Extremely Low-Noise Cryogenic Amplifiers for Radio Astronomy: Past, Present and Future

Marian W. Pospieszalski

Acknowledgment: All the past and present members of the CDL Amplifier Group.

Outline

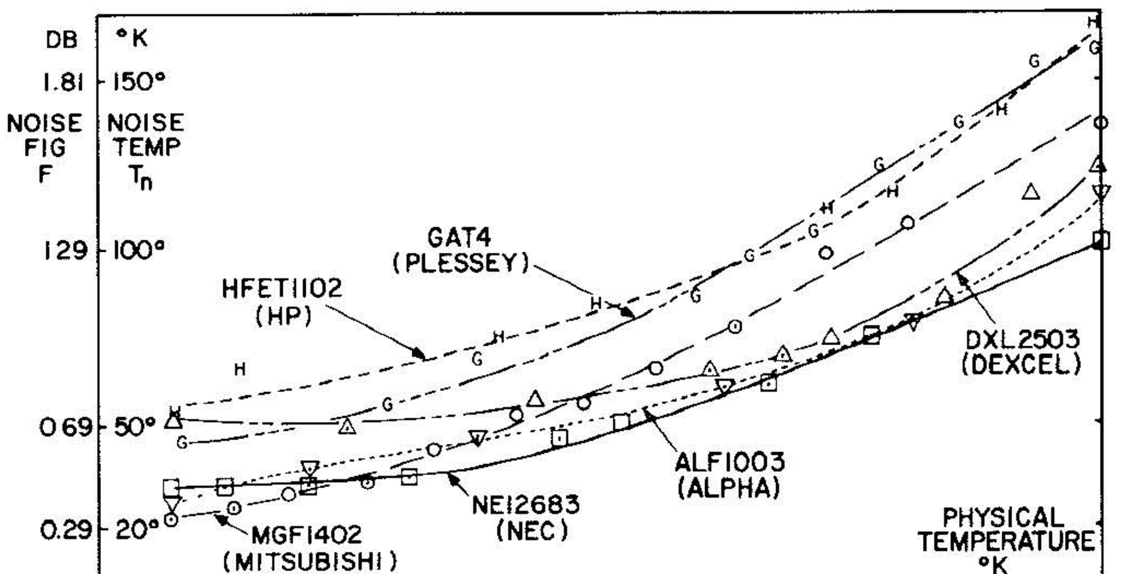
- Short history: important points in the development of cryogenic amplifiers at NRAO
- Review of the state-of the-art of cryogenic amplifiers with InP HFETs and SiGe HBTs.
- Cryogenic transistors and amplifiers: understanding of noise performance
  - Noise models; accuracy of model predictions
  - Dependence on bias, optimal noise bias: "quality of pinch-off"
  - Dependence on ambient temperature
  - Broadband noise matching
- On the limits of achievable noise performance of microwave transistors

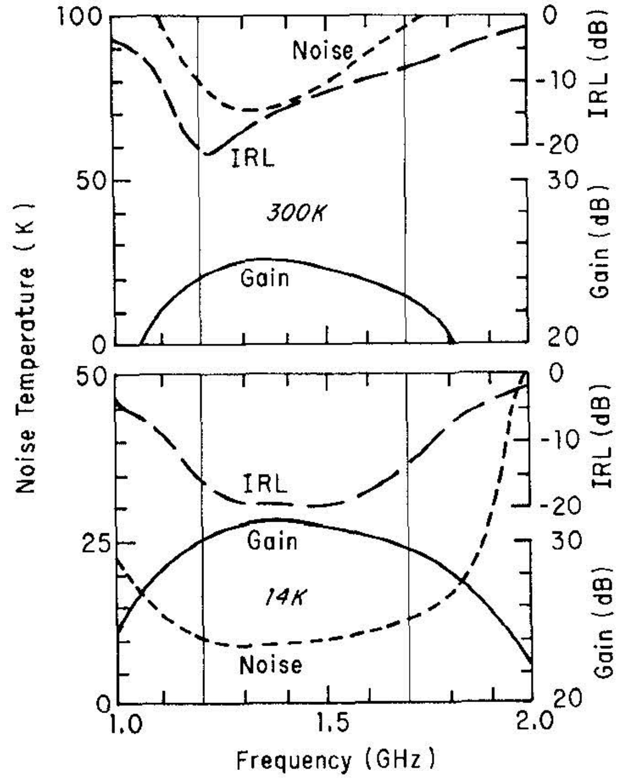
A Short History of FET's

- 1952 - Junction FET (JFET), Shockley (BTL)
- 1966 - Schottky Gate FET (MESFET), Mead (Caltech)
- 1967 - MESFET on GaAs, Hooper and Lehrer (Fairchild)
- 1970 - Prediction of carrier accumulation at heterointerface, Esaki and Tsu (IBM)
  - First cryogenic experiments, Loriou *et al* (France NTC), 120 K at 1 GHz
- 1976 – Cryogenic experiments at X-band ,Liechti *et al*. (HP), 60 K at 12 GHz
- 1978 – Mobility enhancement in GaAs/AlGaAs demonstrated,
  U.S. Patent for HFET (HEMT, TEGFET, MODFET, SDHT), Dingle *et al*. (BTL)

A Short History of FET's (2)

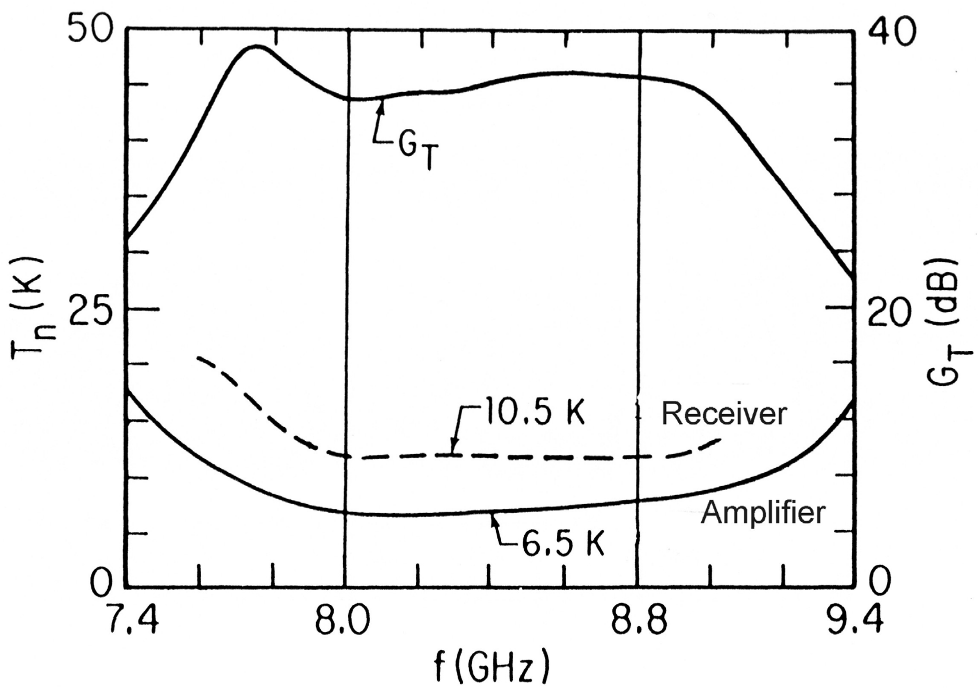
- 1980-82 – Practical cryogenic amplifiers using MESFET's demonstrated
  Weinreb *et al*. (NRAO), 7 K at 1.5 GHz, 20 K at 4.5 GHz



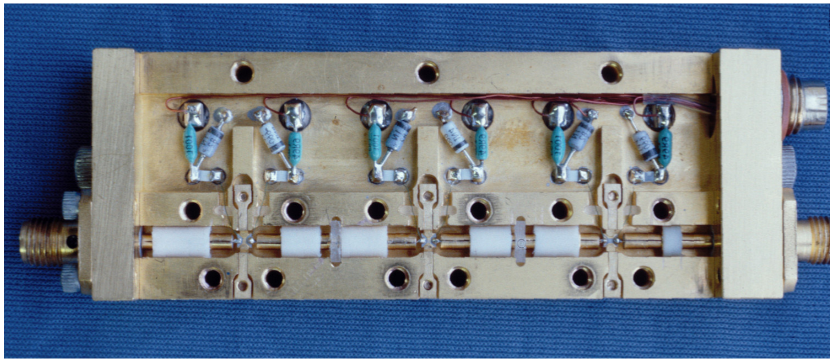


A Short History of FET's (2)

- 1980 – demonstration of HFET (GaAs/AlGaAs) devices, Mimura *et al.* (Fujitsu), Morkoc *et al.* (U. of Illinois, Rockwell)
- 1984 -87 – GaAs/AlGaAs HFET at cryogenic temperatures, Pospieszalski, Weinreb (NRAO), 6 K at 8.4 GHz



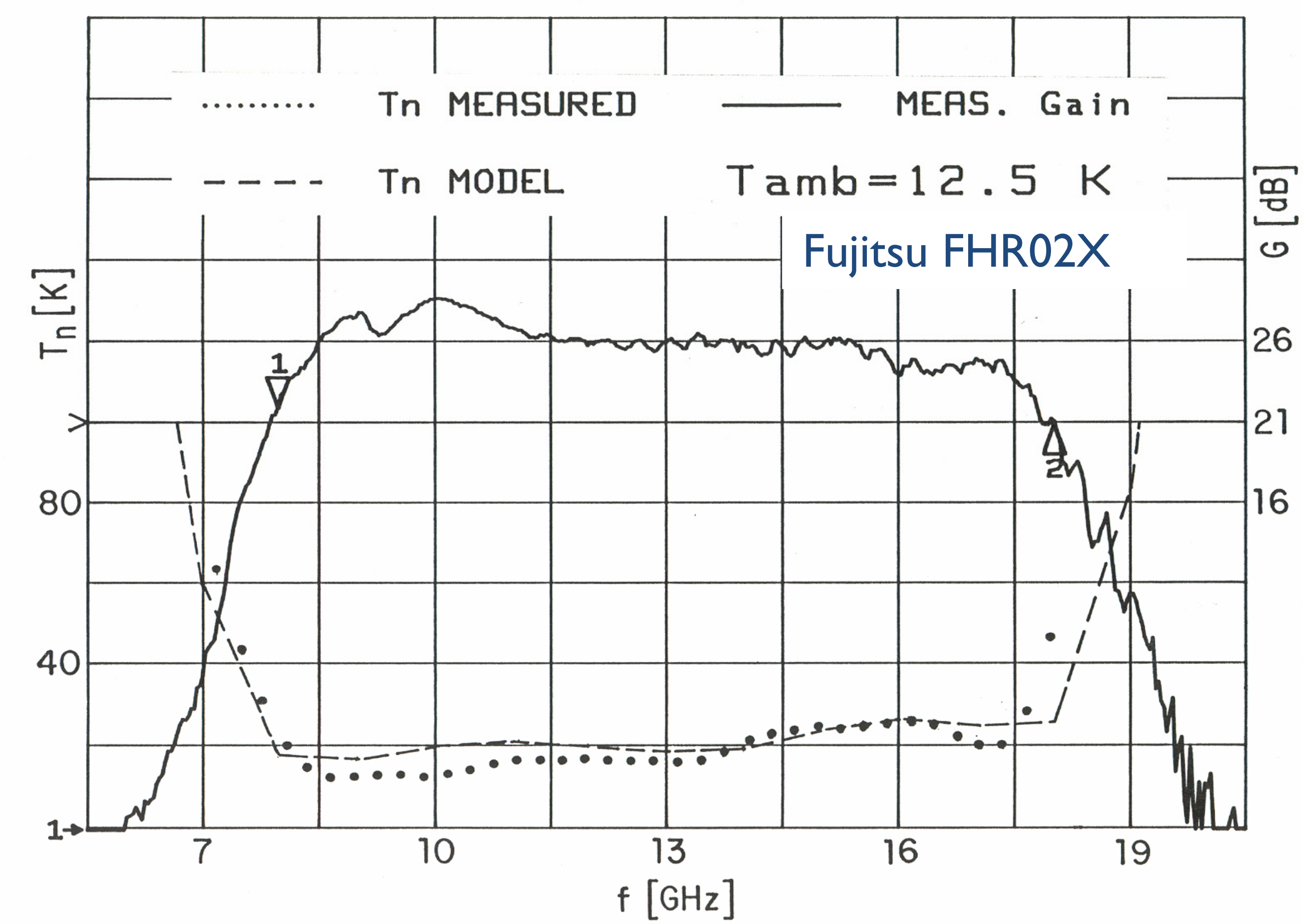
Voyager at Neptune X-band Amplifier



A Short History of FET's (3)

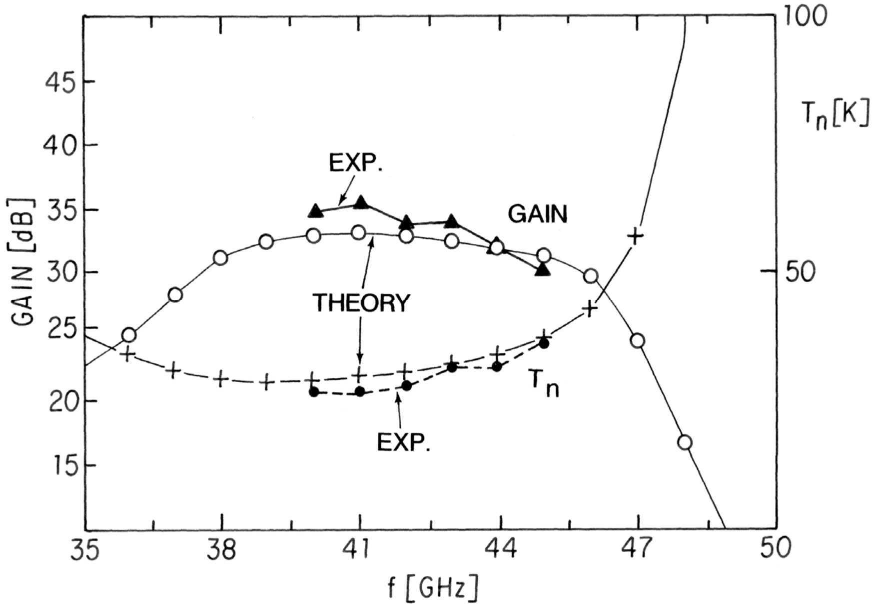
- 1985 – Pseudomorphic HFET (InGaAs/AlGaAs) introduced, Zipperian *et al*. (U.of Illinois), Rosenberg *et al.* (IBM)
- 1987 – Pulse-doped PHEMT introduced, Moll *et al*. (HP)
  - First demonstration of InGaAs/InAlAs/InP HFET's, Morkoc *et al.* (U. of Illinois)
- 1988 – Noise model of FET suitable for cryogenic applications developed, Pospieszalski (NRAO)
  - Pseudmorphic HEMT cooled, Weinreb *et al*. (NRAO), 25 K at 40 GHz (Linear Monolithics)
  - First .1 um gate length InP HFET demonstrated, Mishra *et al.* (HRL) soon joined by TRW, GE and Martin-Marietta (1989-91)

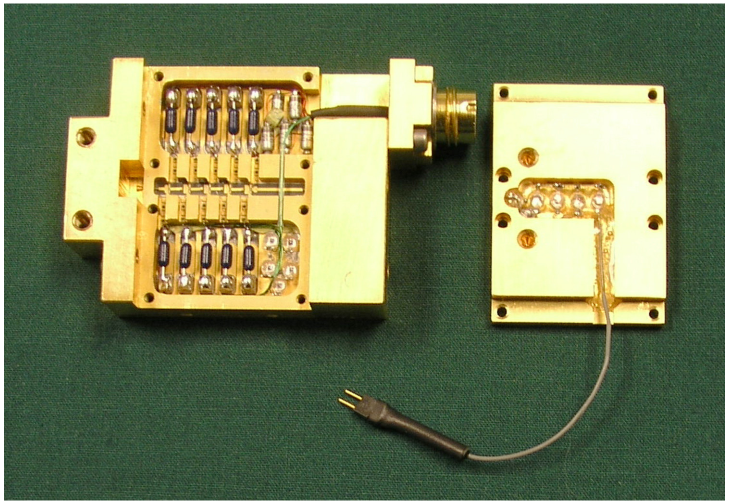
8-18 GHz Amplifier at 12.5 K (1988)



First amplifier designed using "Pospieszalski " noise model

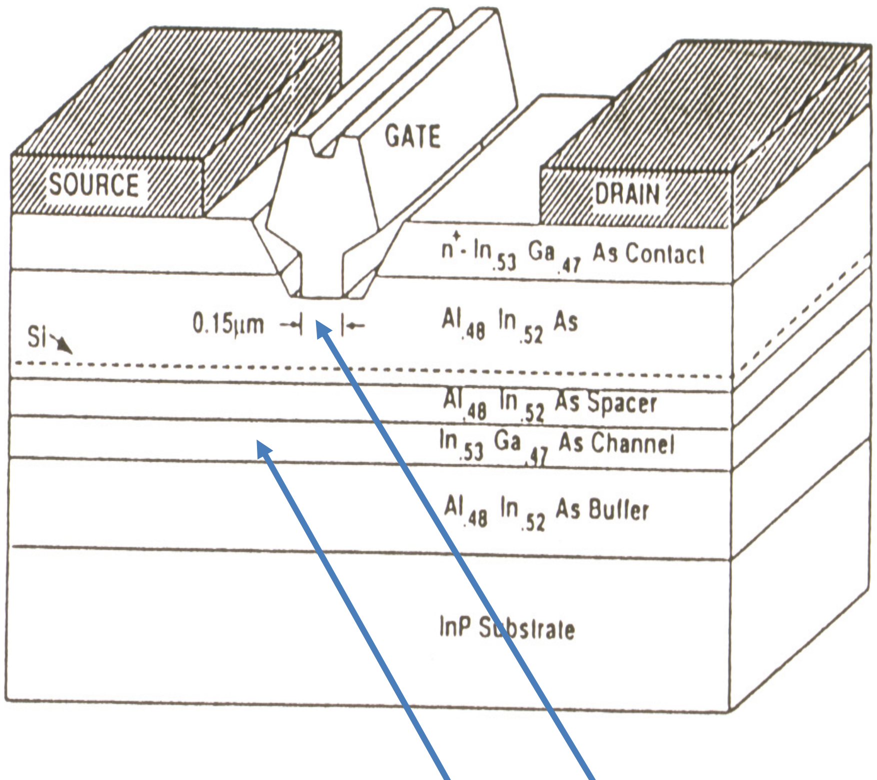
VLBA Q-band Amplifier (1991)

