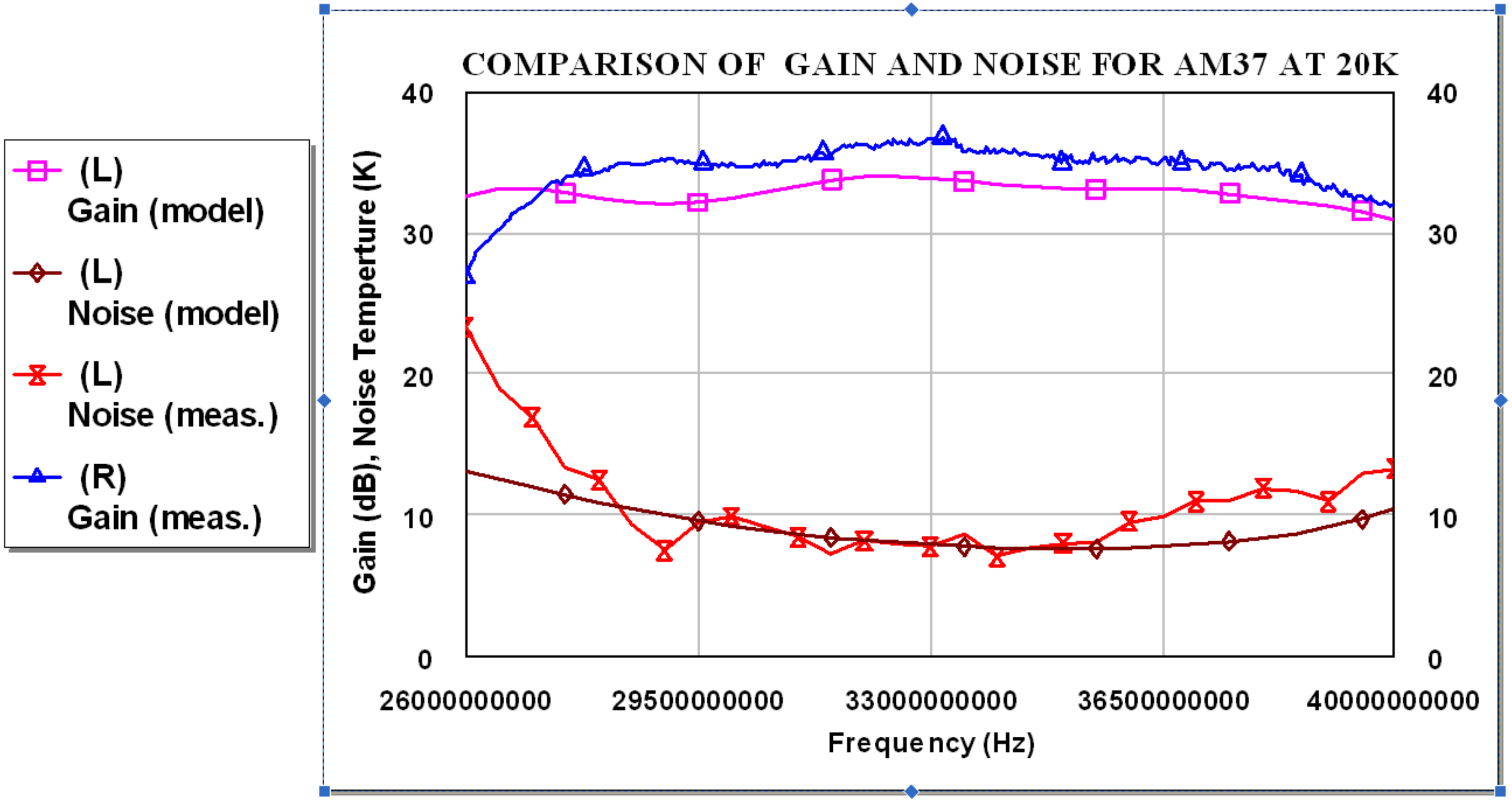
Optimal Noise Bias of InP HFET at 18 K (1993)



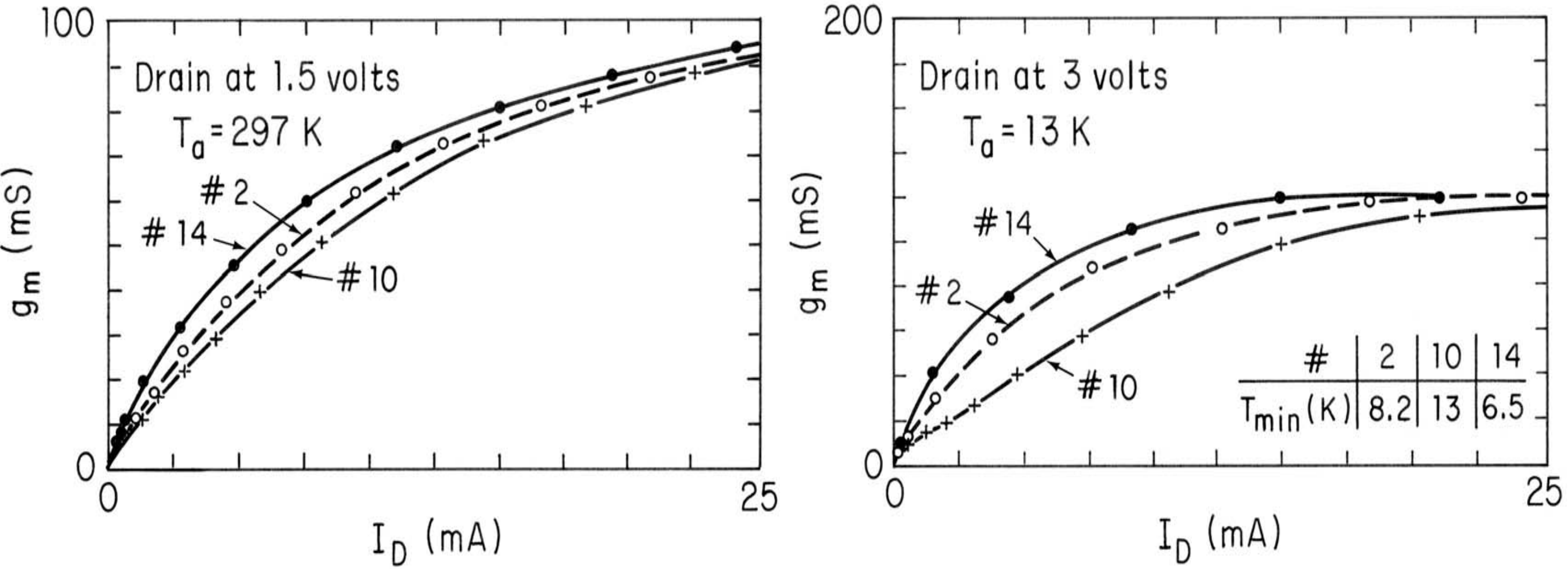
Optimal bias minimizes the value of:

