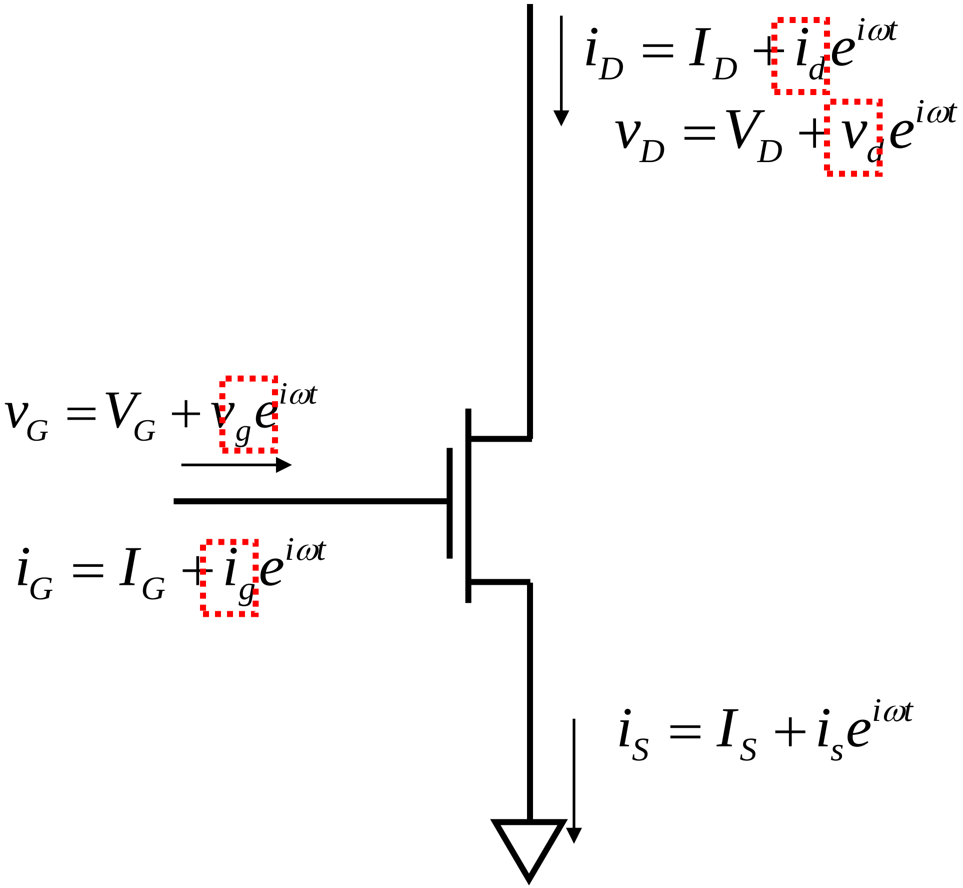
RF CMOS

EECS 277A

Fall 2010

AC equivalent circuit:



$i_D = I_D + \boxed{i_d} e^{i\omega t}$

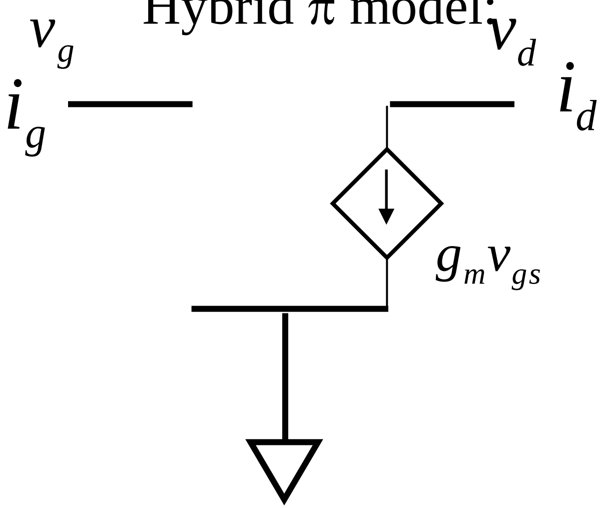
$v_D = V_D + \boxed{v_d} e^{i\omega t}$

$v_G = V_G + \boxed{v_g} e^{i\omega t}$

$i_G = I_G + \boxed{i_g} e^{i\omega t}$

$i_S = I_S + i_s e^{i\omega t}$

Hybrid π model:



$$\begin{pmatrix} i_g \\ i_d \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ g_m & 0 \end{pmatrix} \begin{pmatrix} v_g \\ v_d \end{pmatrix}$$

This is the common-source Y-matrix. You can get all the matrices from it.