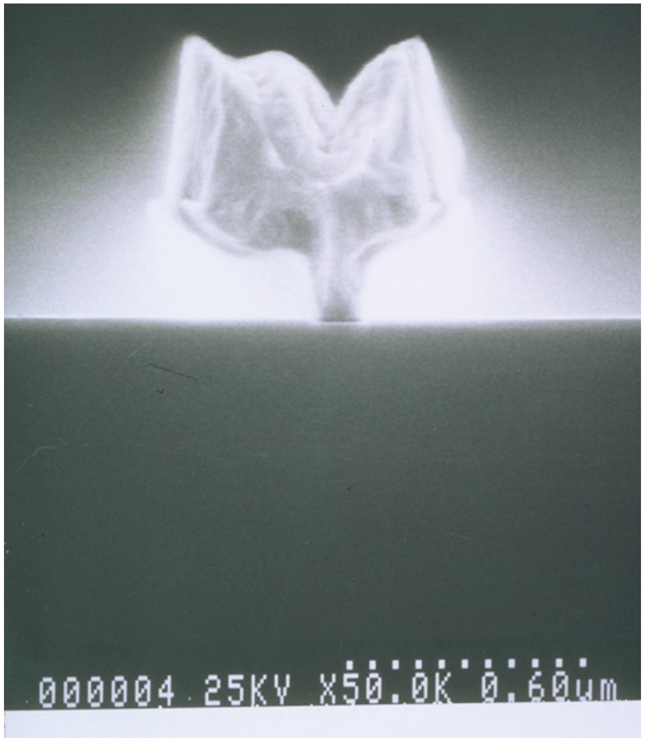




Linear Monolithics – ROHM Research PHEMT with .1 X 100 micron gate has been used
These amplifiers are still in use in majority of VLBA Q-band receivers

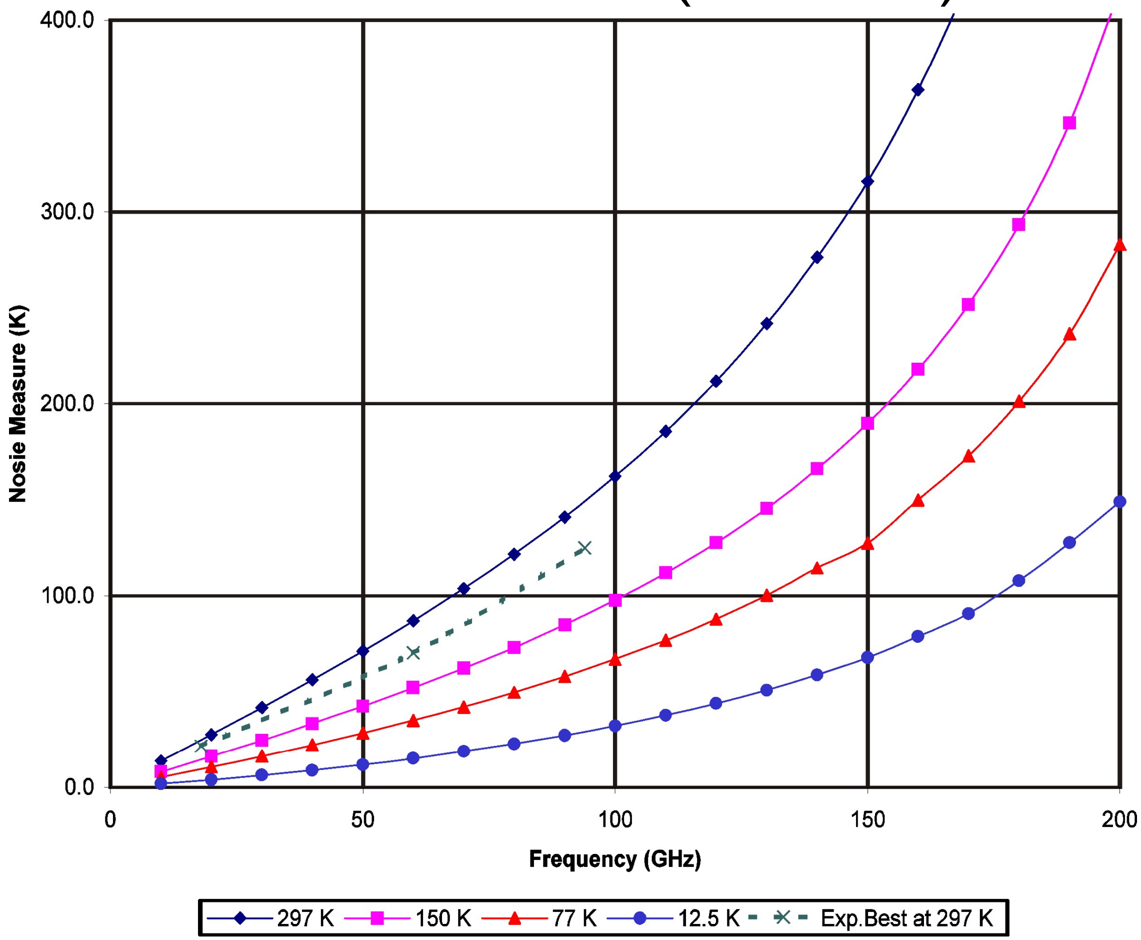
InGaAs/InAlAs/InP HEMT





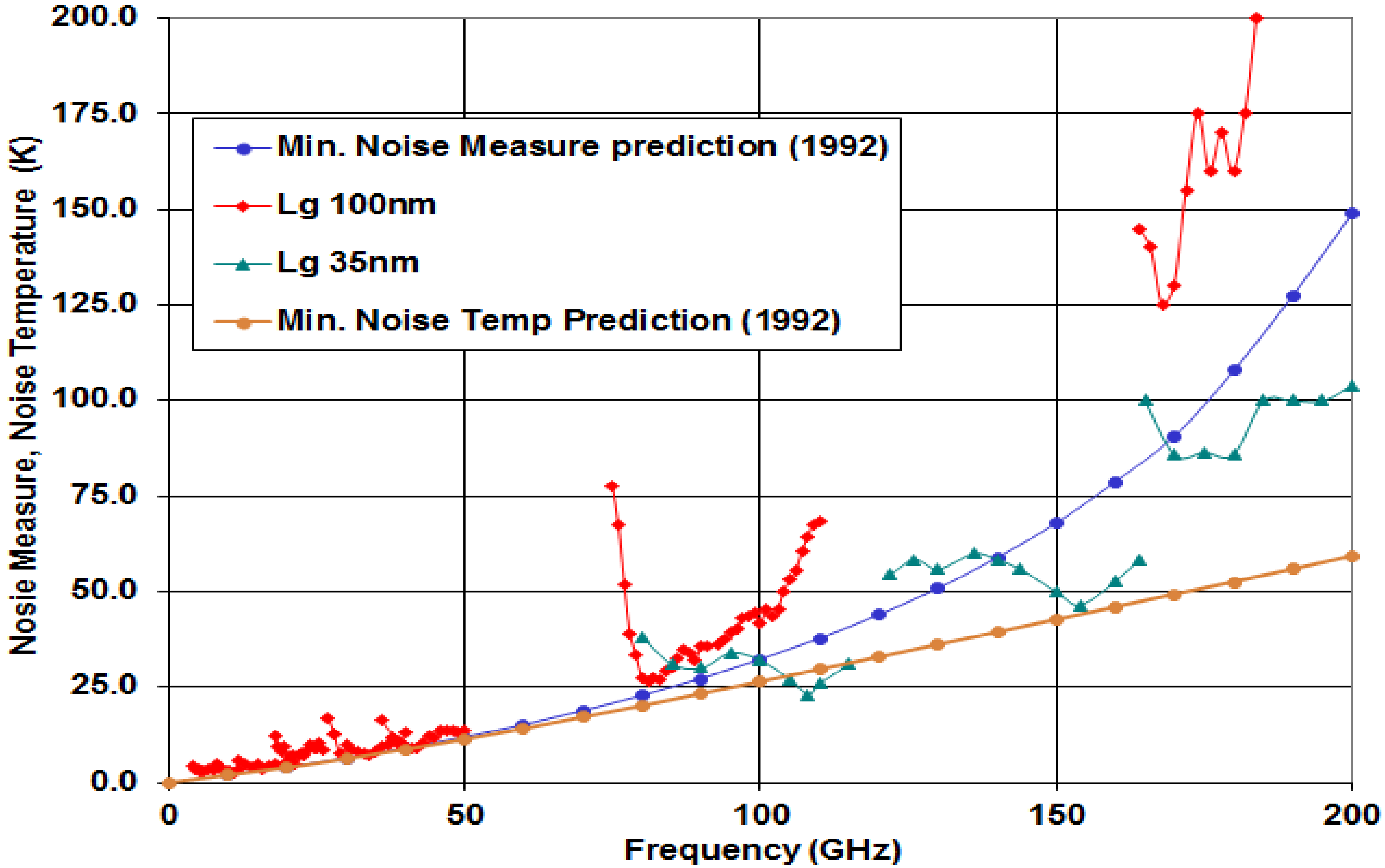
In modern InP HEMTs gate length is down to 20 nm and Indium content in the channel varies up 100 percent

Prediction of InP HEMT Minimum Noise Measure (1991-92)

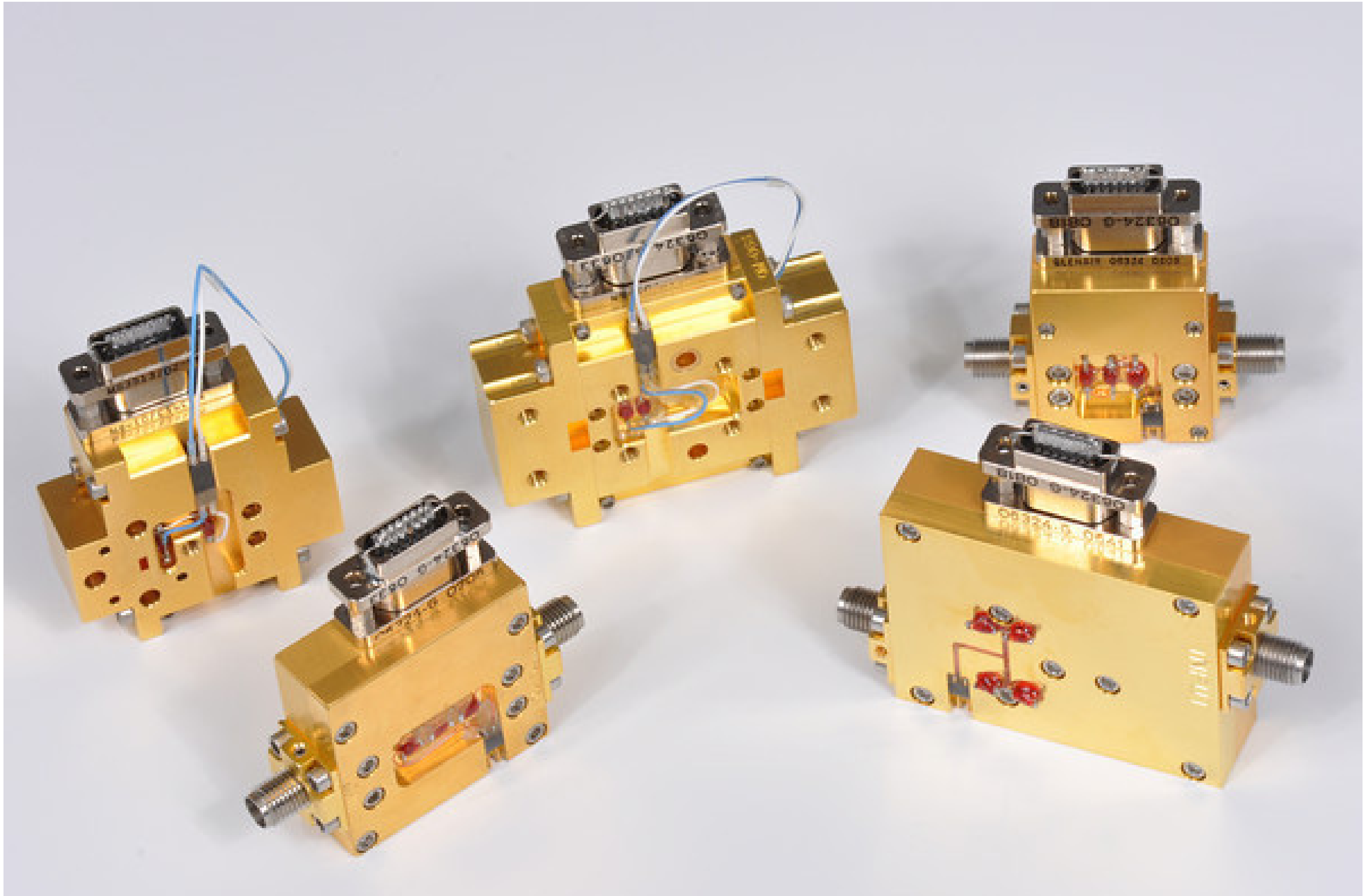


Source:
MMA Memo #67
and paper at 1992
IMS, Albuquerque, NM

State-of–the-Art 2016



JVLA Amplifiers



MIC ("chip and wire") vs. MMIC

MMIC Disadvantages:

- Package typically over-moded (absorbers needed)
- Repair of failures much more difficult,
- If it does not work properly, no diagnosis can be easily performed
- Impossible to modify
- Limited number of chips on a single wafer
- Performance not always repeatable from wafer to wafer

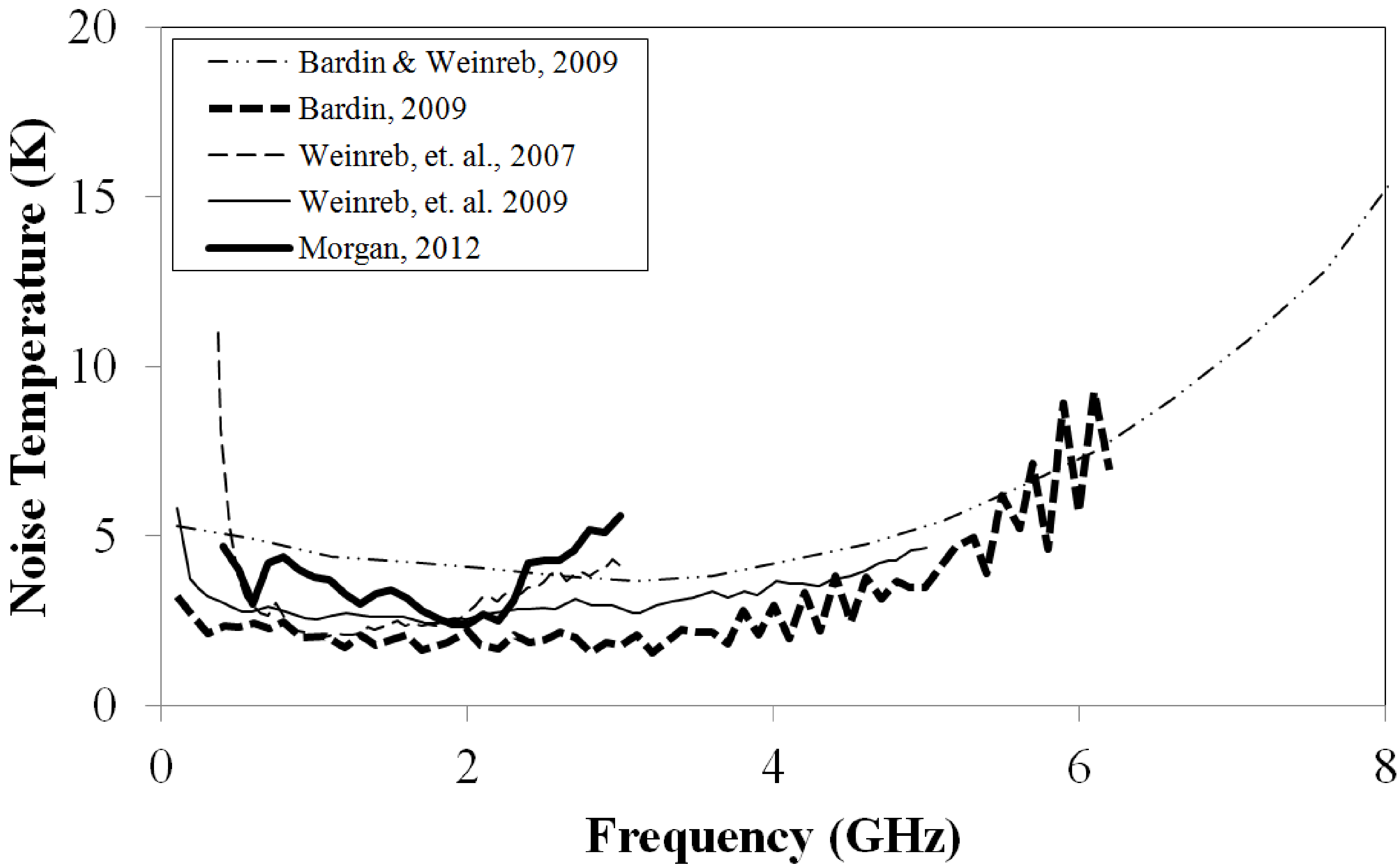
MMIC Advantages:

- Assembly labor (saves anywhere from 1 to 4 days of technician time per amplifier)
- Much better control of design than in case of MIC
- MIC practically impossible to built with devices having gates < 100 nm

What we do not understand about cryogenic HEMTs:

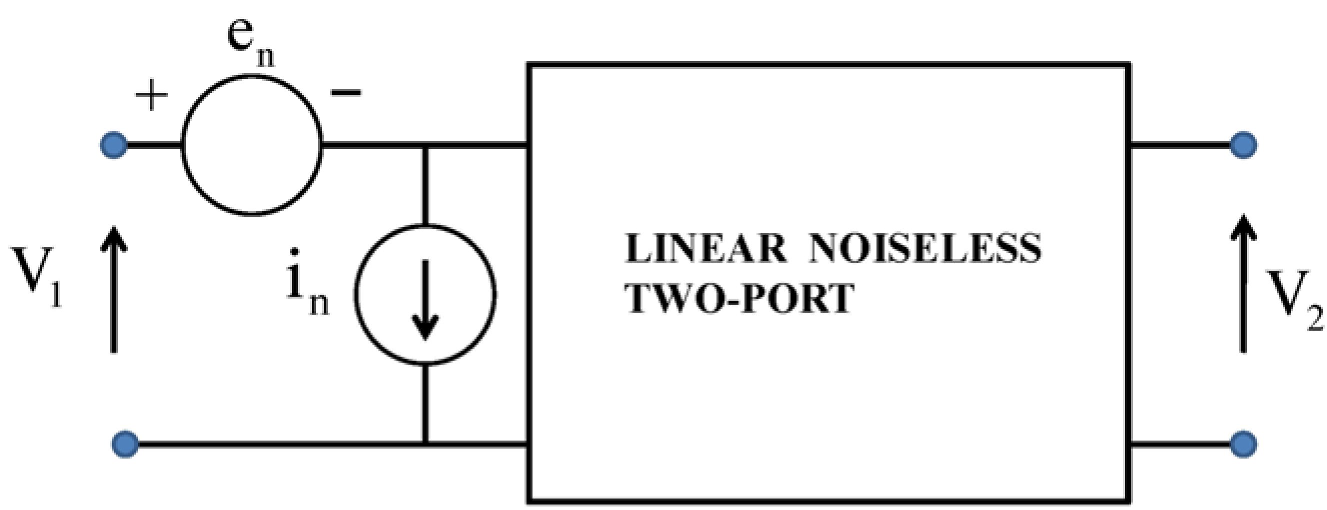
- light illumination: effects on noise and gain, short and long term stability of both
- 1/f gain fluctuations
- what determines the "quality of pinch off"
- DC (or possibly RF) instability in InP HFET's of larger gate periphery (>200 microns)
- so called "current switch off" effect in InP devices which seems to be dependent on device layout
- an additional source of noise with 1/f like spectrum at certain bias usually at drain currents densities slightly higher than typically optimal for noise