$$f\left(V_{ds}, I_{ds}\right) \approx \frac{\sqrt{T_d g_{ds}}}{f_t} \approx \frac{\sqrt{I_D}}{g_m}$$

EVLA K_a Band Amplifier

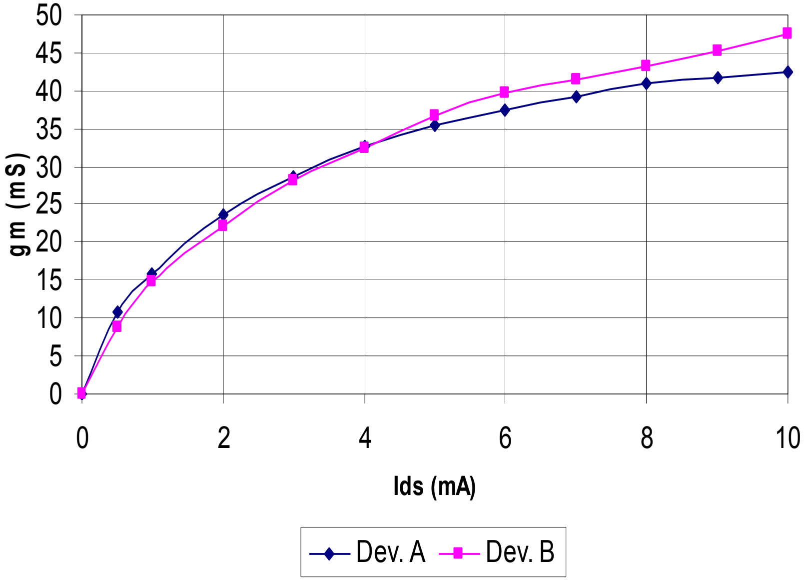


Cryogenic T_{min} at 8.4 GHz and DC Pinch–off Charactersitcs of GE HFET's (1987)

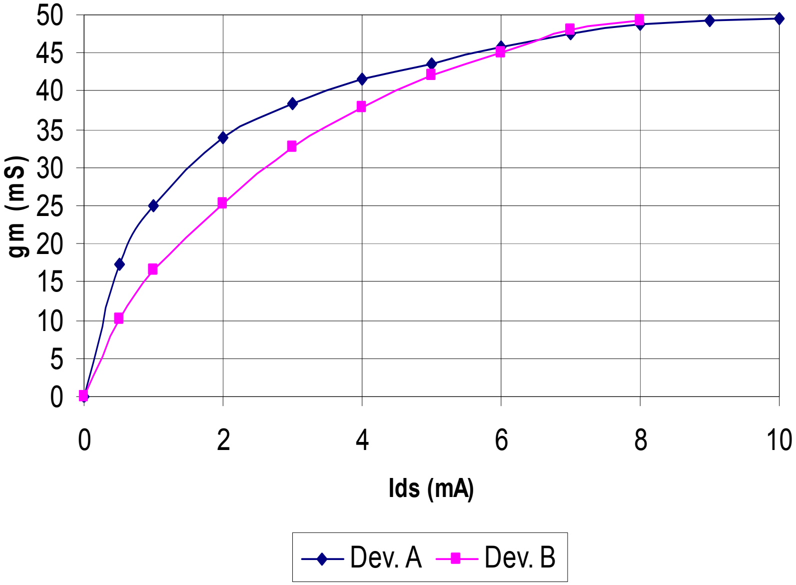


Example of “poor pinch off” InP HFET (1993)