Rules for ac analysis

- From complete circuit, calculate dc currents and voltages
- For ac analysis only:
  - dc voltage source -> short circuit
  - dc current source -> open circuit
- Replace transistor with π or T-model
- Now solve (simplified) ac circuit

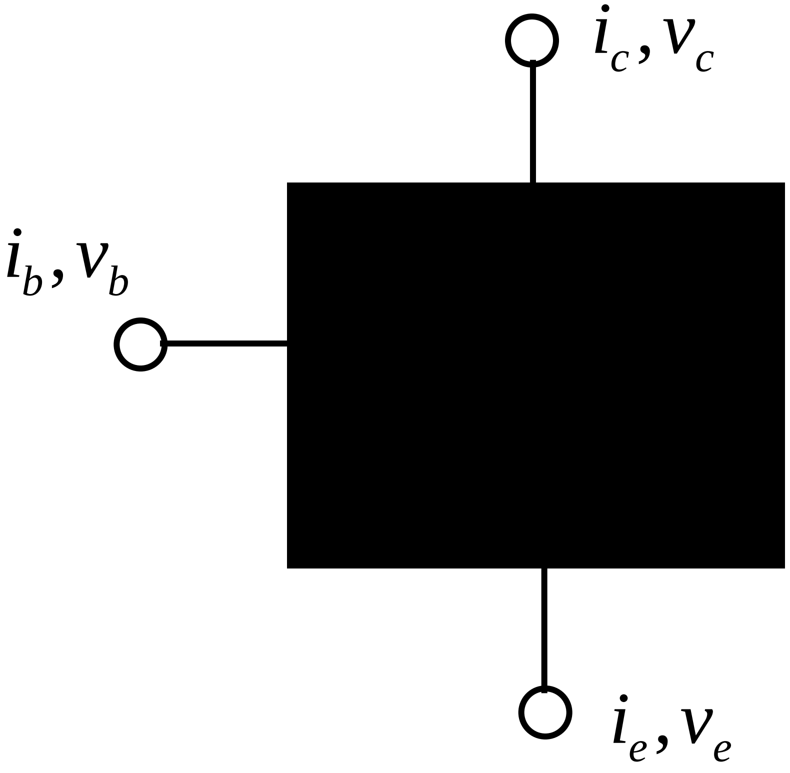
Next

- Generalized y-parameters
- not just common emitters
- Capacitances
- y-parameters from doping profile
- Definition of f_T

General admittance matrix

Last lecture, we had emitter grounded.
Called common emitter configuration:

$$\begin{pmatrix} i_b \\ i_c \end{pmatrix} = \begin{pmatrix} \frac{g_m}{\beta} & 0 \\ \frac{eI_C}{kT} & 0 \end{pmatrix} \begin{pmatrix} v_{be} \\ v_c \end{pmatrix}$$



In general:

$$\begin{pmatrix} i_e \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} . & . & . \\ . & . & . \\ . & . & . \end{pmatrix} \begin{pmatrix} v_e \\ v_b \\ v_c \end{pmatrix}$$

Y-matrix has 9 elements, but once you know 4 you know them all because:

$$i_e = i_b + i_c$$

and: $v_{cb} + v_{be} = v_{ce}$

See book about details procedure to get 9 parameters from only 4.

Three configurations:

Common emitter configuration (v_e=0):

$$\begin{pmatrix} i_b \\ i_c \end{pmatrix} = \begin{pmatrix} y_{bb} & y_{bc} \\ y_{cb} & y_{cc} \end{pmatrix} \begin{pmatrix} v_b \\ v_c \end{pmatrix} = [y]_e \begin{pmatrix} v_b \\ v_c \end{pmatrix}$$

Common base configuration (v_b=0):

$$\begin{pmatrix} i_e \\ i_c \end{pmatrix} = \begin{pmatrix} y_{ee} & y_{ec} \\ y_{ce} & y_{cc} \end{pmatrix} \begin{pmatrix} v_e \\ v_c \end{pmatrix} = [y]_b \begin{pmatrix} v_e \\ v_c \end{pmatrix}$$

Easiest to calculate from doping profile.