Best Cryogenic SiGe Amplifiers



What We Do Understand

Common Noise Representations of 2-Ports



$$g_n = \frac{\overline{|i_n|^2}}{4kT_0 df} \qquad R_n = \frac{\overline{|e_n|^2}}{4kT_0 df} \qquad T_0 = 290\ \text{K}$$

$$\rho = \frac{\overline{e_n^* i_n}}{\sqrt{\overline{|e_n|^2}\,\overline{|i_n|^2}}}$$

k –Boltzmann constant

Caltech, January 17, 2014
17

Common Noise Representations of 2-Ports (2)

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

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

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

Allowed Values of Noise Parameters

For All Linear Noisy Two-Ports: $|\rho| \leq 1$ ⟺ $T_{min} \leq 4NT_o$

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

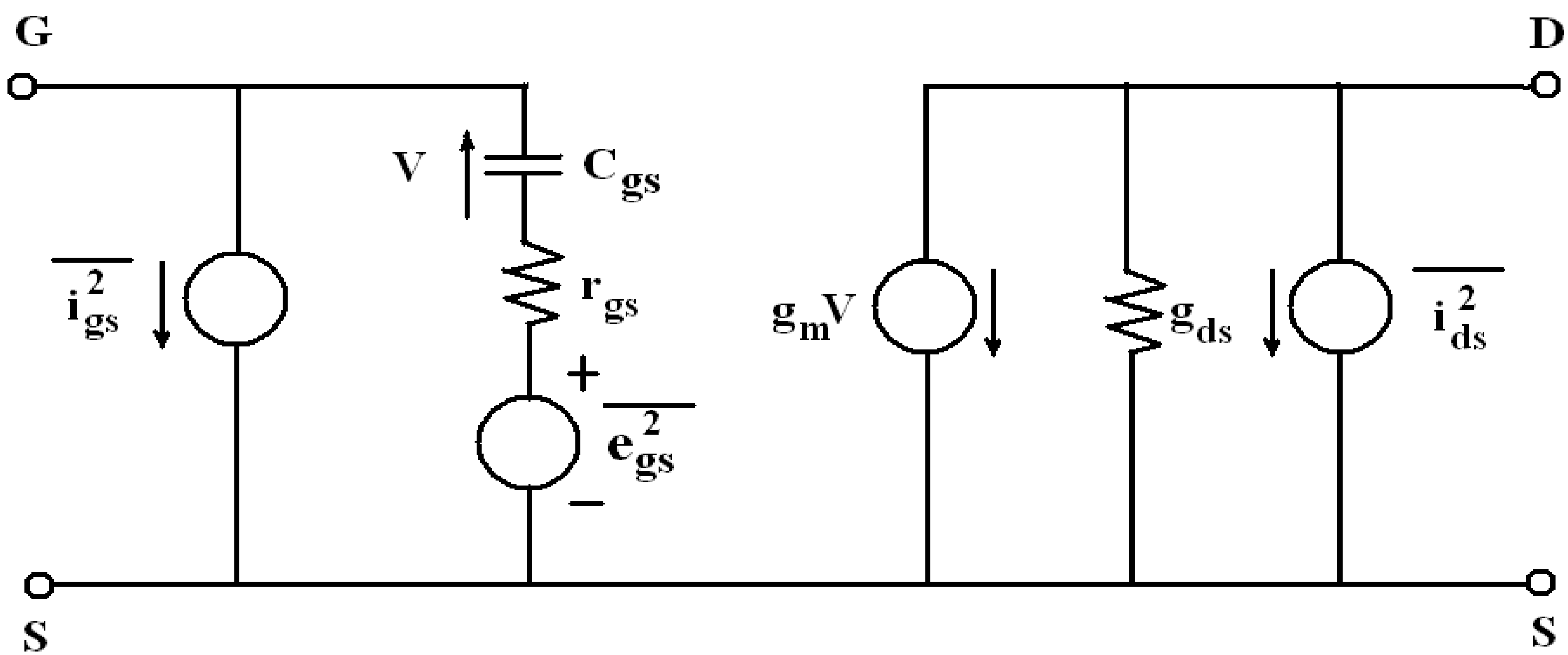
If therefore Re(ρ) ≥ 0 and correlation matrix is Hermitian and non-negative definite, than always

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

For all microwave transistors for useful frequency range :

$$\frac{4NT_0}{T_{min}} \approx 2$$

Simplest Noise Equivalent Circuit of a FET



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

Noise Parameters of FET: Low Frequency Approximation

For: $A\left(\frac{f_t}{f}\right)^2 >> 1$ and $\overline{i_{gs}^{\,2}} = 2\,qI_{gs}\Delta f$

$$T_{min}^{L} = \sqrt{2\,qI_{gs} r_{gs} \frac{T_g}{k}}$$

$$R_{opt}^{L} = \sqrt{2\,kr_{gs} \frac{T_g}{qI_{gs}}}$$

$$g_n^{L} = \frac{qI_{gs}}{2\,k\,T_o}$$

$$\frac{4\,NT_o}{T_{min}} \cong 2$$

Noise Parameters of FET: High Frequency Approximation

But still for:

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

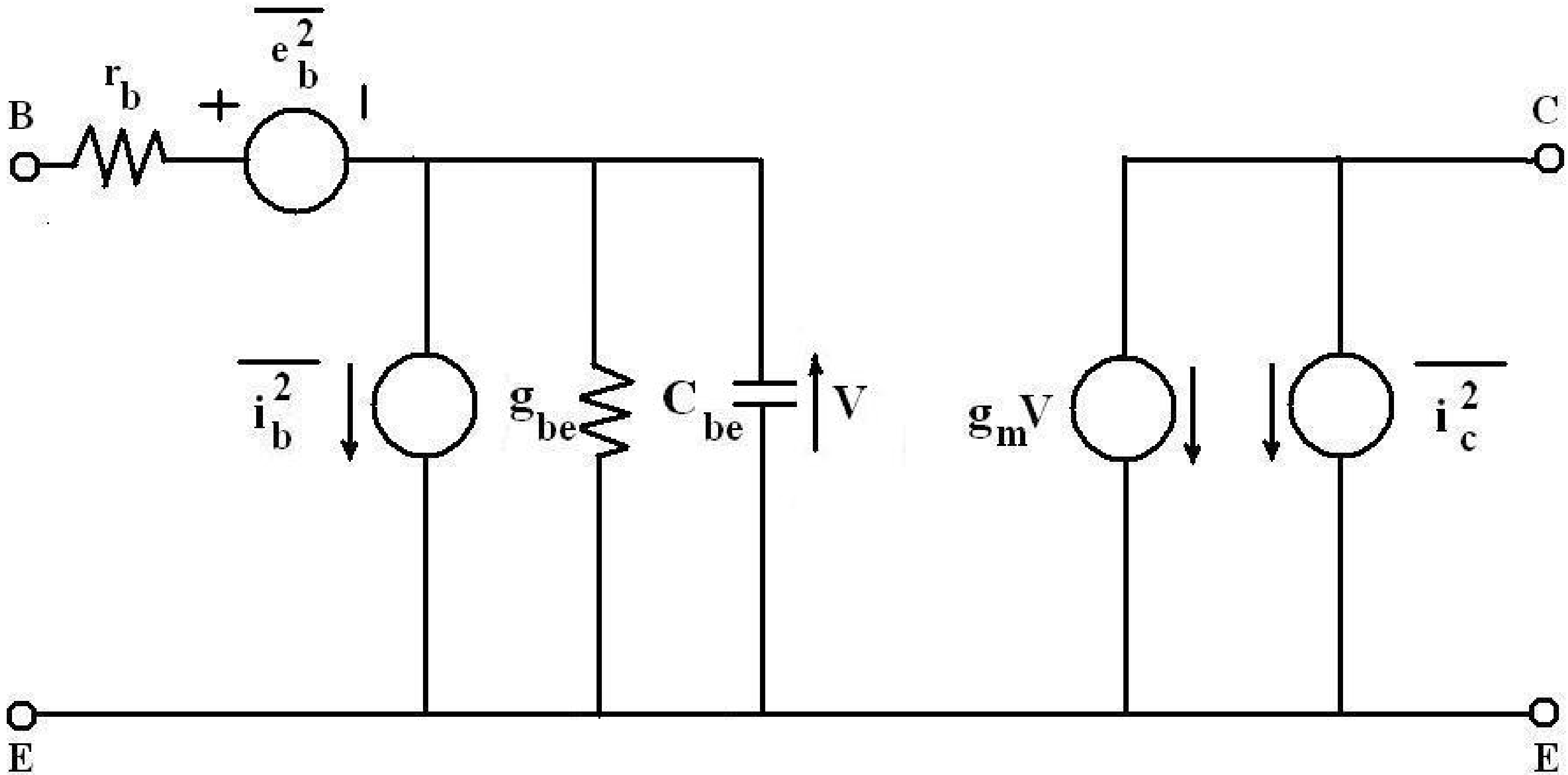
$$R_{opt} \cong \frac{f_t}{f} \sqrt{\frac{r_{gs}\, T_g}{g_{ds}\, T_d}}$$

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

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

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

Simplest Noise Equivalent Circuit of Intrinsic HBT



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

InP HFET vs. SiGe HBT

InP HFET

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

SiGe HBT

$$f << \frac{f_t}{\sqrt{\beta}} \text{ and } \beta >> 1$$

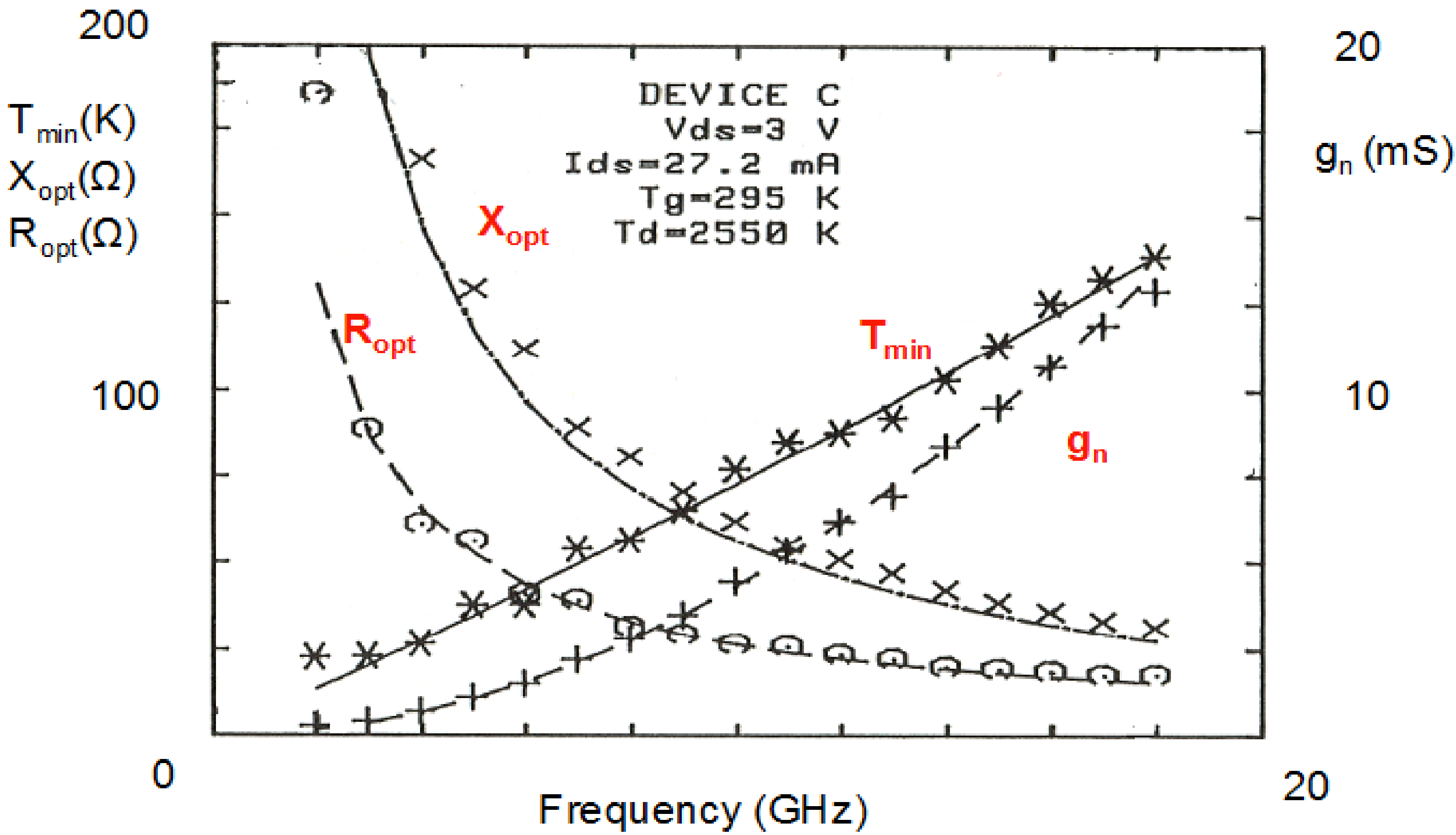
$$T_{min} = \sqrt{\frac{2\, qI_b T_a r_b}{k}}$$

$$f >> \frac{f_t}{\sqrt{\beta}} \text{ and } \beta >> 1$$

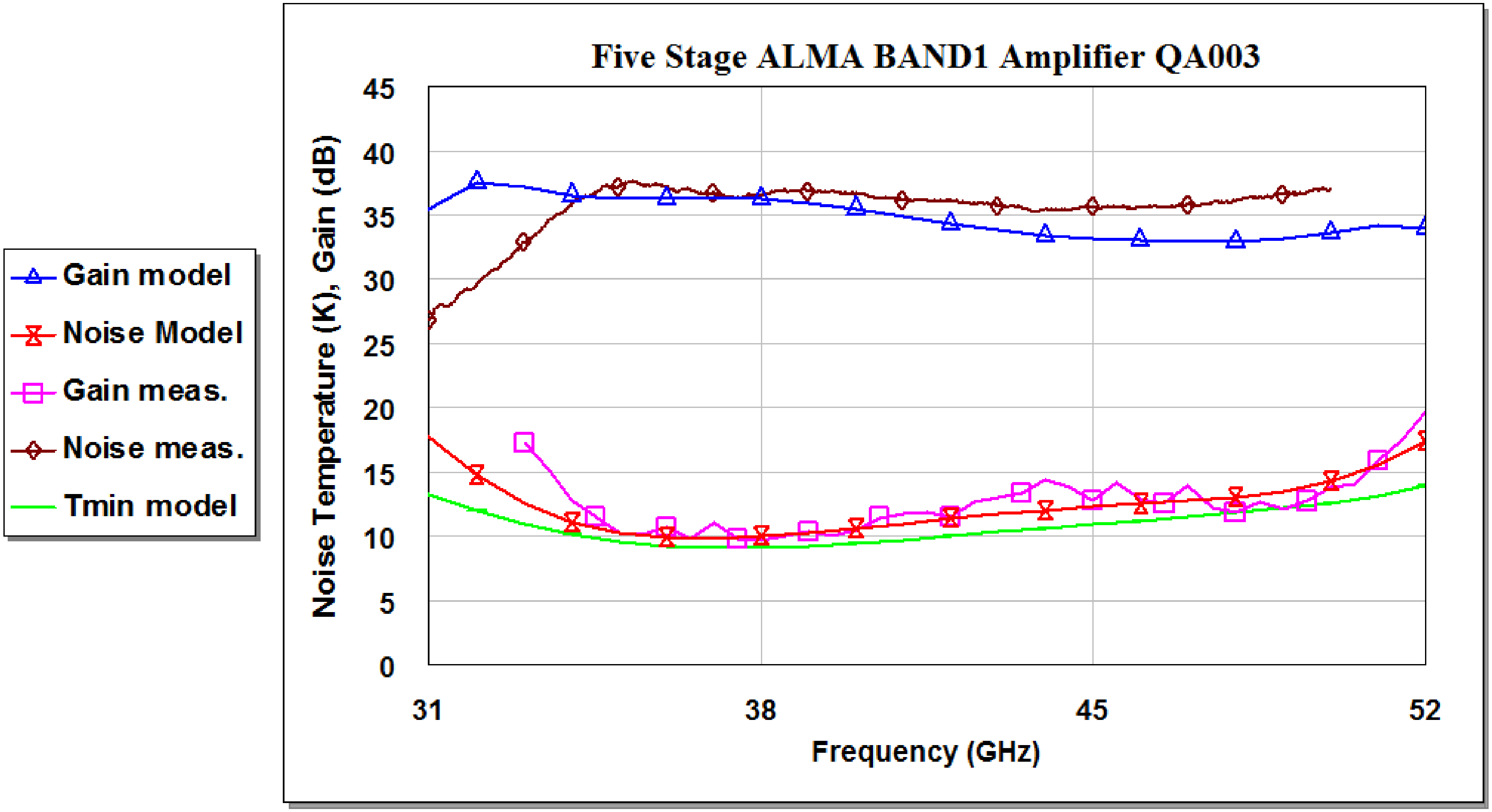
$$T_{min} = \frac{f}{f_t}\sqrt{\frac{2\, qI_c T_a r_b}{k}}$$