T_a=297 K

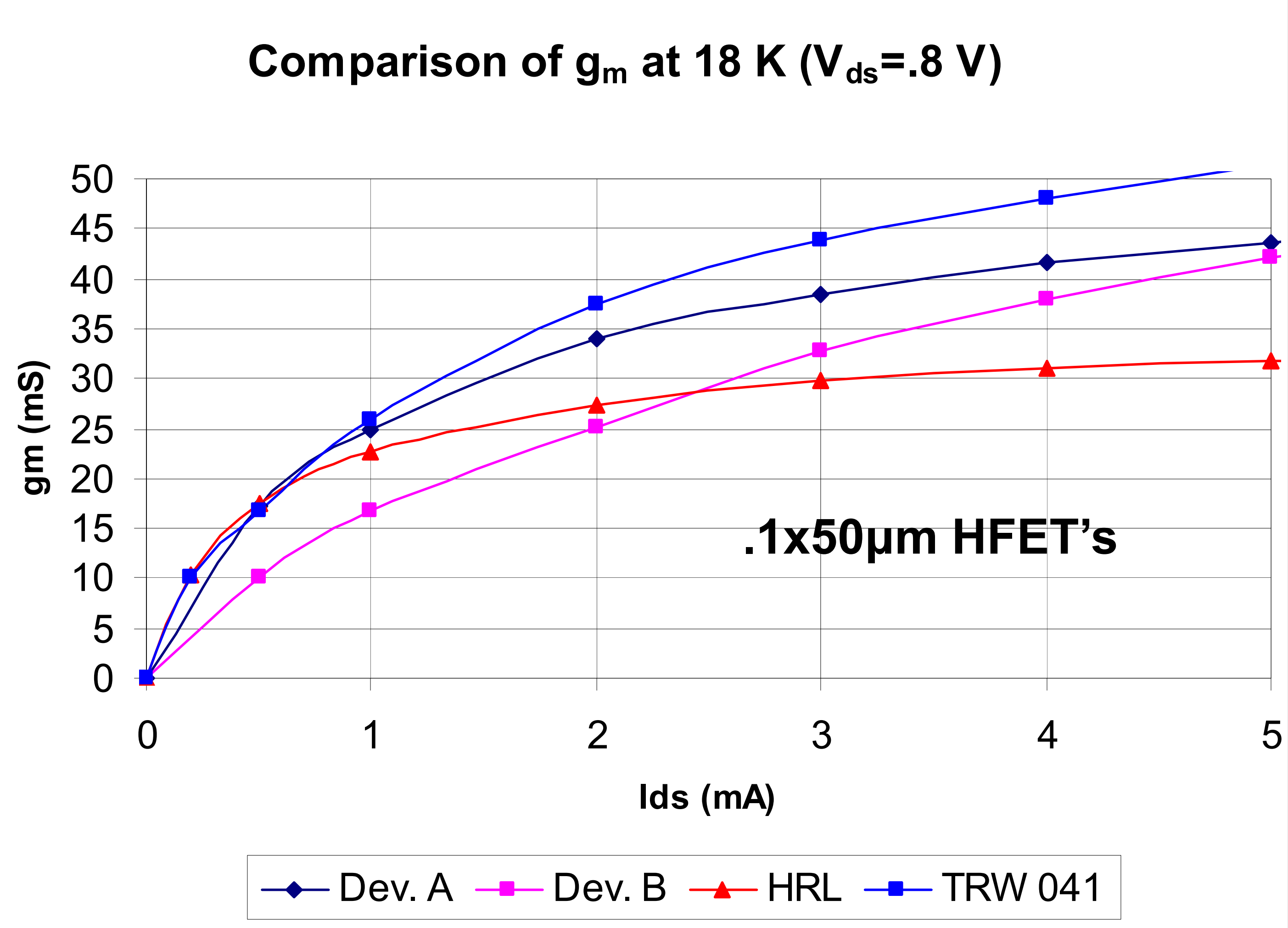


Ta=18 K



	T_{min}(297 K)	T_{min}(18 K)	at 40 GHz
Dev. A	148	12	
Dev. B	134	21	

Comparison of GE/MM, HRL and TRW HFET's



Device Scaling: Gate Width

$$T_{min} \cong 2\frac{f}{f_t}\sqrt{g_{ds}\,T_d\,r_t\,T_g}$$

$$R_{opt} \cong \frac{f_t}{f}\sqrt{\frac{r_t\,T_g}{g_{ds}\,T_d}}$$

$$r_t = r_{gs} + r_g + r_s$$

$$f\left(V_{ds}, I_{ds}\right) \approx \frac{\sqrt{T_d g_{ds}}}{f_t} \approx \frac{\sqrt{I_D}}{g_m}$$

Width ↗ R_{opt} ↘

T_{min} → in principle

T_{min} ↗ in practice

Device Scaling: Gate Length

$$T_{min} \cong 2\frac{f}{f_t}\sqrt{g_{ds}\,T_d\,r_t\,T_g}$$

$$f_t \cong \frac{g_m}{2\pi(C_{gs}+C_{gd})}$$

Length ↘ $r_t g_{ds}$ ↗ f_t ↗ T_{min} ↘

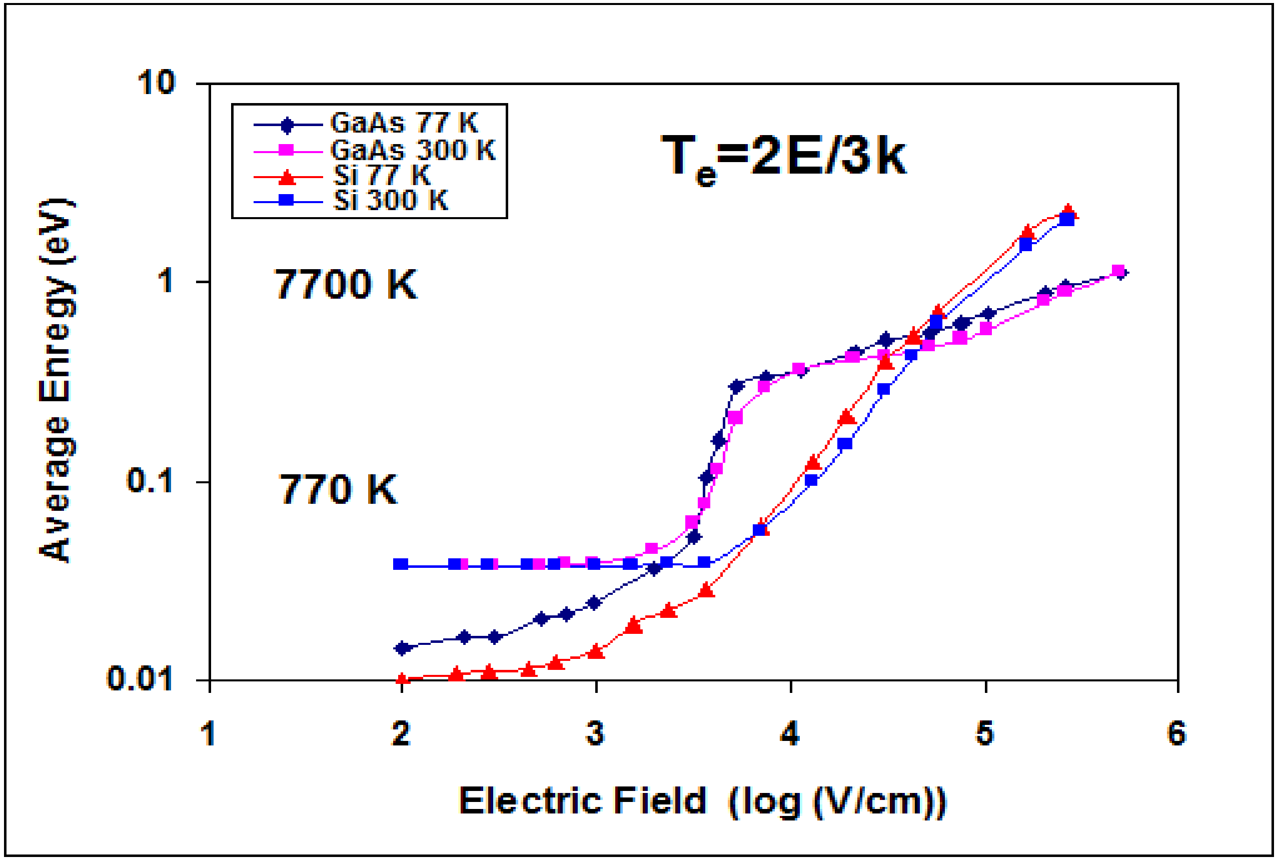
$T_g \cong$ Ambient temp.

T_d depends on channel structure and current I_d but mostly not on ambient temperature

For every wafer structure there must exist a lower limit on T_{min} upon further device scaling

Dependence of T_d on device structure and properties of electron transport in the channel is not known

“Hot electron” noise



After Fischetti, IEEE Trans. ED vol. 38, p.634, March 1991

To Cool or Not to Cool

1). No cryogenic performance can be predicted from room temperature performance

2). For well behaved cryo-devices the rule of thumb for amplifiers are:

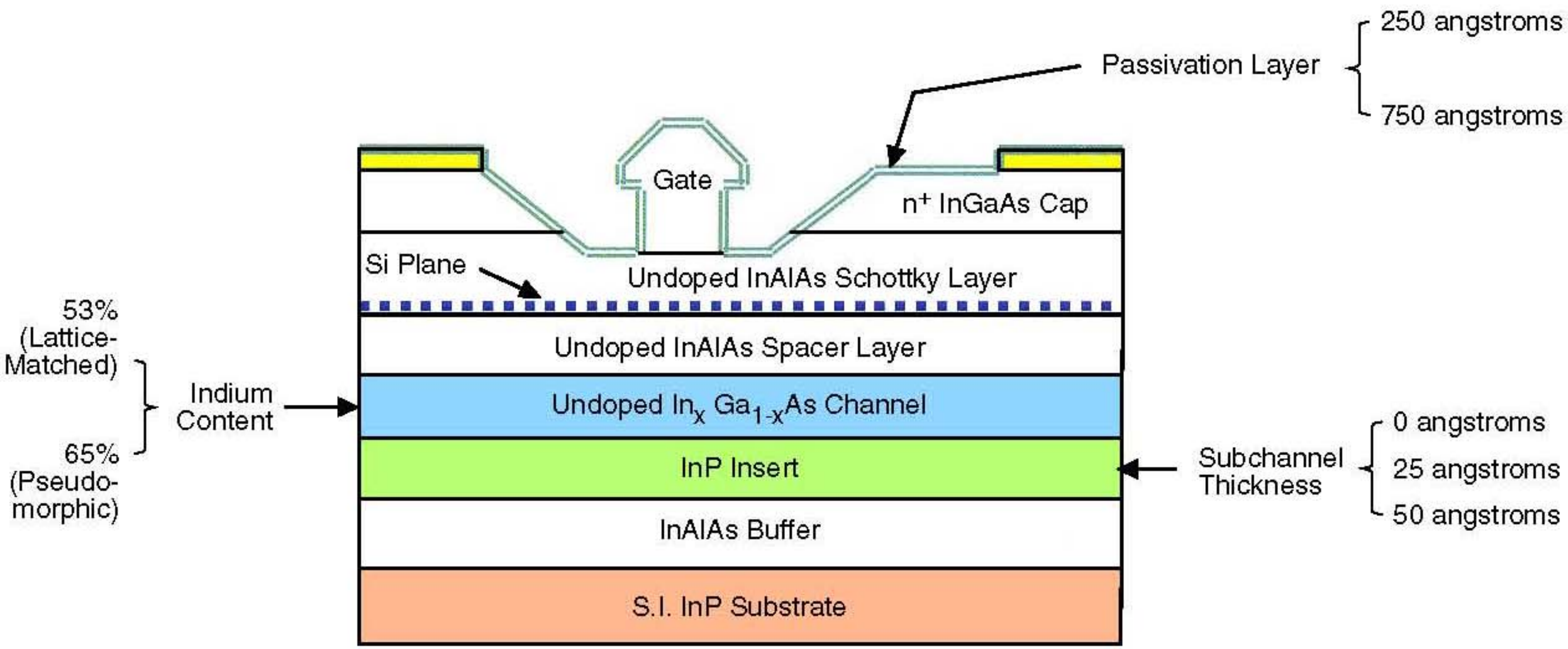
$$T_n(77K) \approx \sqrt{5} \times T_n(15K)$$