Accuracy of Noise Model

Experimental Example of GaAs MESFET

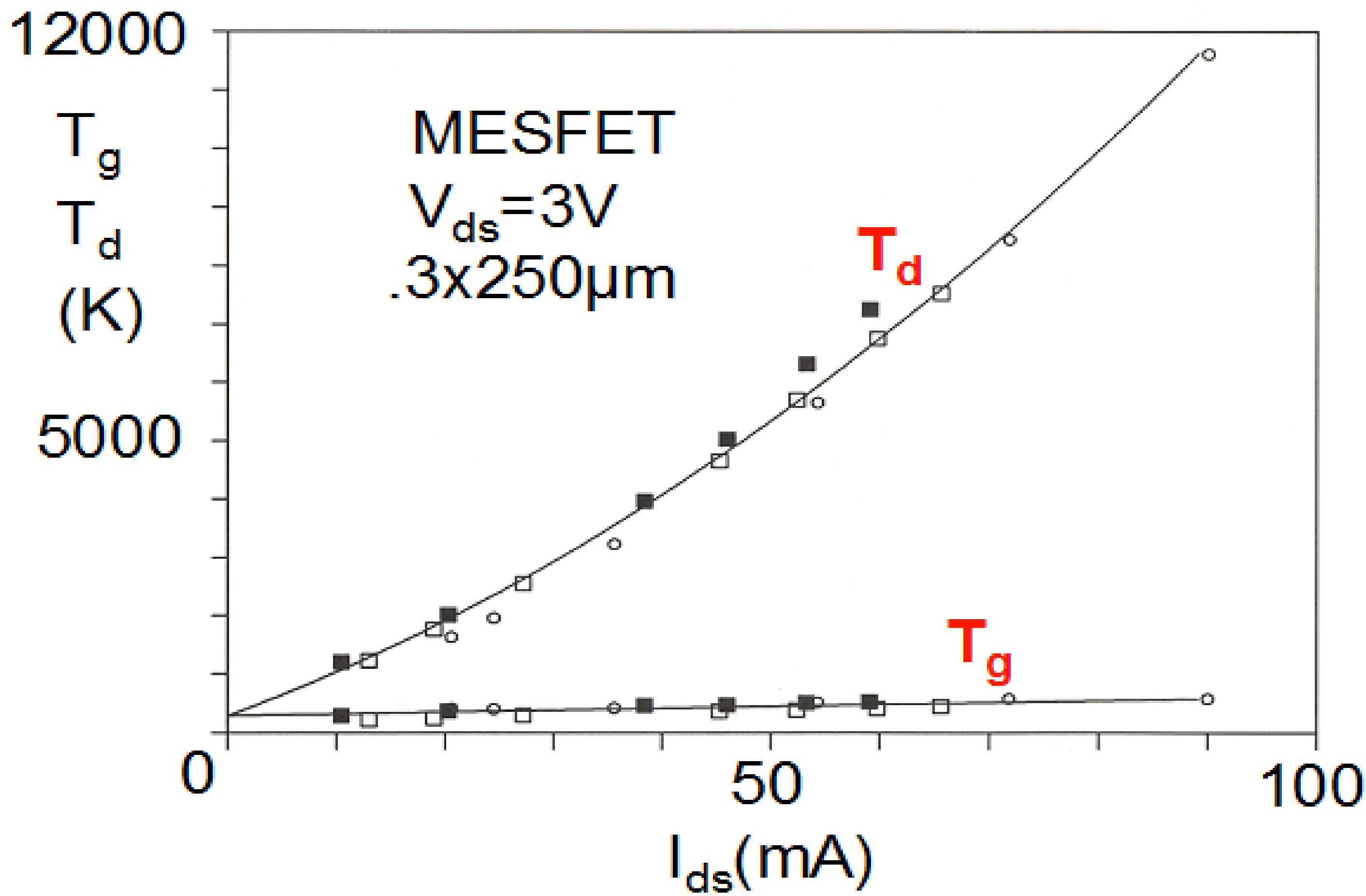


ALMA Band #1 5 Stage Amplifier: Modeled and Measured Results at 20 K

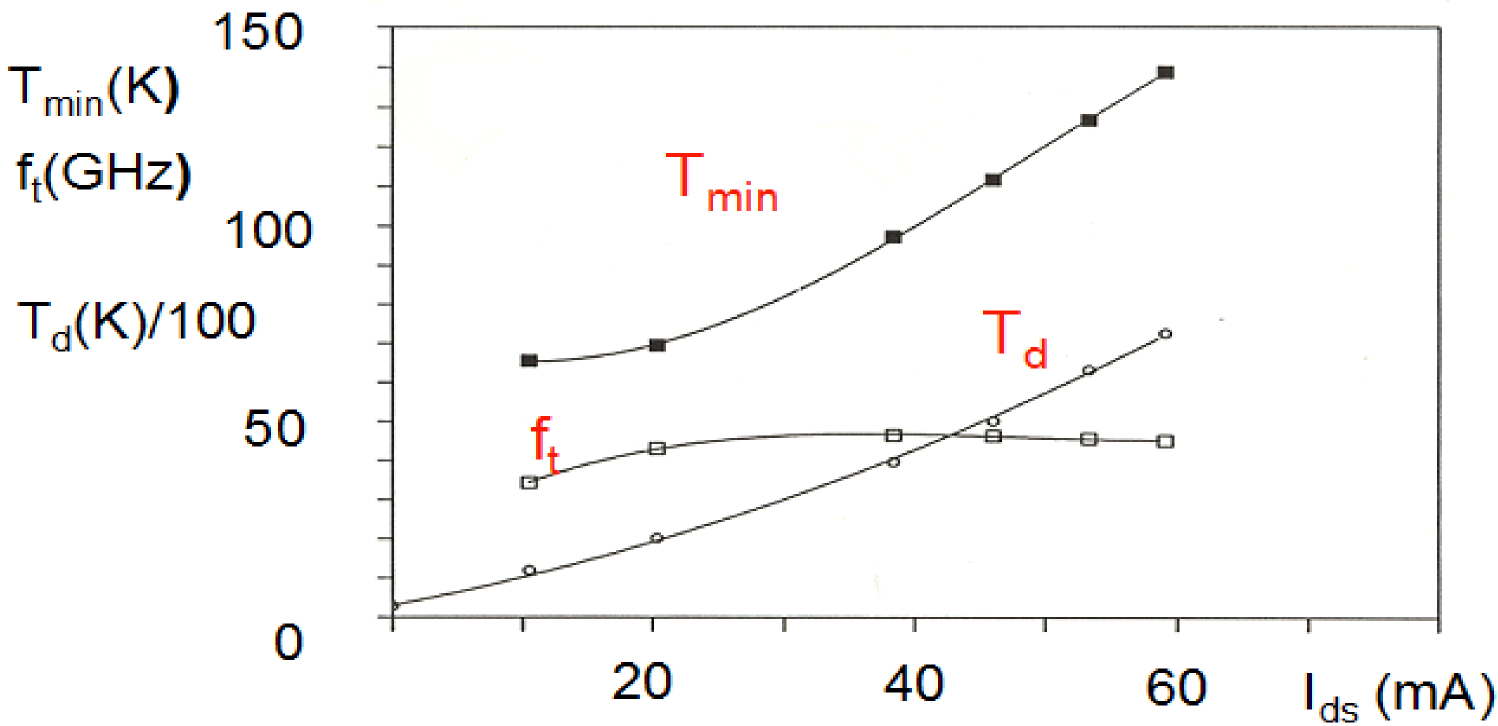


Bias Dependence

Example of T_g and T_d Dependence on I_d

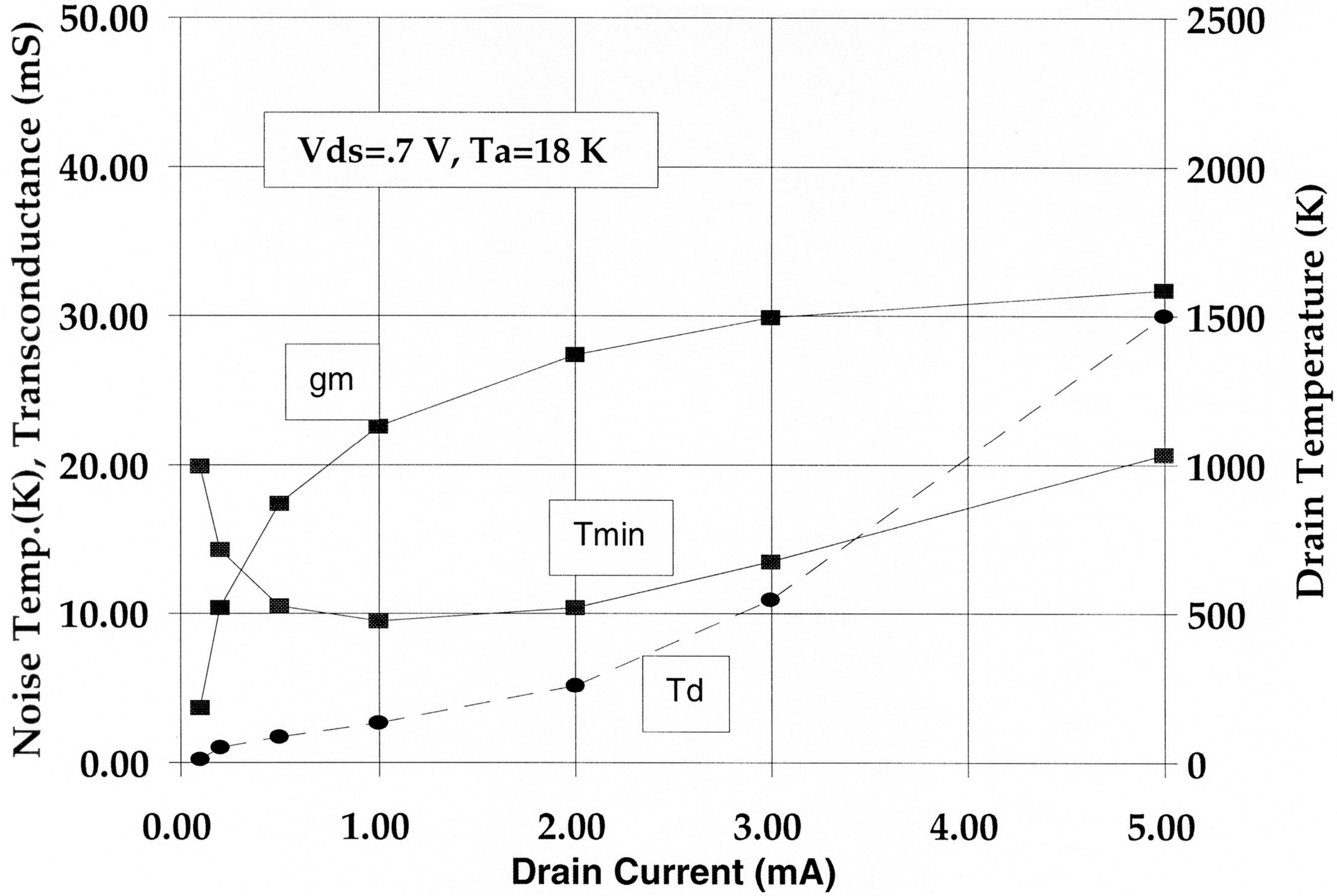


Optimal Noise Bias of GaAs FET at 297 K (1991)



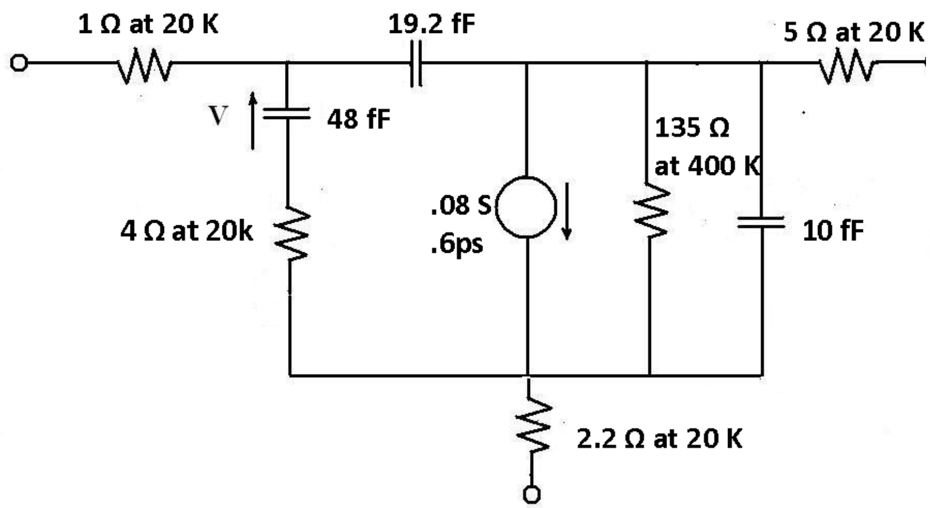
Optimal bias is minimizing the value of: $f(V_{ds}, I_{ds}) = \frac{\sqrt{T_d \; g_{ds}}}{f_T}$

Optimal Noise Bias of InP HFET at 18 K (1994)

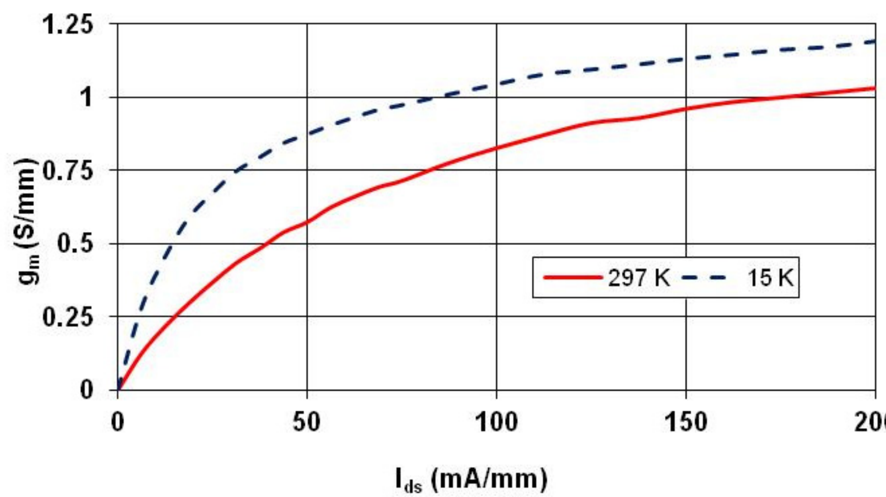


Example of Equivalent Circuit and $g_m(I_{ds})$ Characteristics of Cryo3 InP HFET

Equivalent circuit of cryo3 device



$g_m(I_{ds})$ characteristics



L_g=80nm, W_g=80µm

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

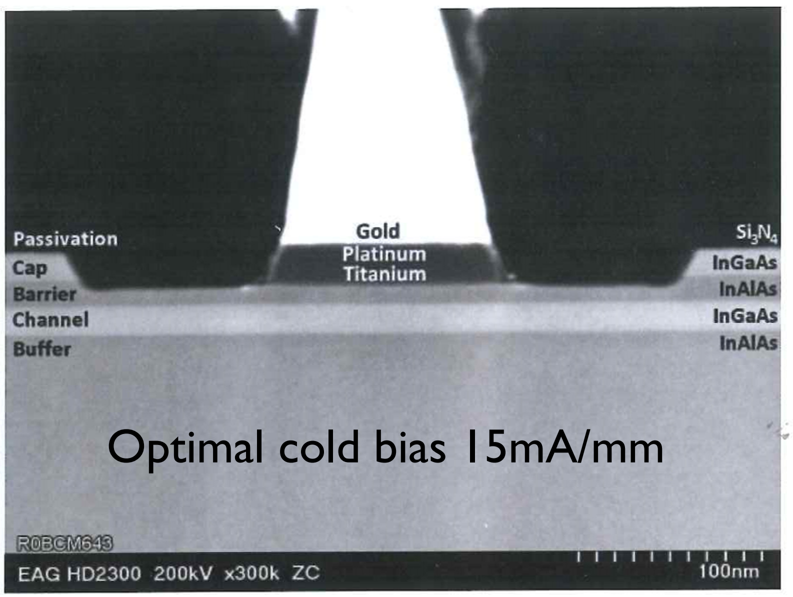
Typical optimal Ids bias:
75mA/mm at 297 K,
20-25 mA/mm at 20 K

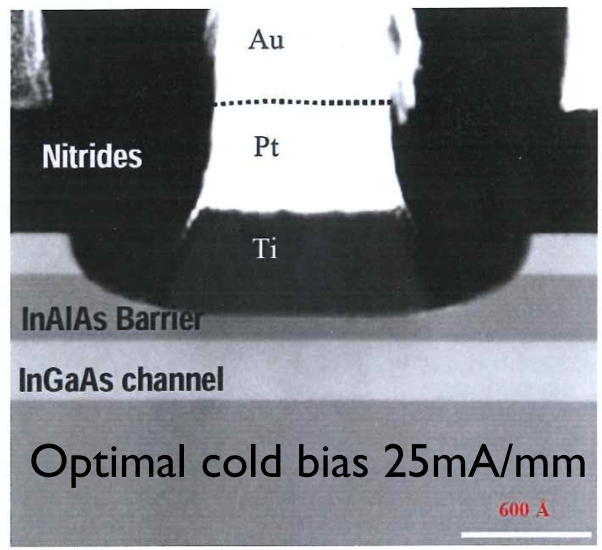
T_{min} Dependence on Bias (Summary)

$$T_{min} \cong 2\frac{f}{f_t}\sqrt{g_{ds}\,T_d\,r_t\,T_g} \cong \frac{f}{f_{max}}\sqrt{T_d T_g} \qquad f_t \cong \frac{g_m}{2\pi(C_{gs}+C_{gd})}$$

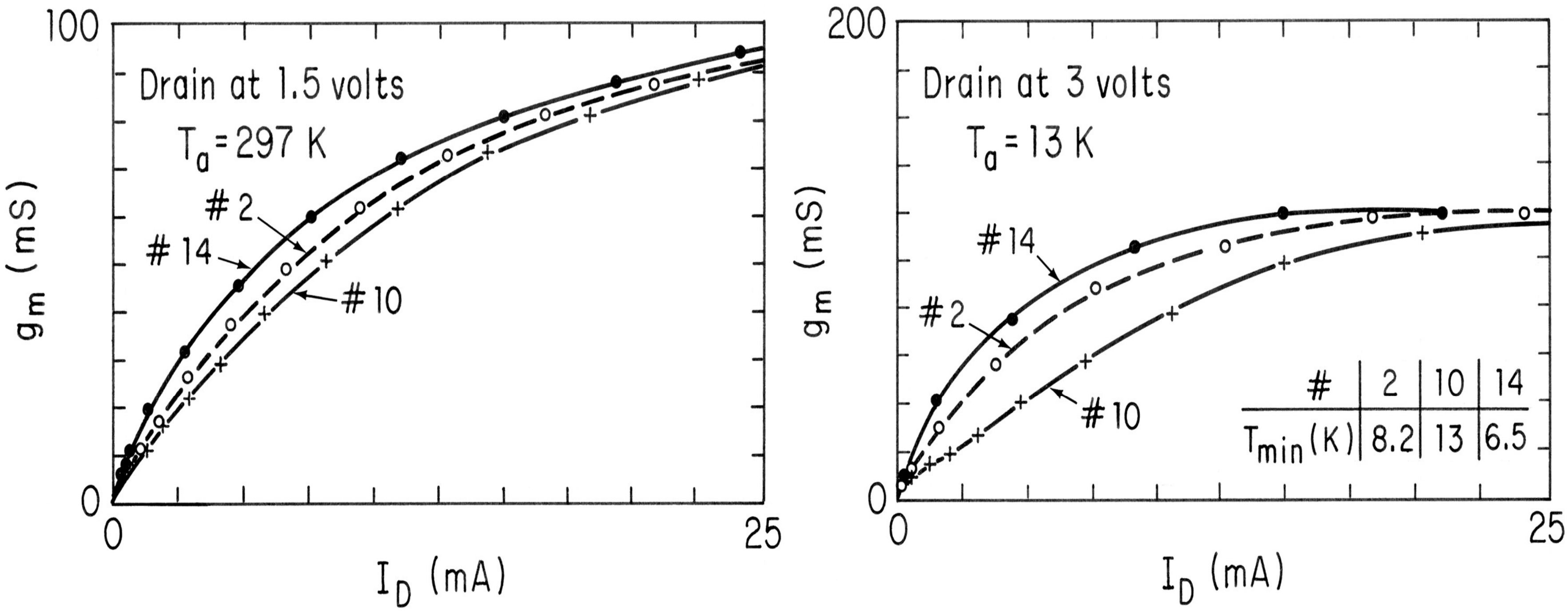
Noise optimal bias is minimizing the value of: $f(V_{ds}, I_{ds}) \approx \frac{\sqrt{I_{ds}}}{g_m}$