No change in bias upon cooling

$$T_n(297K) \approx 10 \times T_n(15K)$$

Optimal bias at each temperature

NGST/JPL CRYO3 WAFER



Wafer 4099-040 (Pseudomorphic InGaAs Channel, 750 Å Passivation Layer, 50 Å InP Insert)

Wafer 4044-041 (Pseudomorphic InGaAs Channel, 250 Å Passivation Layer, 25 Å InP Insert)

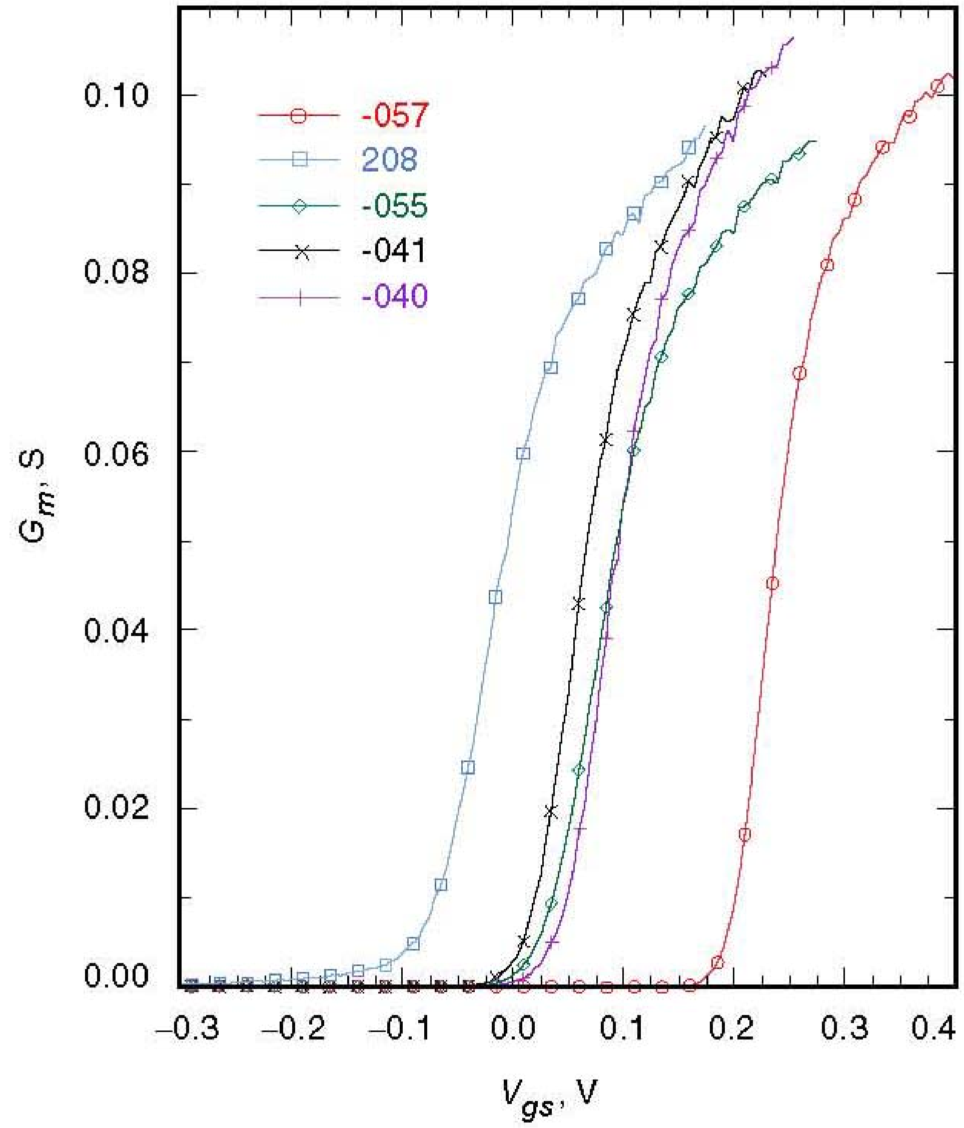
Wafer 4080-055 (Lattice-Matched InGaAs Channel, 750 Å Passivation Layer, 25 Å InP Insert)

Wafer 4080-057 (Lattice-Matched InGaAs Channel, 750 Å Passivation Layer, 50 Å InP Insert)

Wafer 4074-090 (Pseudomorphic InGaAs Channel, 750 Å Passivation Layer, No InP Insert)

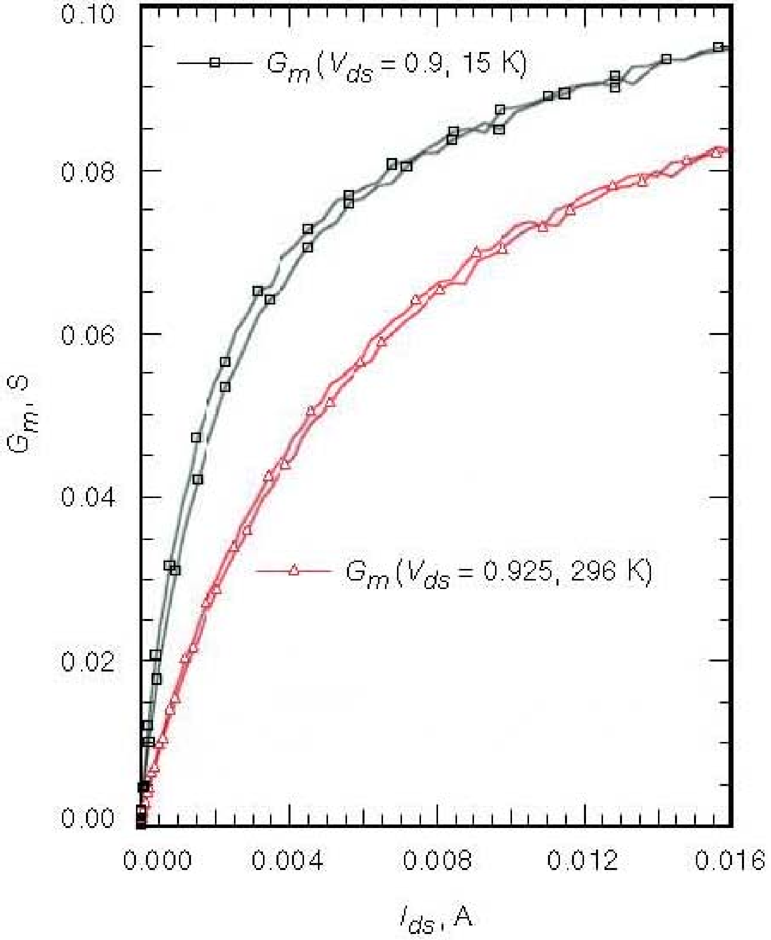
Wafer 4094-038 (Pseudomorphic InGaAs Channel, 250 Å Passivation Layer, No InP Insert)
(This Wafer Did Not Survive Processing)