The importance of gate recess technology (Joel Schleeh, Chalmers/LNF)





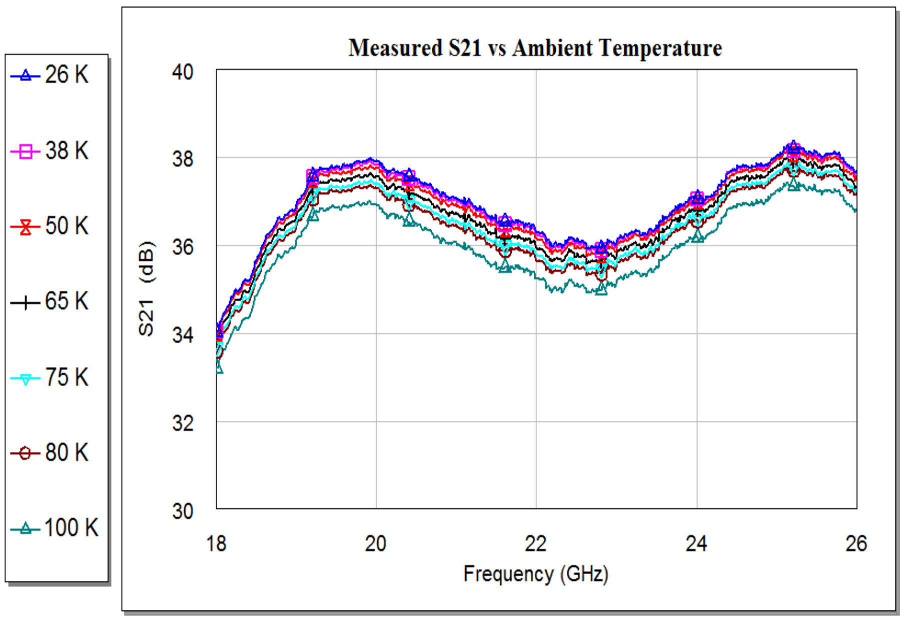
Cryogenic T_{min} at 8.4 GHz and dc pinch–off charactersitcs of GE HFET's (1987)

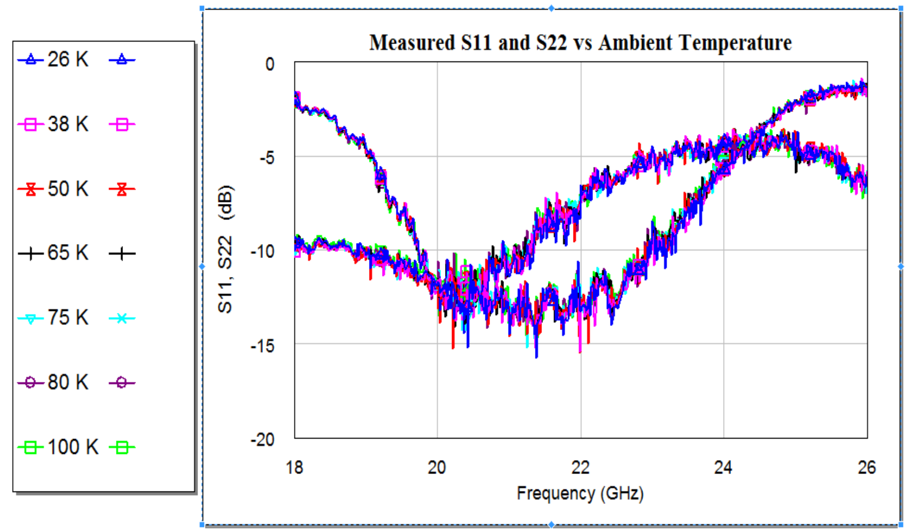


#	2	10	14
T_{min} (K)	8.2	13	6.5

Ambient Temperature Dependence

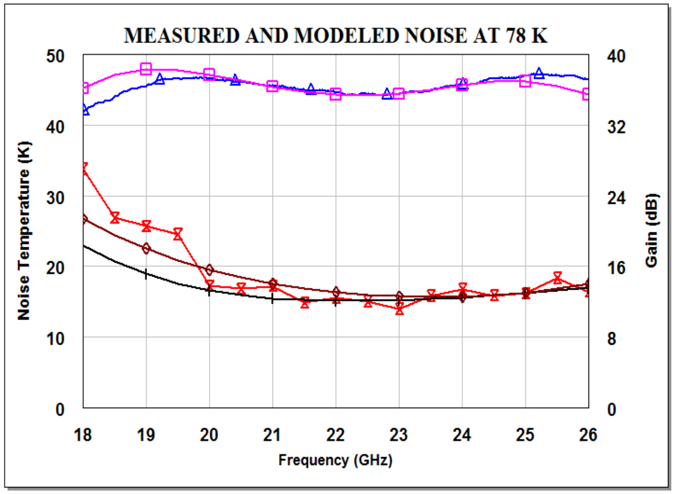
S-Parameters of K-Band Amplifier Versus Ambient Temperature

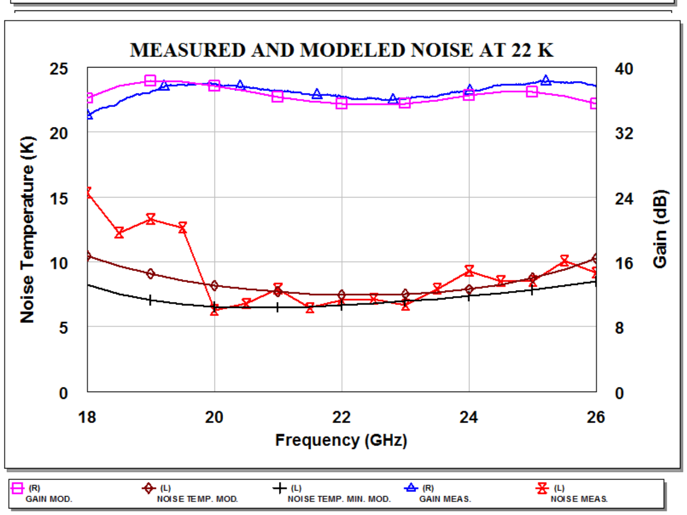


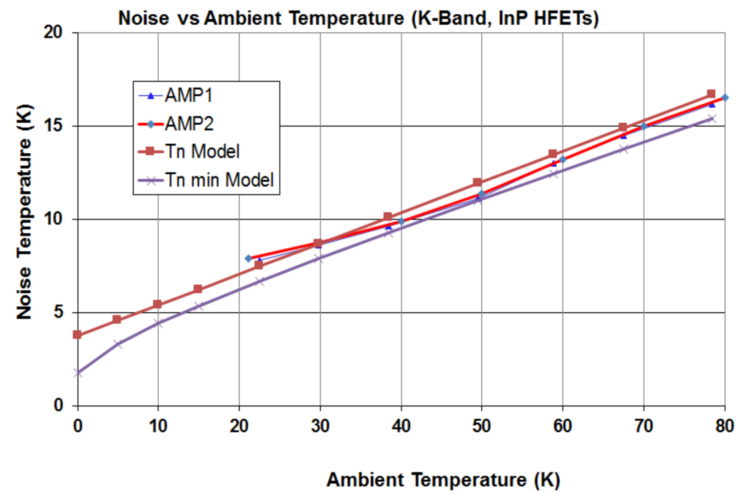


RWW 2017

Noise Temperature of K-Band Amplifier Versus Ambient Temperature







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

T_d is proportional current I_d but is independent of ambient temperature

RWW 2017

Broad Band Noise Matching

Any FET or Bipolar Transistor is practically a THREE Noise Parameter Device

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

$$\frac{4NT_0}{T_{min}} \cong 2 \qquad \Gamma_g = 0$$

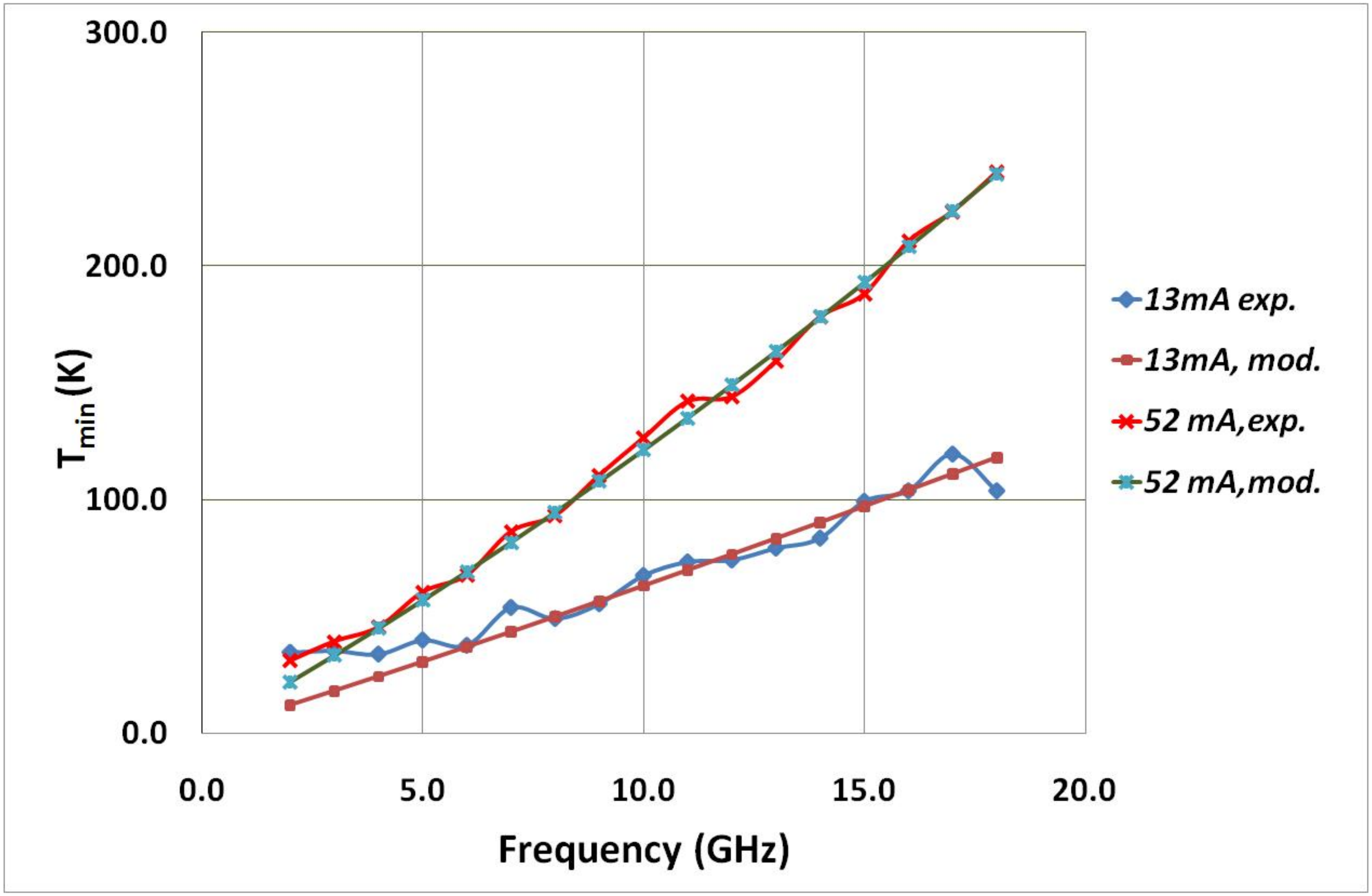
$$T_n \cong T_{min} \frac{\left|\Gamma_{opt}\right|^2}{\left(1-\left|\Gamma_{opt}\right|^2\right)}$$

For a given frequency range chose Γ_{opt} close to SC center.

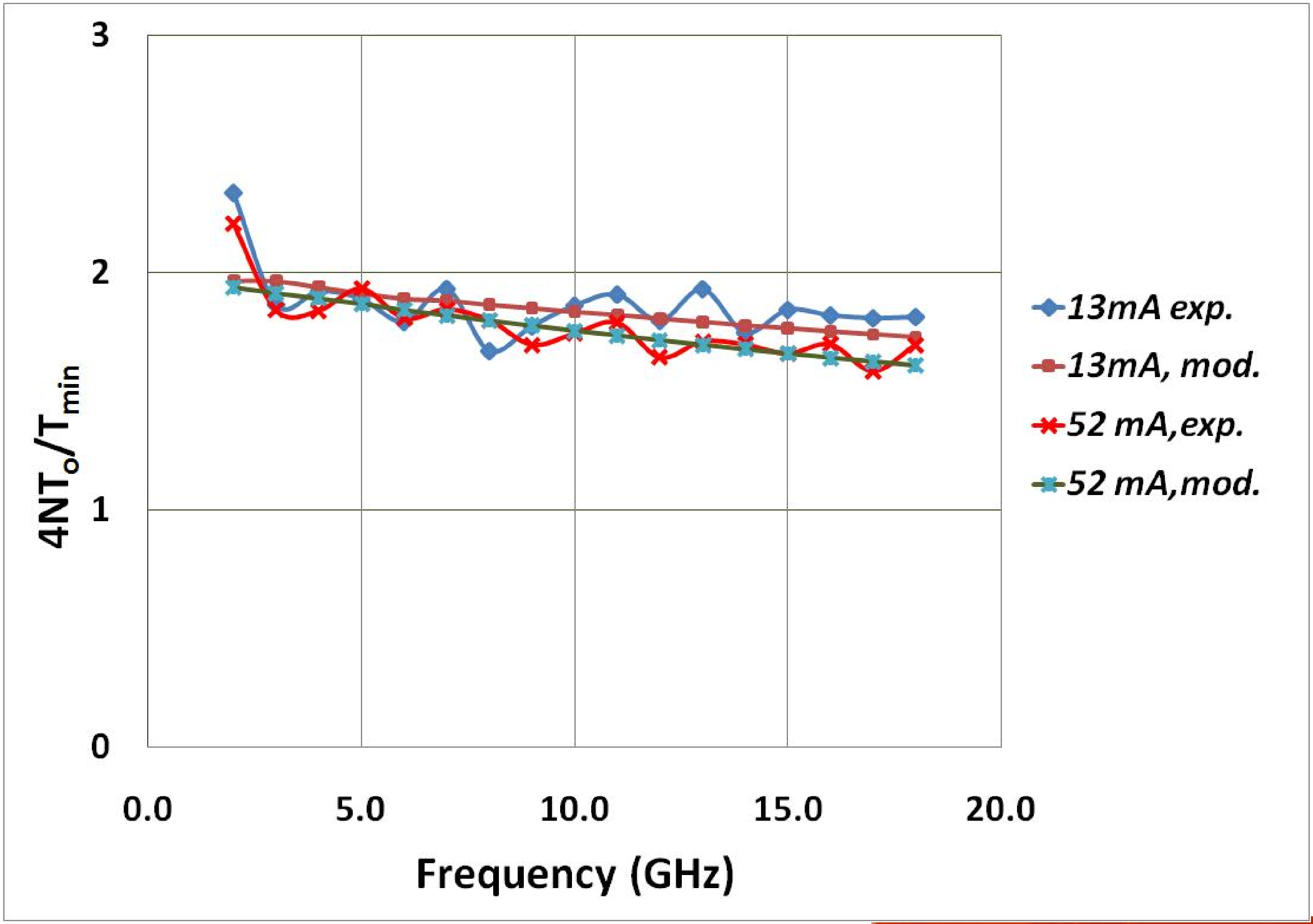
In practice, for a given frequency range average T_n is:

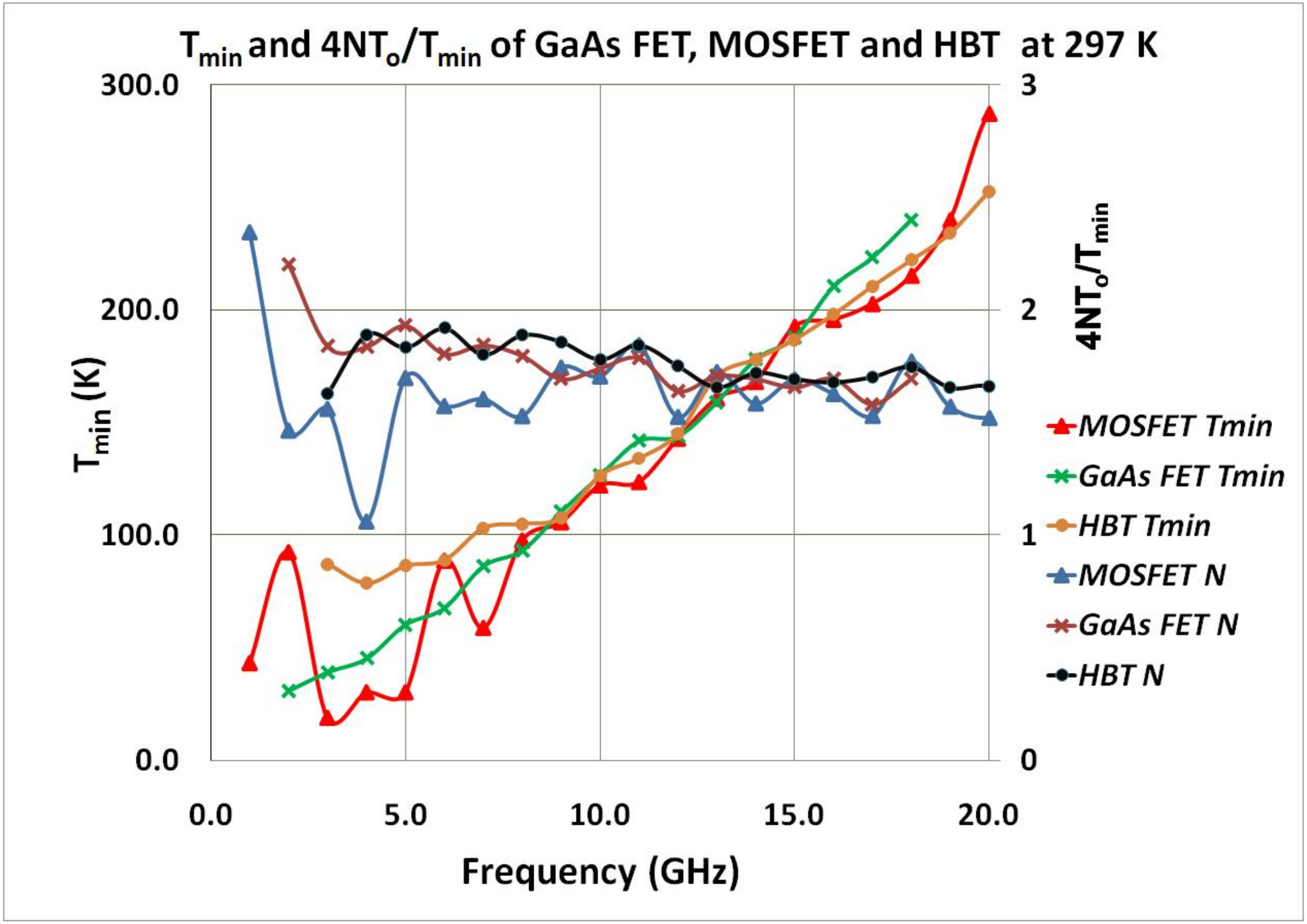
$$\frac{1}{f_{max} - f_{min}} \int_{f_{min}}^{f_{max}} T_n df \approx M_{min}(f_{max})$$