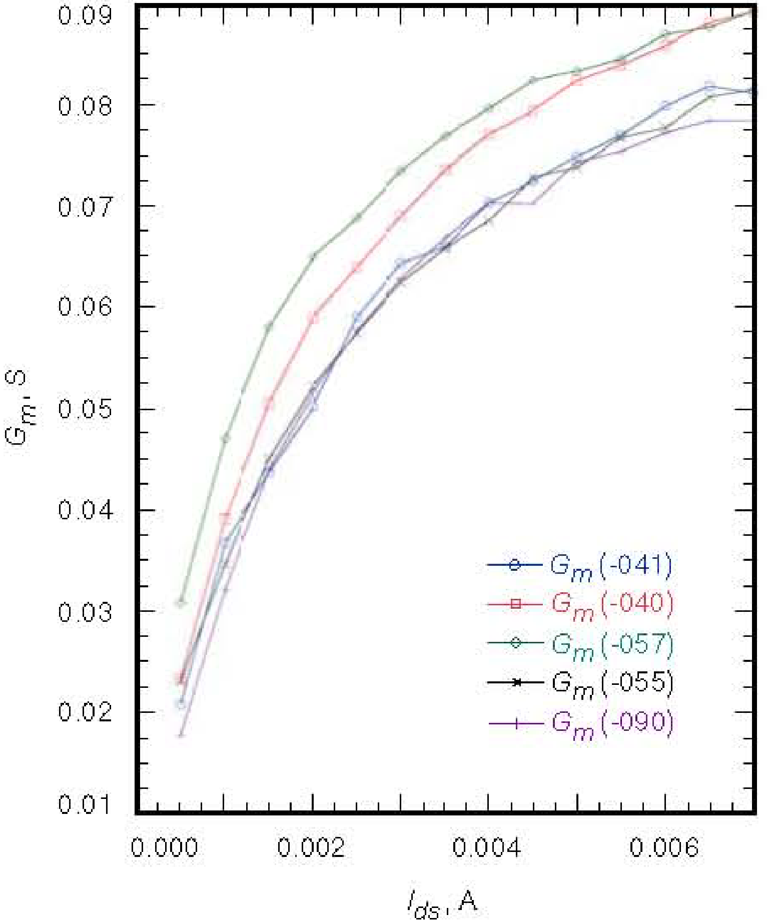
Cryo3 Wafer g_m vs V_{gs}



J.Shell,IPN Progress Report 42-169, JPL, May 2007

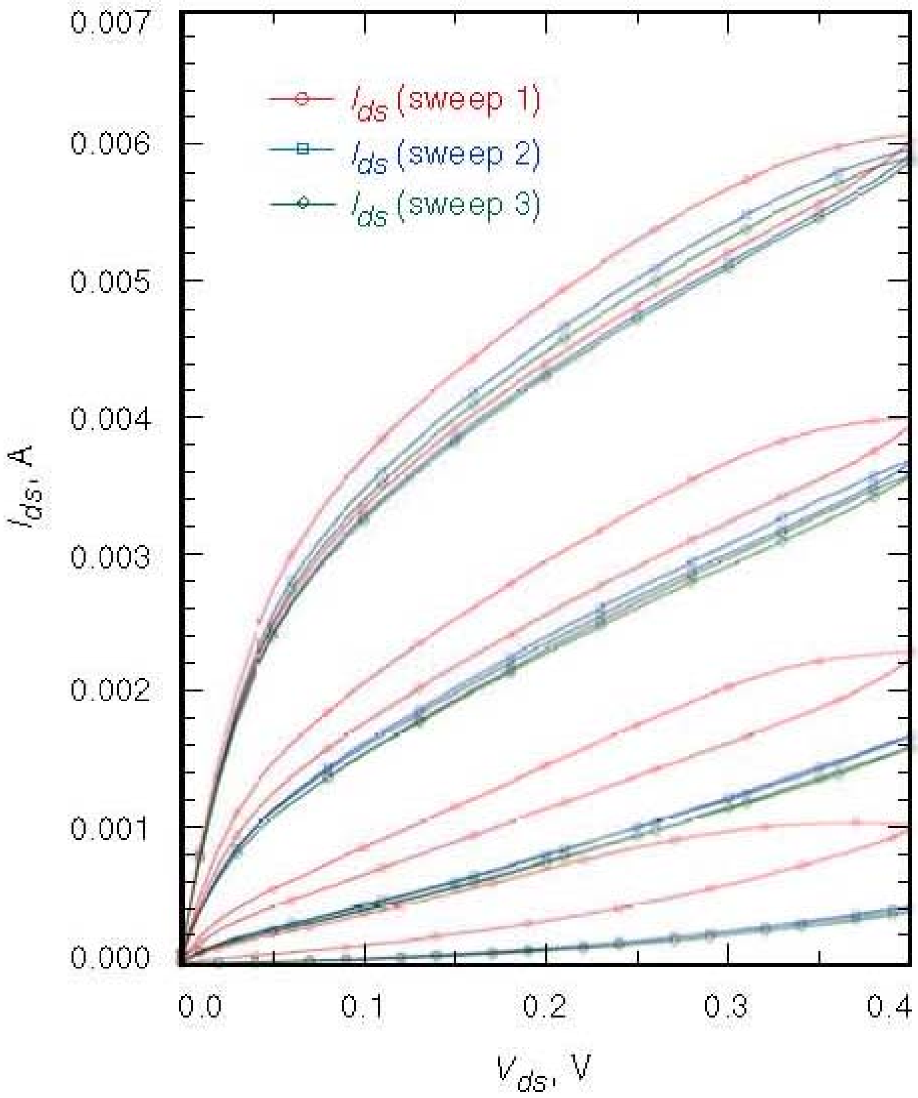
Cryo3 Wafer g_m vs V_{gs}





J.Shell,IPN Progress Report 42-169, JPL, May 2007

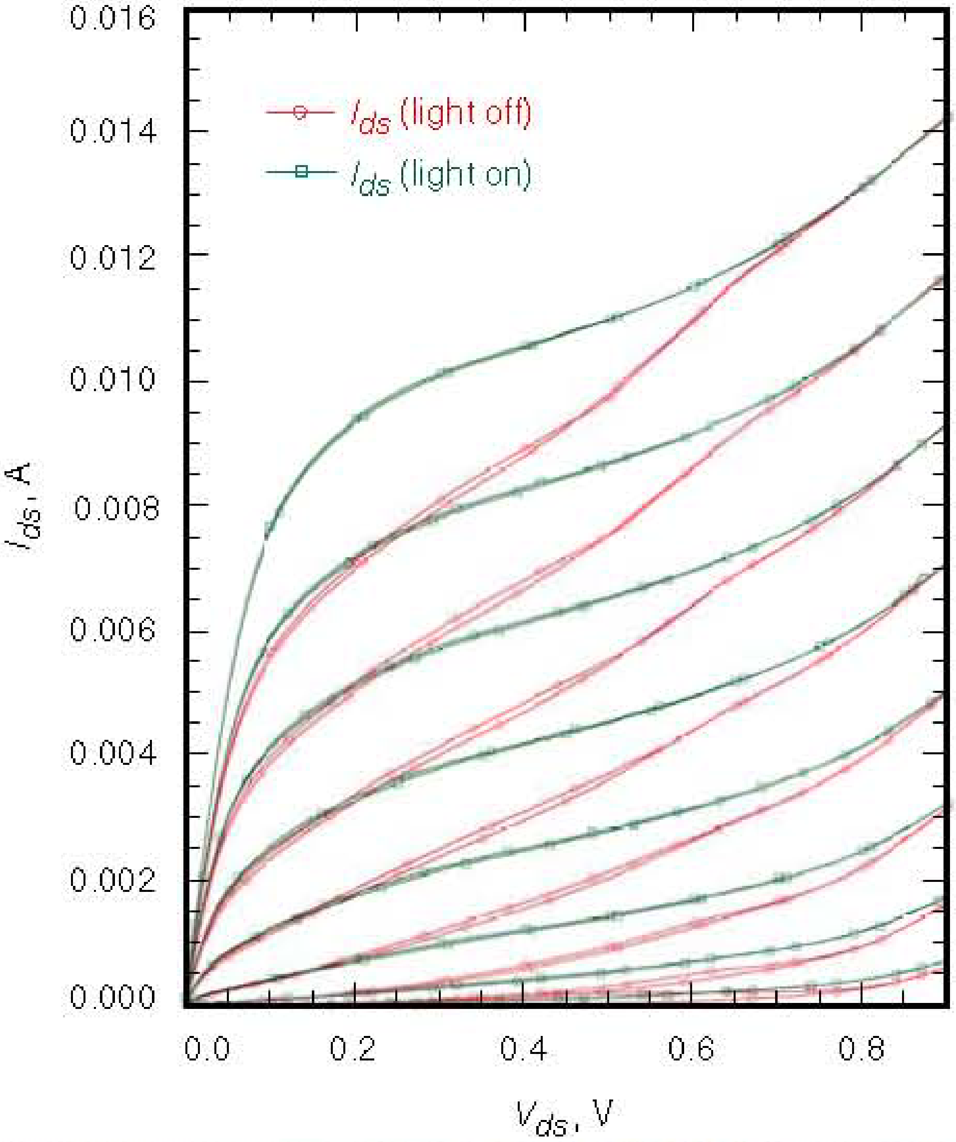
Cryo3 Wafer g_m vs V_{gs}



Double sweeps taken in fast succession

J.Shell,IPN Progress Report 42-169, JPL, May 2007

Cryo3 041 Wafer I-V Characteristics



J.Shell,IPN Progress Report 42-169, JPL, May 2007

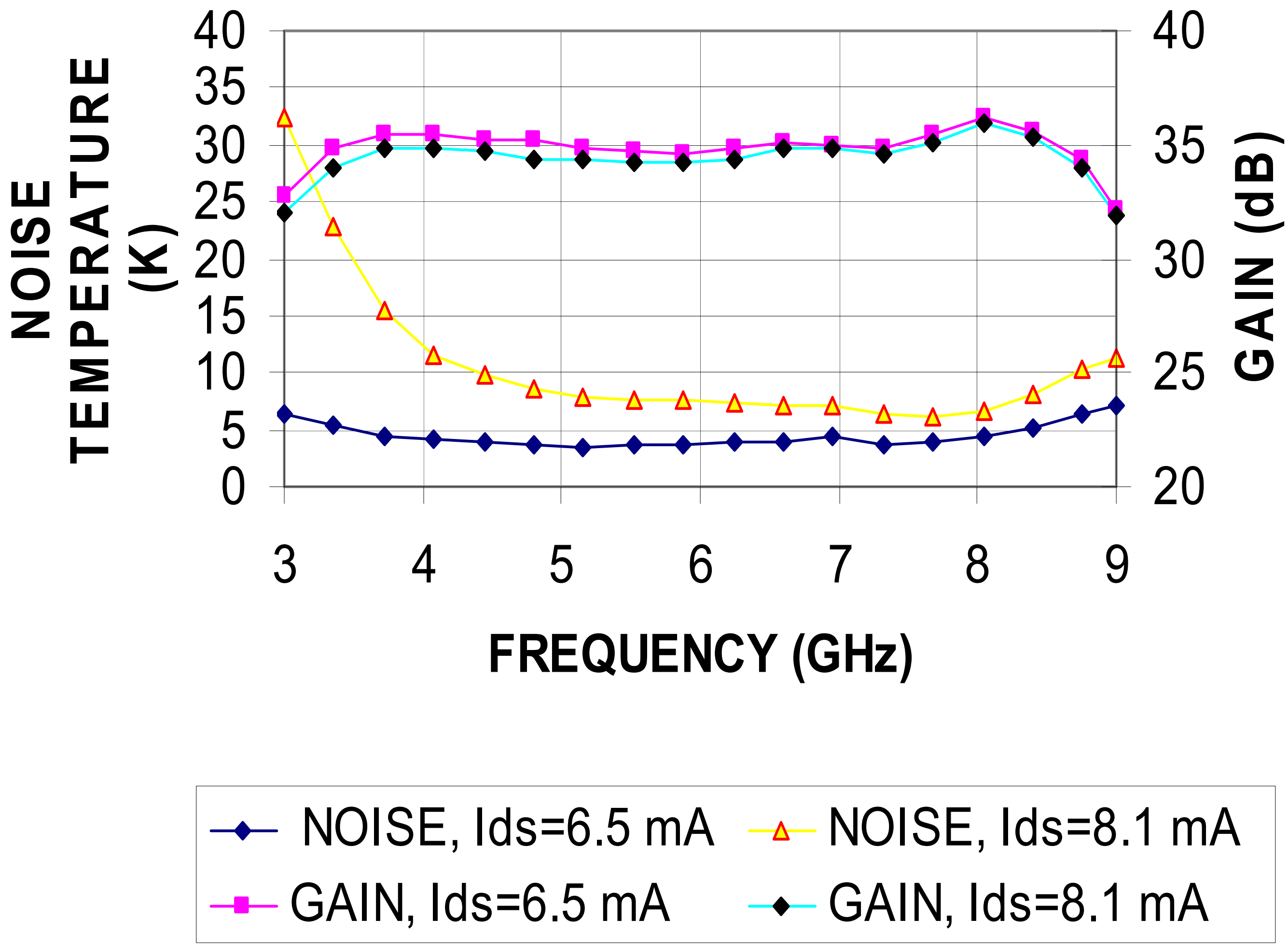
Cryo3 Questions Still Open:

- 300 µm wide InP HFET’s do not behave as expected from scaling (this applies to all the discrete wafers evaluated at NRAO)

- 200 µm from cryo3 wafer exhibit a very strong dependence of noise on drain voltage at L, S and C bands

- 80 and 60µm wide devices from cryo3 4044-041 wafer exhibit (sometimes) dc instability which seems to be related to device layout

4_8 GHz AMPLIFIER AT 15 K



Final Observations

- Only three wafer runs of InP discrete devices (NRAO/HRL, WMAP/HRL, NGST/JPL cryo3) have been used in construction of great majority of amplifiers for radio astronomy (VLA/EVLA,VLBA, GBT, ALMA band6, CBI, SZ-Array, WMAP, Planck LFI, VSA, AMI, MPI, JPL/DSN and others)
- No single wafer devices have ever been fully understood
- There has been no significant progress in the low noise performance of cryogenic FET's for the past 16 years; Are we approaching the limits?
- Amplifier noise temperature is no longer the dominant component of the system noise for radio astronomy instruments with cryogenic receivers