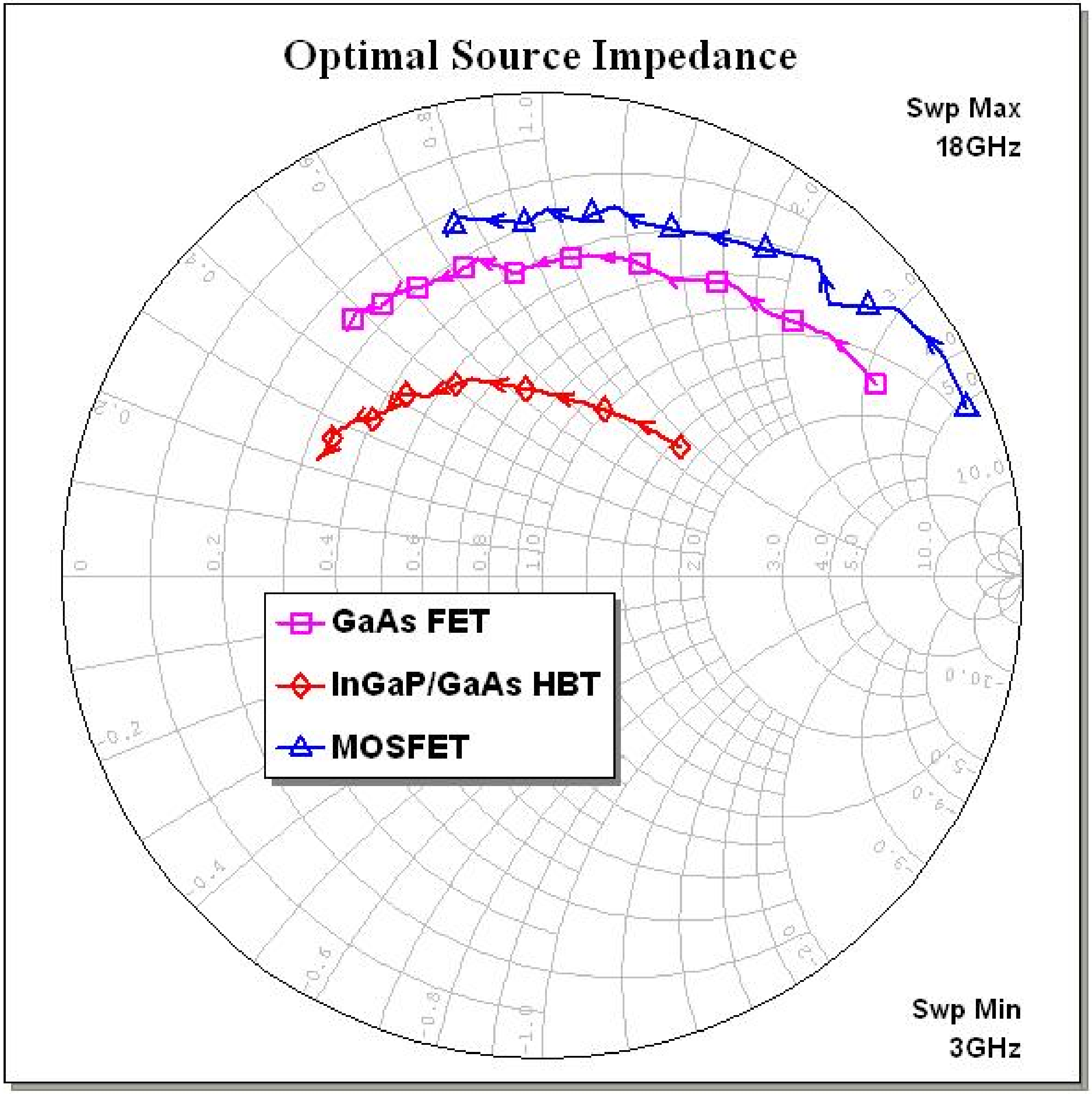
Measured and Modeled T_{min} of a FET



Measured and Modeled $4NT_0/T_{min}$ of a FET




T_{min} and $4NT_o/T_{min}$ of GaAs FET, MOSFET and HBT at 297 K
300.0
200.0
100.0
0.0
T_{min} (K)
3
2
1
0
$4NT_o/T_{min}$
0.0
5.0
10.0
15.0
20.0
Frequency (GHz)
MOSFET Tmin
GaAs FET Tmin
HBT Tmin
MOSFET N
GaAs FET N
HBT N


Optimal Source Impedance
Swp Max
18GHz
Swp Min
3GHz
GaAs FET
InGaP/GaAs HBT
MOSFET

Device Scaling: Gate Width

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

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

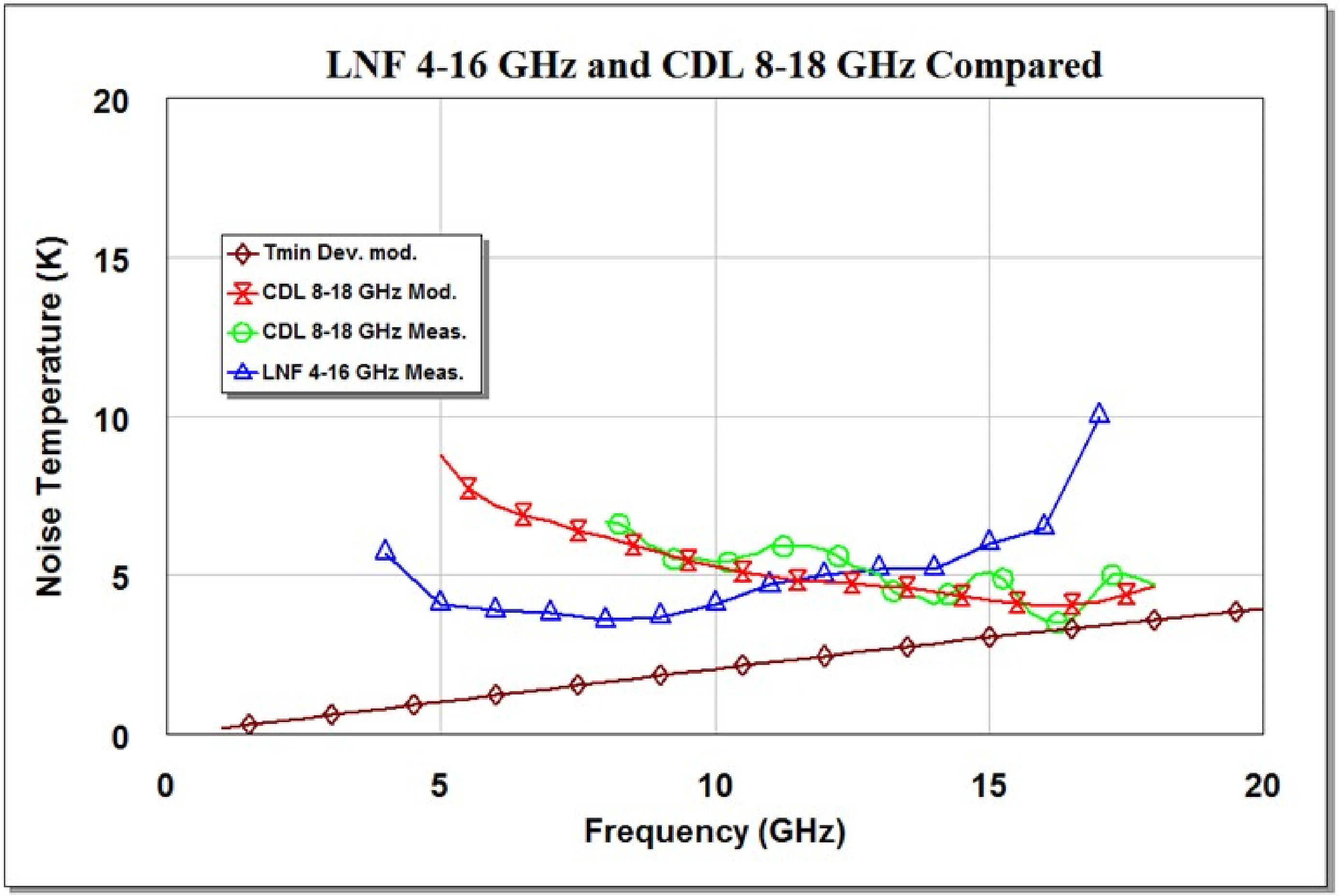
$$r_t = r_{gs} + r_g + r_s$$

Width ↗ R_{opt} ↘

T_{min} → in principle

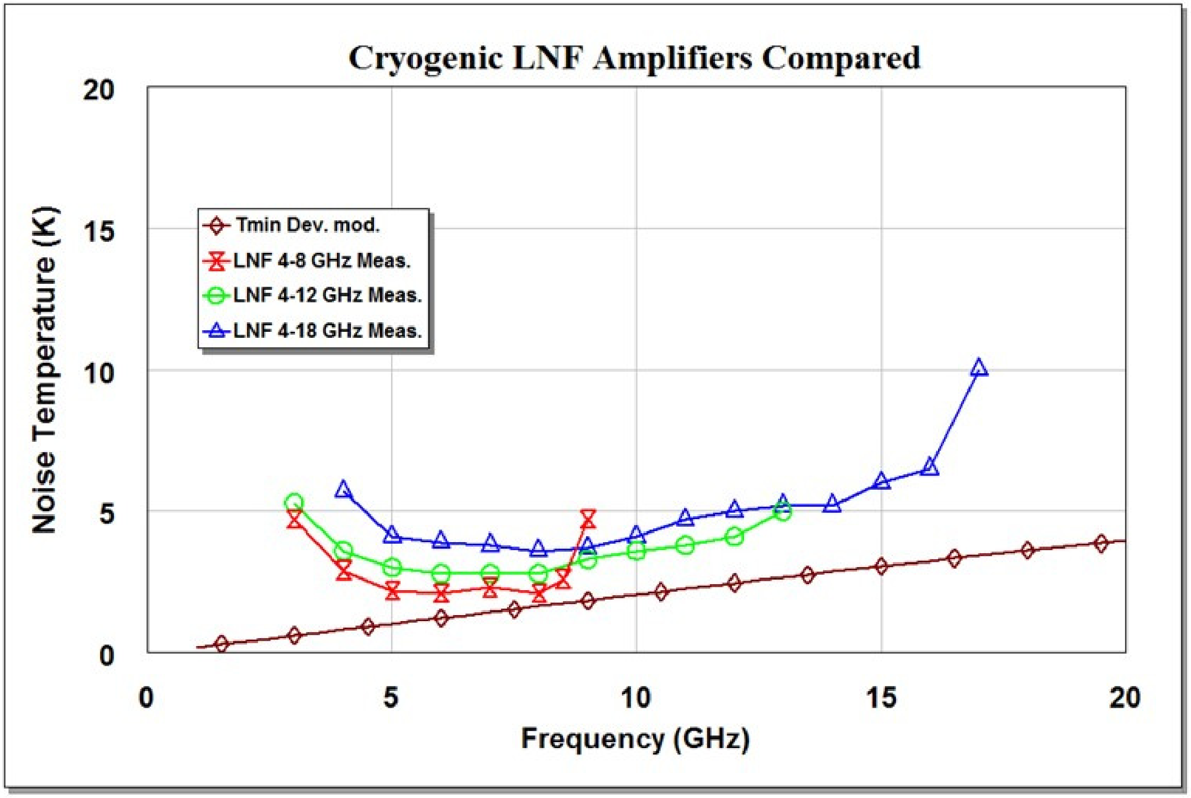
T_{min} ↗ in practice

Broad Band Noise Matching Illustration (1)



ALMA Memo #601, 2016

Broad Band Noise Matching Illustration (11)



Low Noise Factory Catalog Data: http://www.lownoisefactory.com/

ALMA Memo #601, 2016

Device Scaling: Gate Length

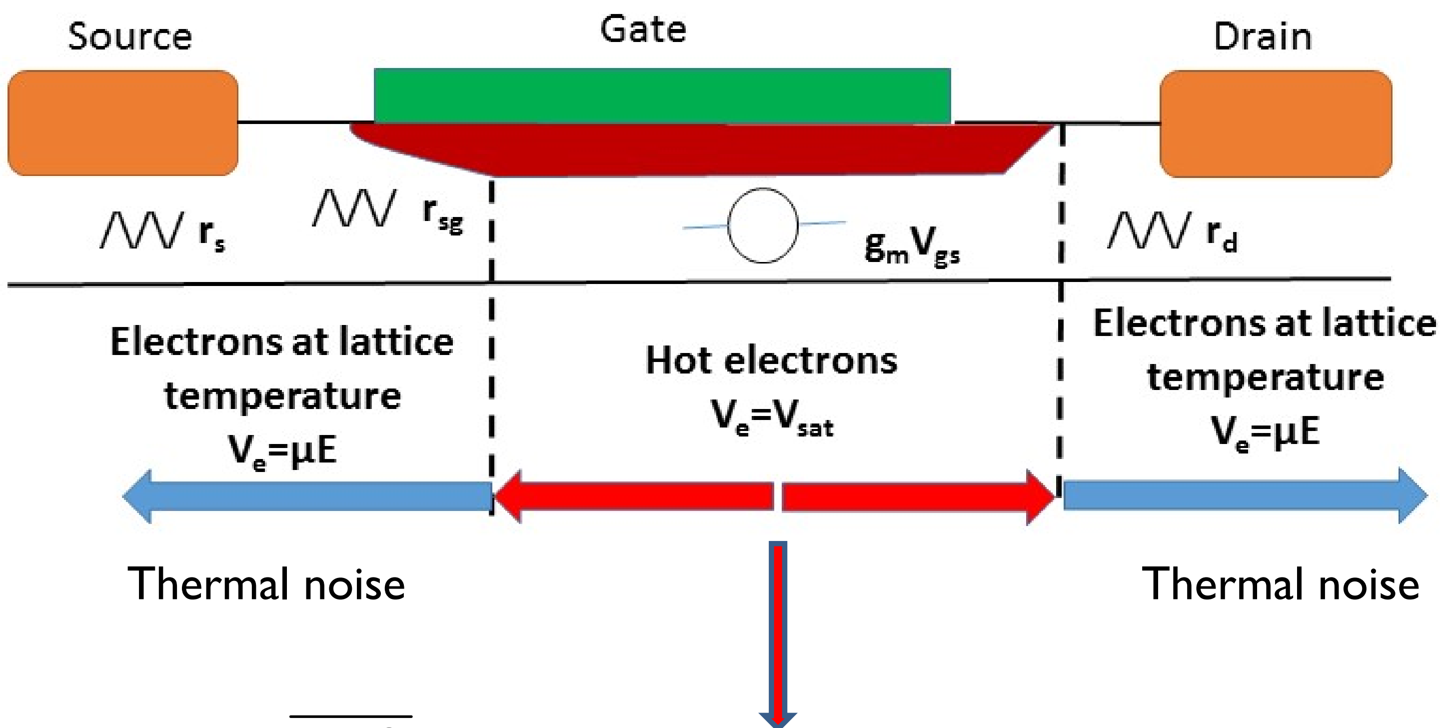
$$T_{min} \cong 2\frac{f}{f_t}\sqrt{g_{ds}\,T_d\,r_t\,T_g} \cong \frac{f}{f_{max}}\sqrt{T_d T_a}$$

$L_g \searrow \quad f_{max} \nearrow \quad T_{min} \searrow \quad$ if $T_d \approx const.$

But within a measurement error no device demonstrated T_{min} lower than that predicted 25 years ago.

The best cryogenic wafers: Chalmers (130 nm), NGSTCryo3 (80-100 nm), NGST (35 nm) exhibit progressively better f_{max} and M_{min} but about the same minimum $\mathbf{T_{min}}$ because T_d increases for deep submicron gate lengths.

General and (Very Simple) Picture of Noise in FETs:

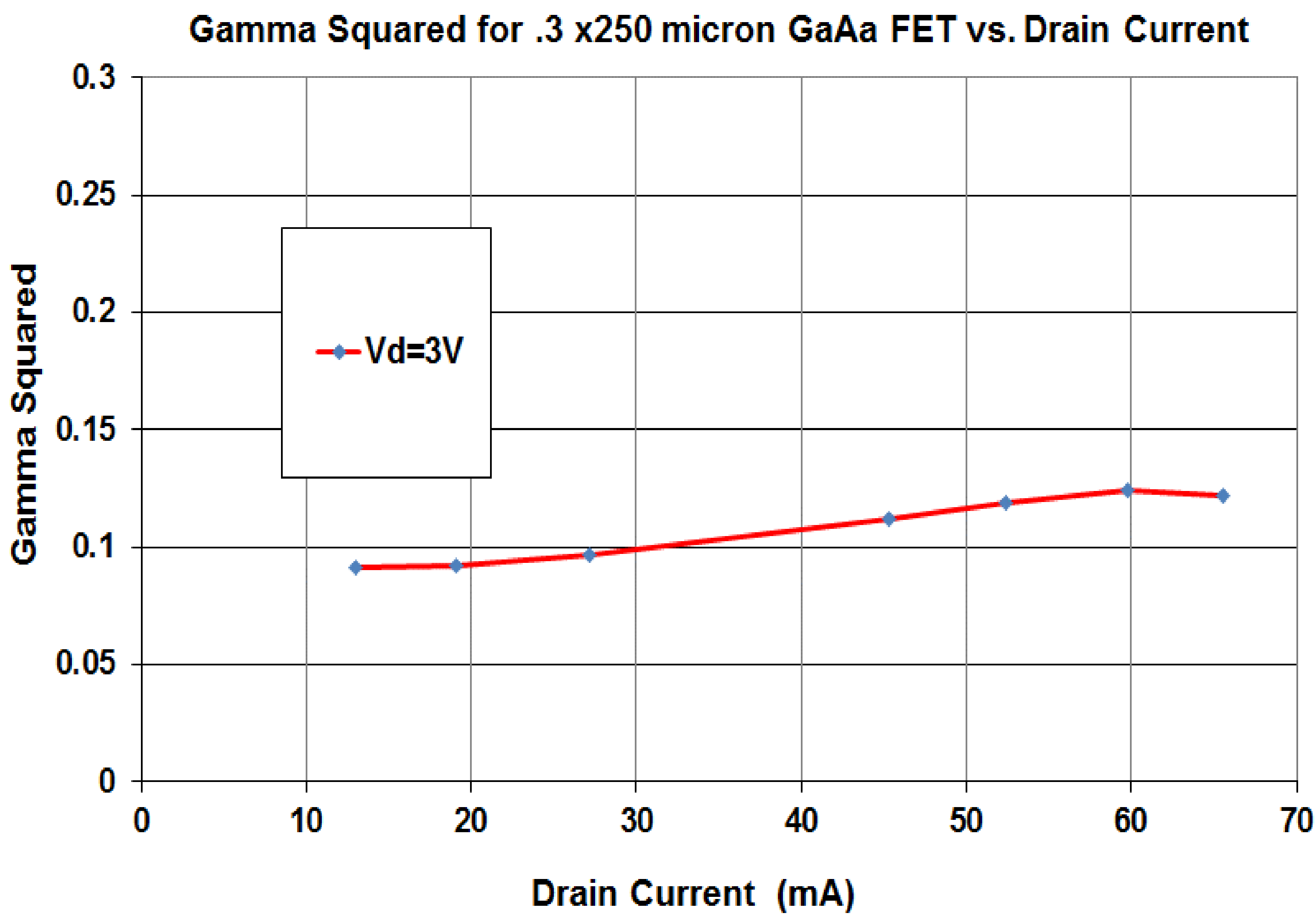


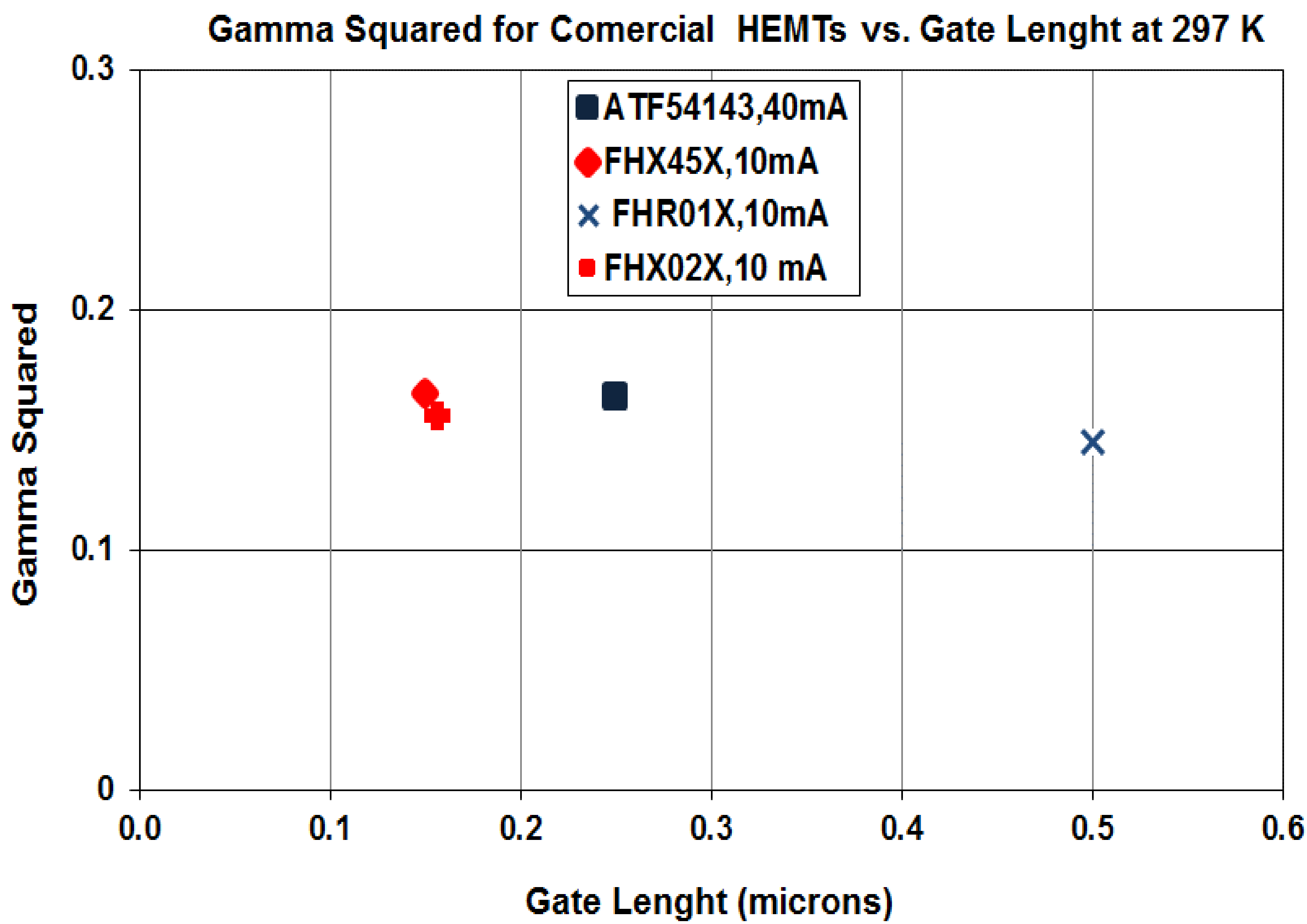
$$\overline{i_{ds}^{2}} = 4kT_d\, g_{ds}\, \Delta f = \Gamma^2\, 2qI_d\, \Delta f$$

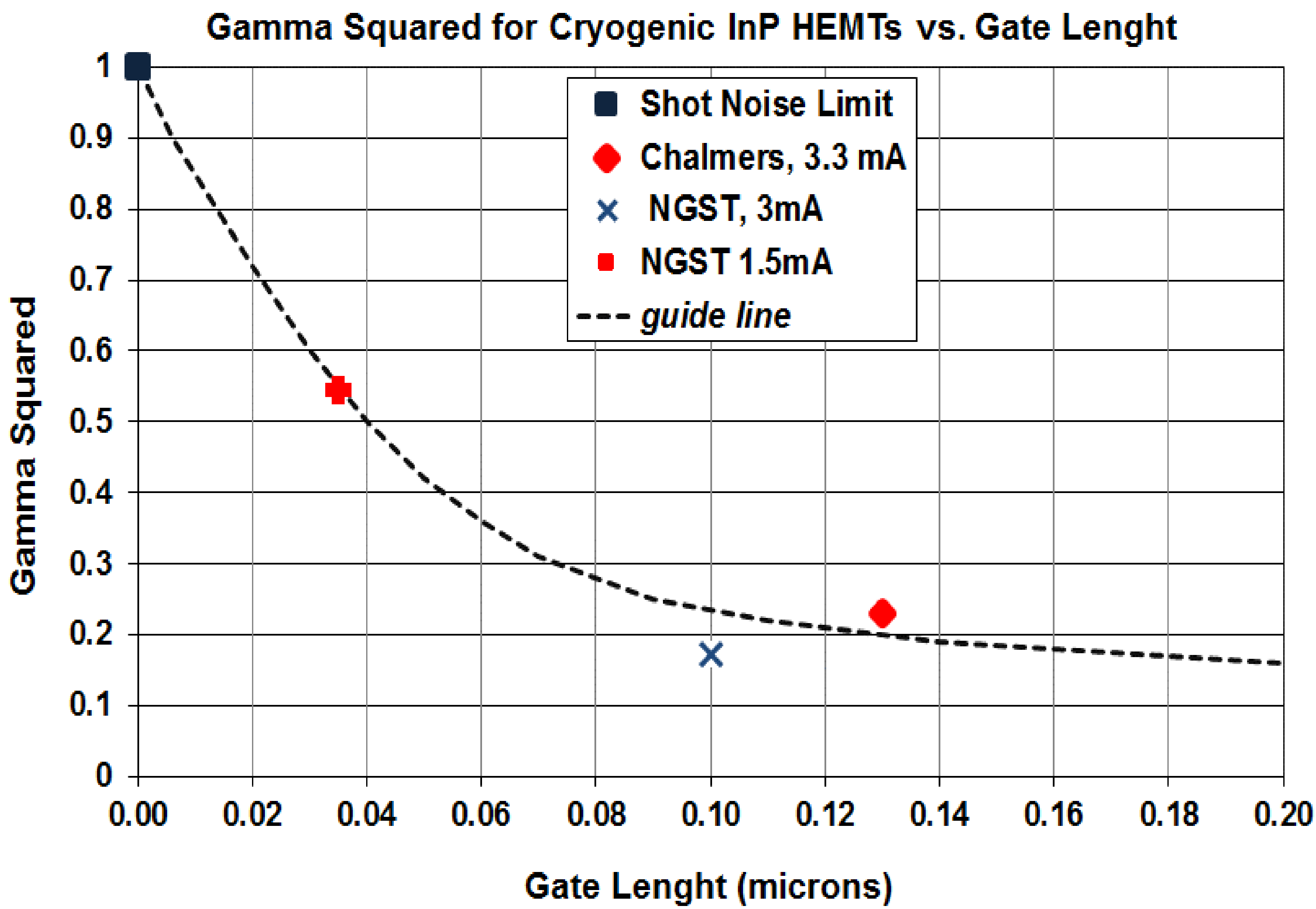
Γ^2 shot noise suppression factor

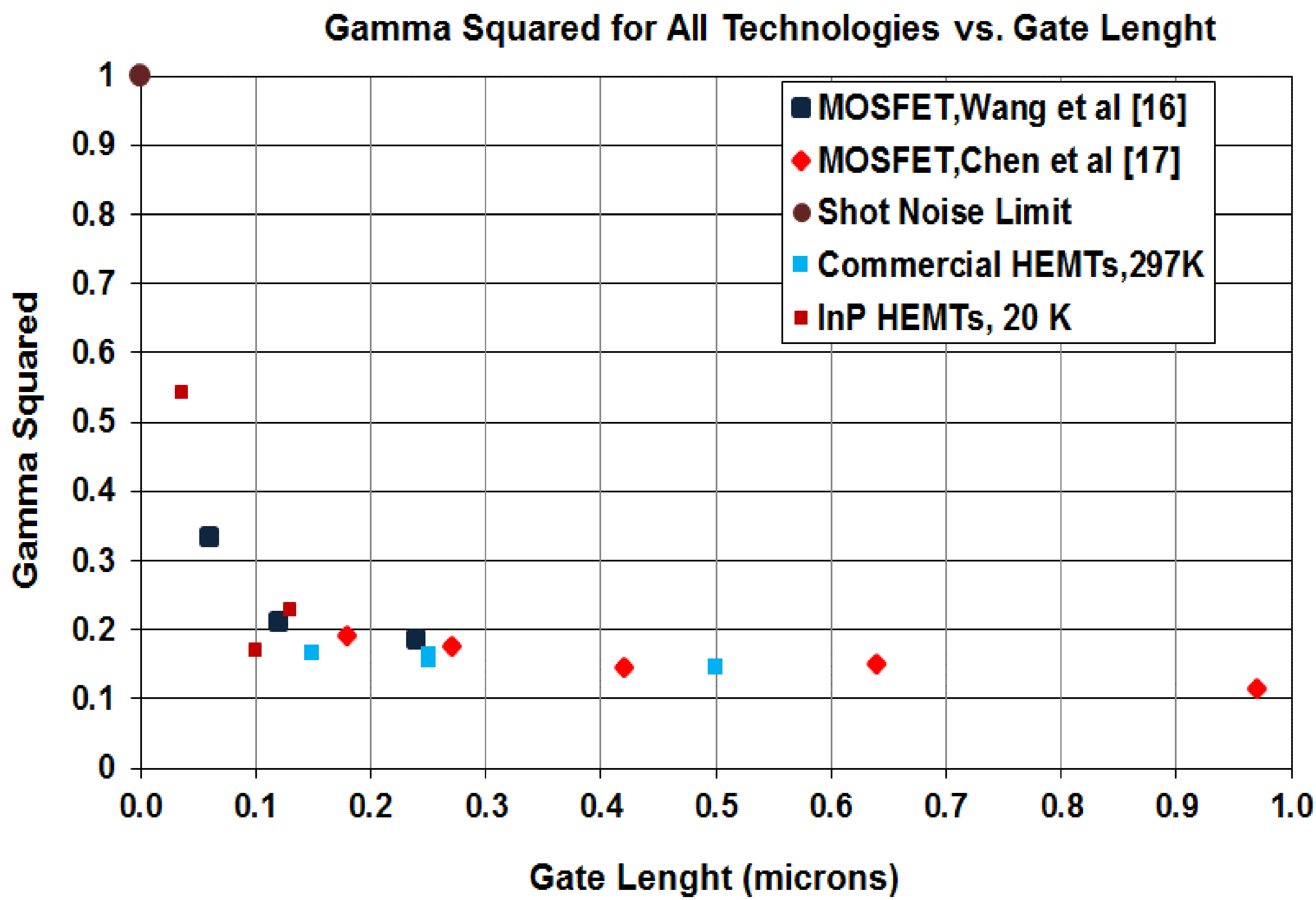
Γ^2 should:

- be approximately independent of FET bias and its physical temperature.
- for long gates Γ^2 should assume a constant value while for short gates it should increase as in the limit for $L_g \to 0$, a pure shot noise should be observed and $\Gamma^2 \to 1$.
- As the average energies of hot electrons in Si, GaAs and InGaAs which form channels of all modern FETs are not that different for electric fields larger than 10^4 V/cm (1 eV), Γ^2 should be only weakly dependent on a particular semiconductor structure


Gamma Squared for .3 x250 micron GaAa FET vs. Drain Current
Gamma Squared
Drain Current (mA)
Vd=3V
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70


Gamma Squared for Comercial HEMTs vs. Gate Lenght at 297 K
ATF54143,40mA
FHX45X,10mA
FHR01X,10mA
FHX02X,10 mA
Gamma Squared
Gate Lenght (microns)
0.3
0.2
0.1
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6

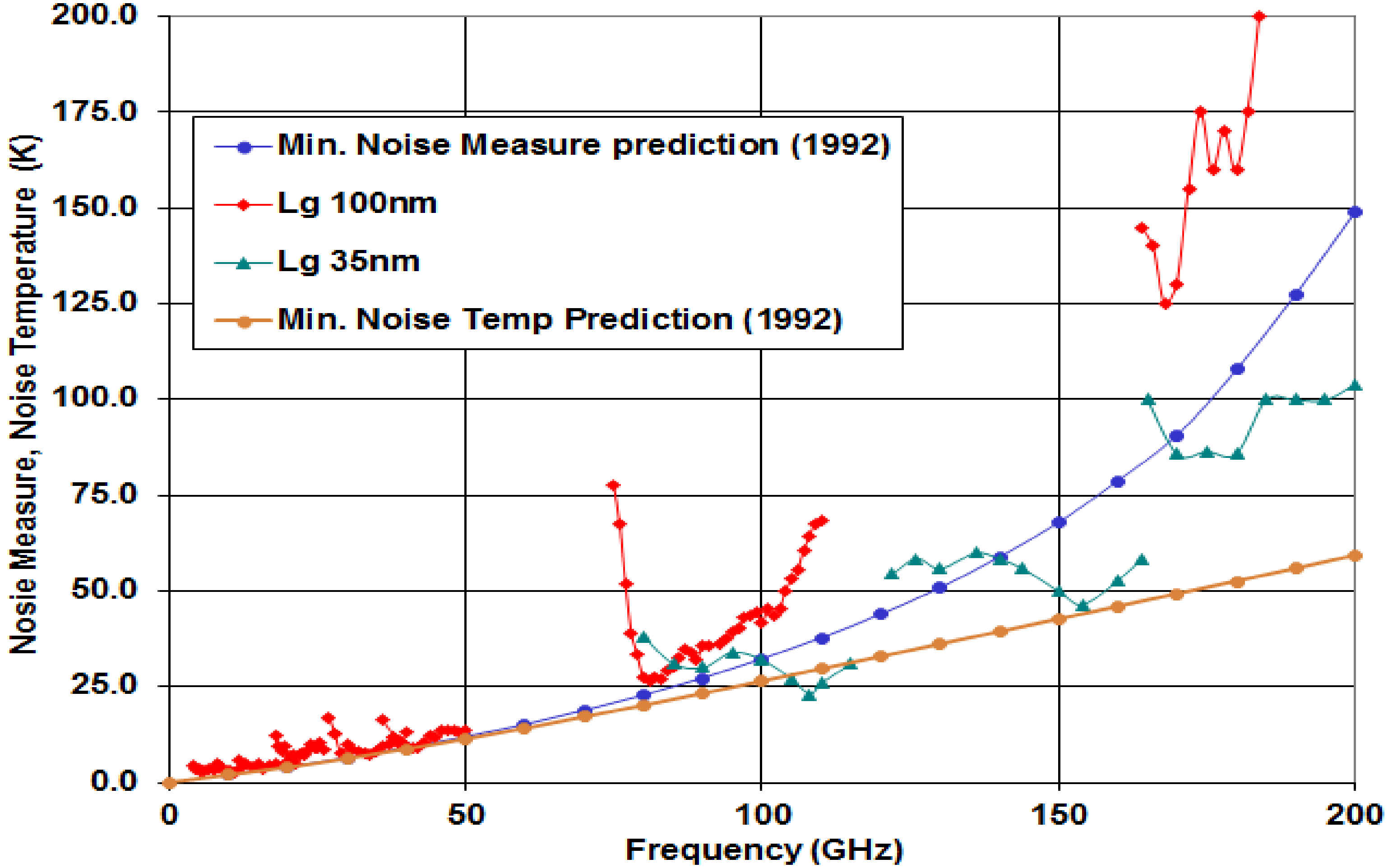

Gamma Squared for Cryogenic InP HEMTs vs. Gate Lenght
Gamma Squared
Gate Lenght (microns)
Shot Noise Limit
Chalmers, 3.3 mA
NGST, 3mA
NGST 1.5mA
guide line
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20


Gamma Squared for All Technologies vs. Gate Lenght
Gamma Squared
Gate Lenght (microns)
MOSFET,Wang et al [16]
MOSFET,Chen et al [17]
Shot Noise Limit
Commercial HEMTs,297K
InP HEMTs, 20 K
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Concluding Remarks

- Only three wafer runs of InP discrete devices (NRAO/HRL, WMAP/HRL, NGST/JPL cryo3) have been used in construction of great majority of radio astronomy instruments: VLA/EVLA,VLBA, GBT, ALMA band6, CBI, SZ-Array, WMAP, Planck LFI (K_a and Q), VSA, AMI, MPI, JPL/DSN and others.
- MMICs with very competitive noise are now becoming available.
- There has been no significant progress in the low noise performance of cryogenic HFET's in the past 15 years, as we are approaching the limits determined by the principle of operation
- Amplifier noise temperature is no longer the dominant component of the system noise for radio astronomy instruments with cryogenic receivers
- SiGe HBT offer competitive noise temperatures only at low frequencies but offer significantly better 1/f gain variations.

State-of–the-Art 20….?



www.nrao.edu
science.nrao.edu
public.nrao.edu

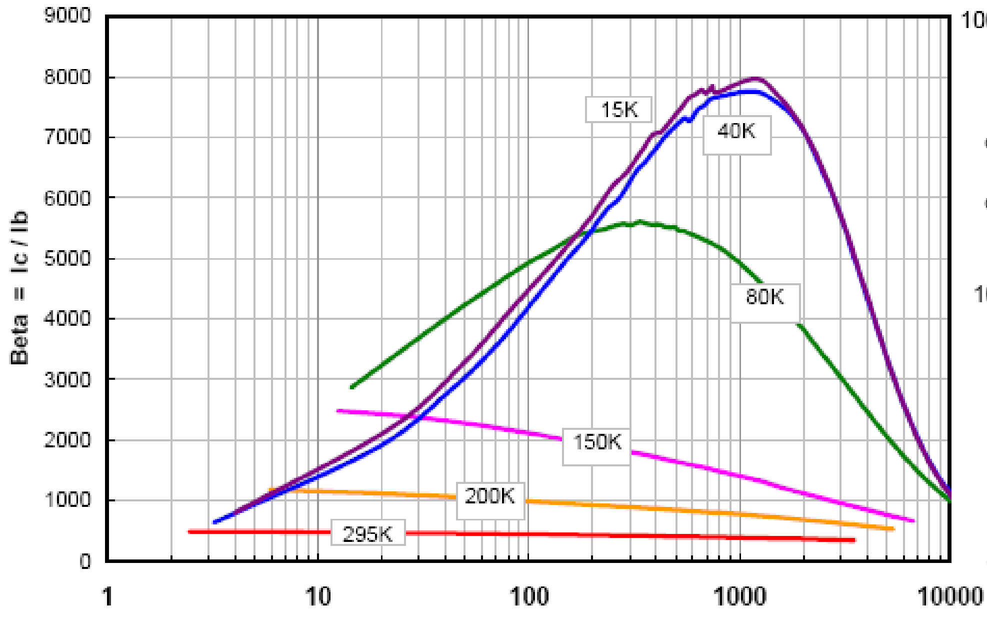
The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

SiGe HBT

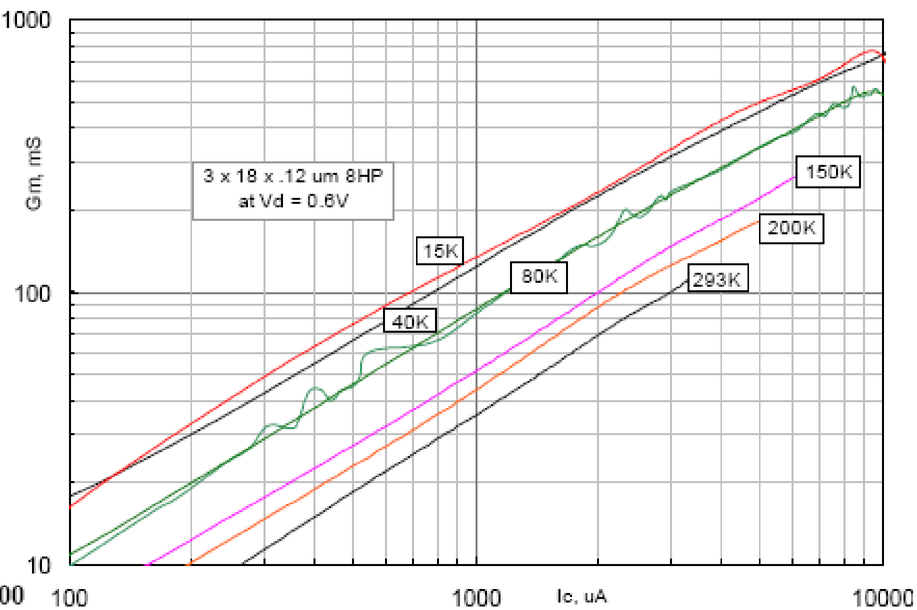
Courtesy of J.Bardin
University of Massachusetts

$$f >> \frac{f_t}{\sqrt{\beta}} \text{ and } \beta >> 1$$

Beta increases from 300 to 8000!



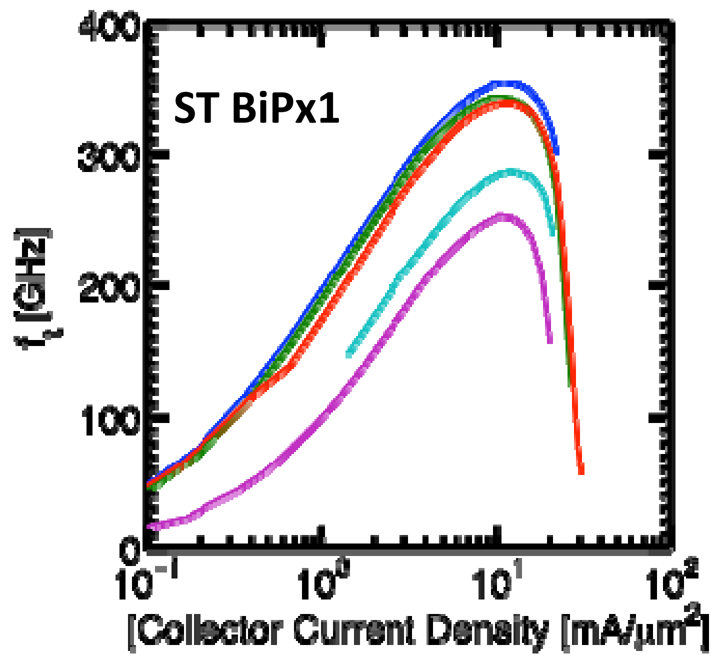
Gm increases by factor of 3!

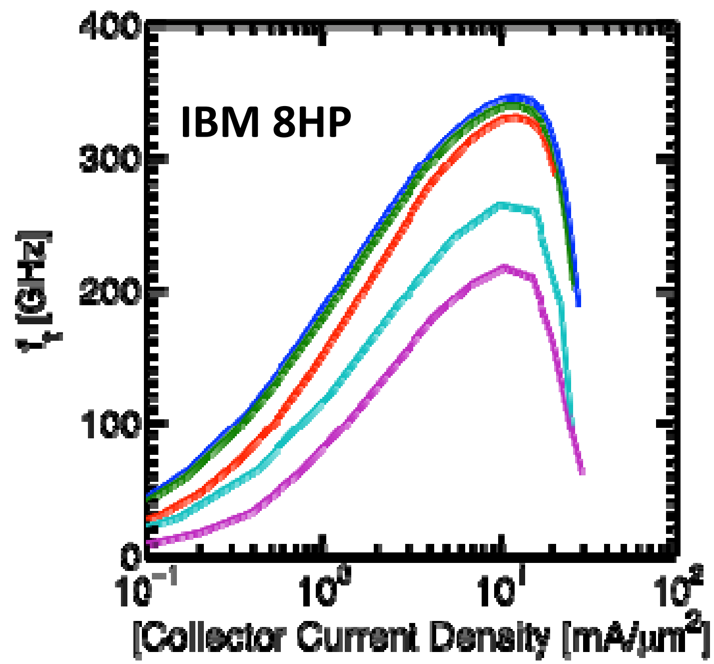


Extracted f_t *of SiGe HBT*

Courtesy of J.Bardin
University of Massachusetts

Typical peak f_t increase of 50% observed with cooling to 18 K!





18K 50K 77K 200K 300K

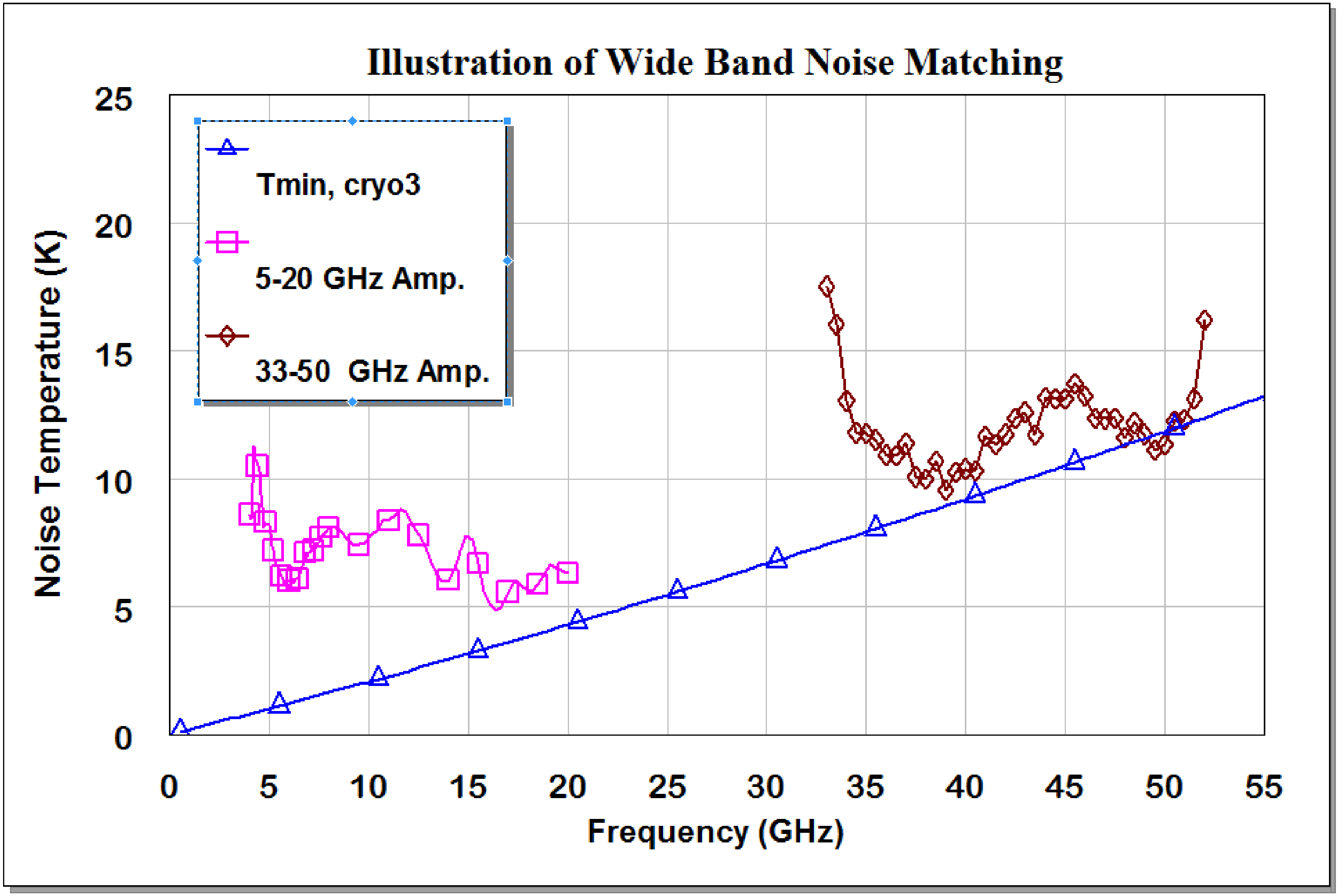
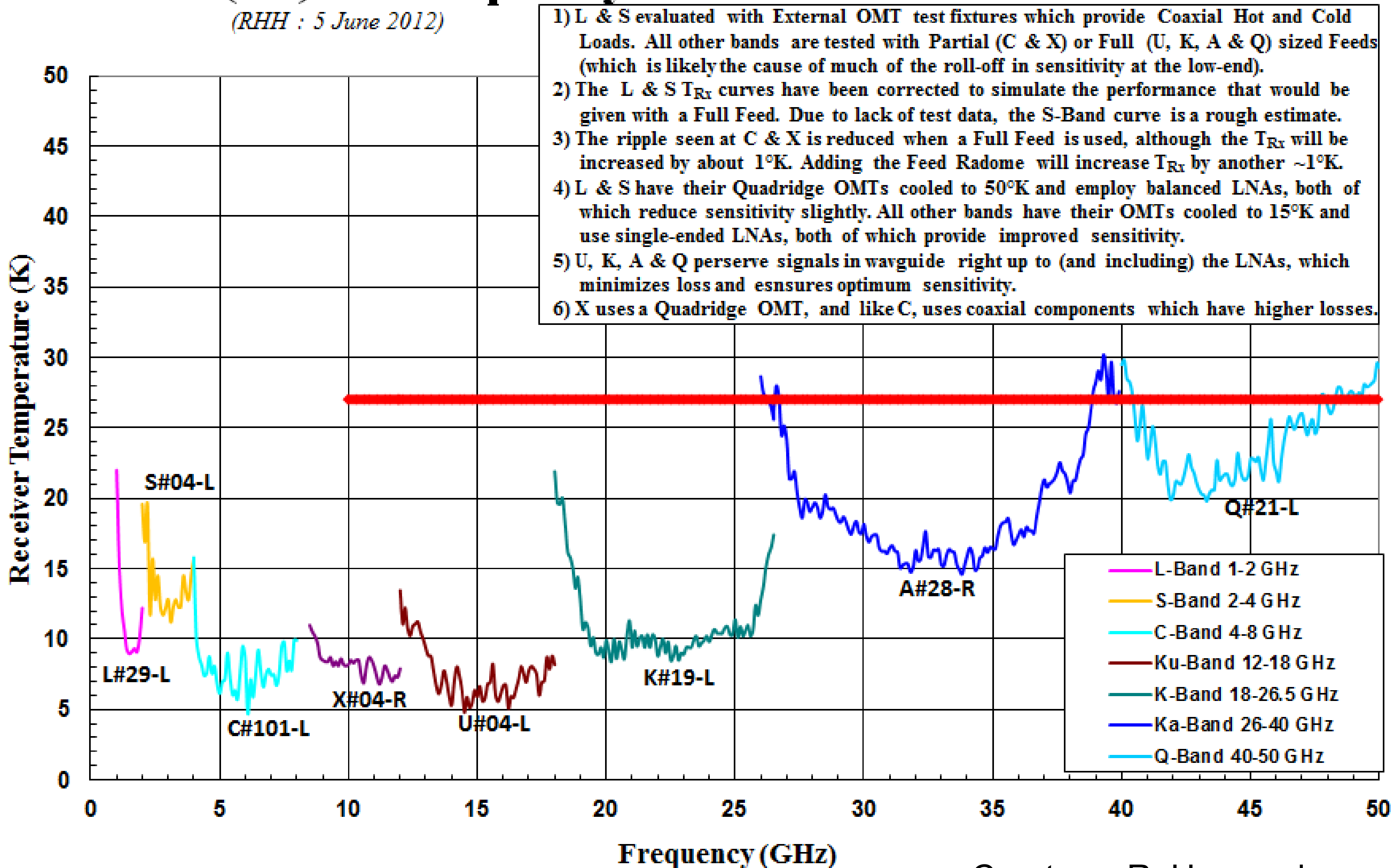


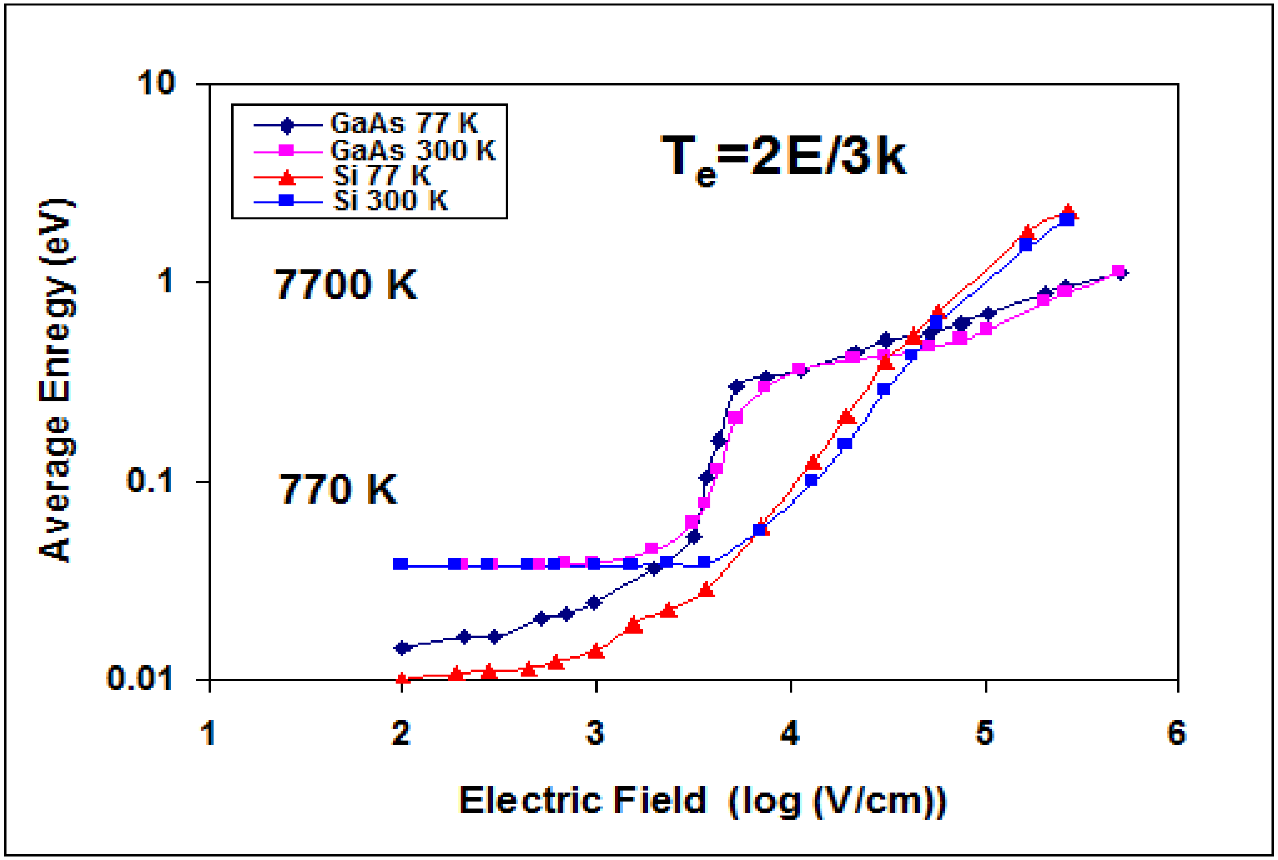
Illustration of Wide Band Noise Matching
Tmin, cryo3
5-20 GHz Amp.
33-50 GHz Amp.
Noise Temperature (K)
0
5
10
15
20
25
0
5
10
15
20
25
30
35
40
45
50
55
Frequency (GHz)

T(Rx) vs. Frequency for JVLA Receiver Bands



Courtesy: R. Hayward

“Hot electron” noise



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