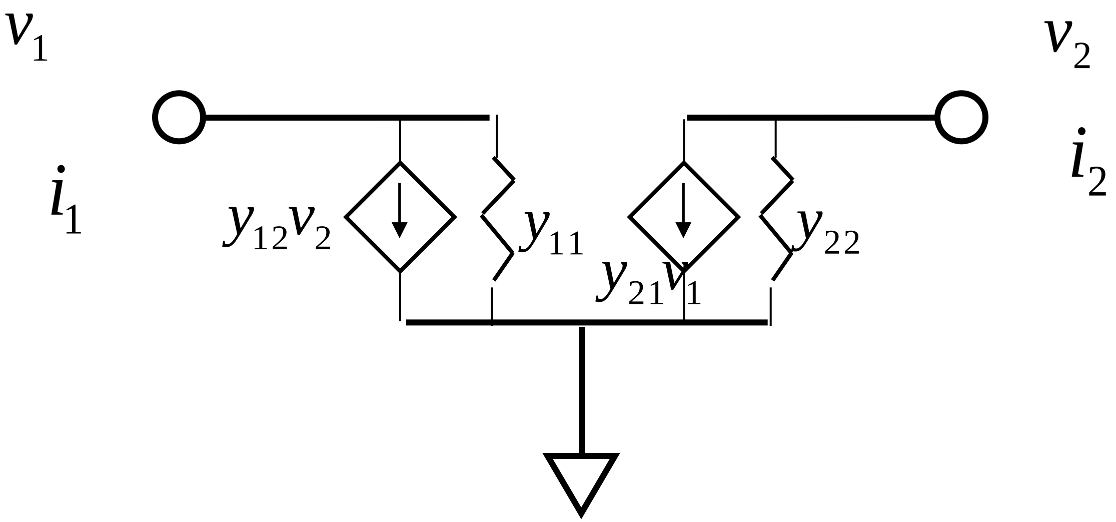
Common collector configuration (v_c=0):

$$\begin{pmatrix} i_b \\ i_e \end{pmatrix} = \begin{pmatrix} y_{bb} & y_{be} \\ y_{eb} & y_{ee} \end{pmatrix} \begin{pmatrix} v_b \\ v_e \end{pmatrix} = [y]_c \begin{pmatrix} v_b \\ v_e \end{pmatrix}$$

Generalized π model:

Regardless of which configuration you use, the following π model applies:

$$\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}$$

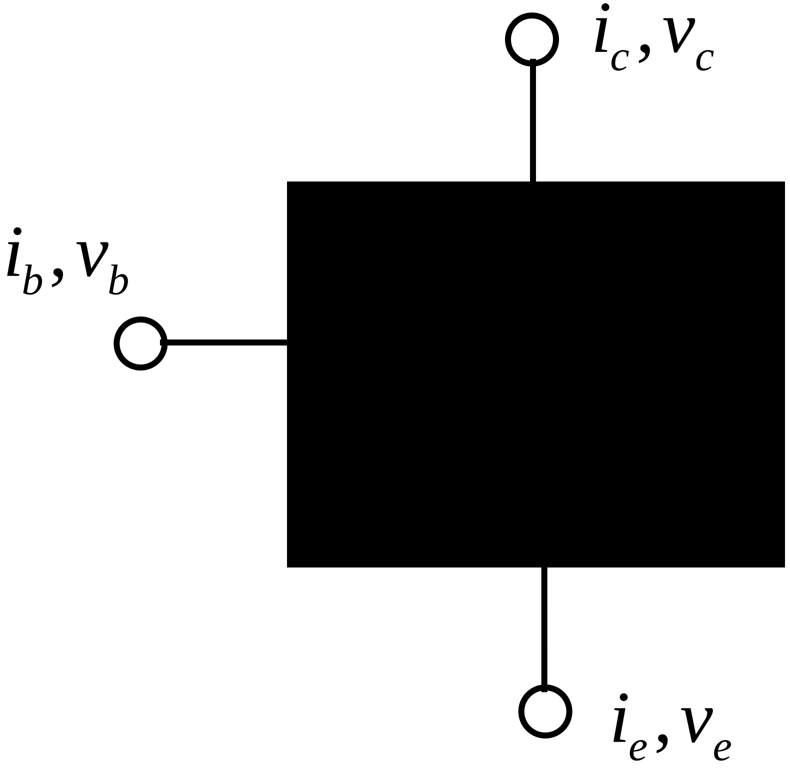


Common emitter: 1=base, 2=collector
Common base: 1=emitter, 2=collector
Common collector: 1=base, 2= emitter

You might be used to
V=IR

General impedance matrix

$$\begin{pmatrix} v_e \\ v_b \\ v_c \end{pmatrix} = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \begin{pmatrix} i_e \\ i_b \\ i_c \end{pmatrix}$$



Y-matrix has 9 elements, but once you know 4 you know them all because:

h matrix:

$$\begin{pmatrix} v_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} i_1 \\ v_2 \end{pmatrix}$$

Common emitter: 1=base, 2=collector
Common base: 1=emitter, 2=collector
Common collector: 1=base, 2= emitter

Note: In general, matrix elements depend on dc currents, dc voltages, and frequency. Spec. sheet (or model) will provide the matrix elements as a table vs. frequency, usually for only one bias current.

Common emitter h matrix:

$$\begin{pmatrix} v_b \\ i_c \end{pmatrix} = \begin{pmatrix} h_{11e} & h_{12e} \\ h_{21e} & h_{22e} \end{pmatrix} \begin{pmatrix} i_b \\ v_c \end{pmatrix}$$

- Early effect:

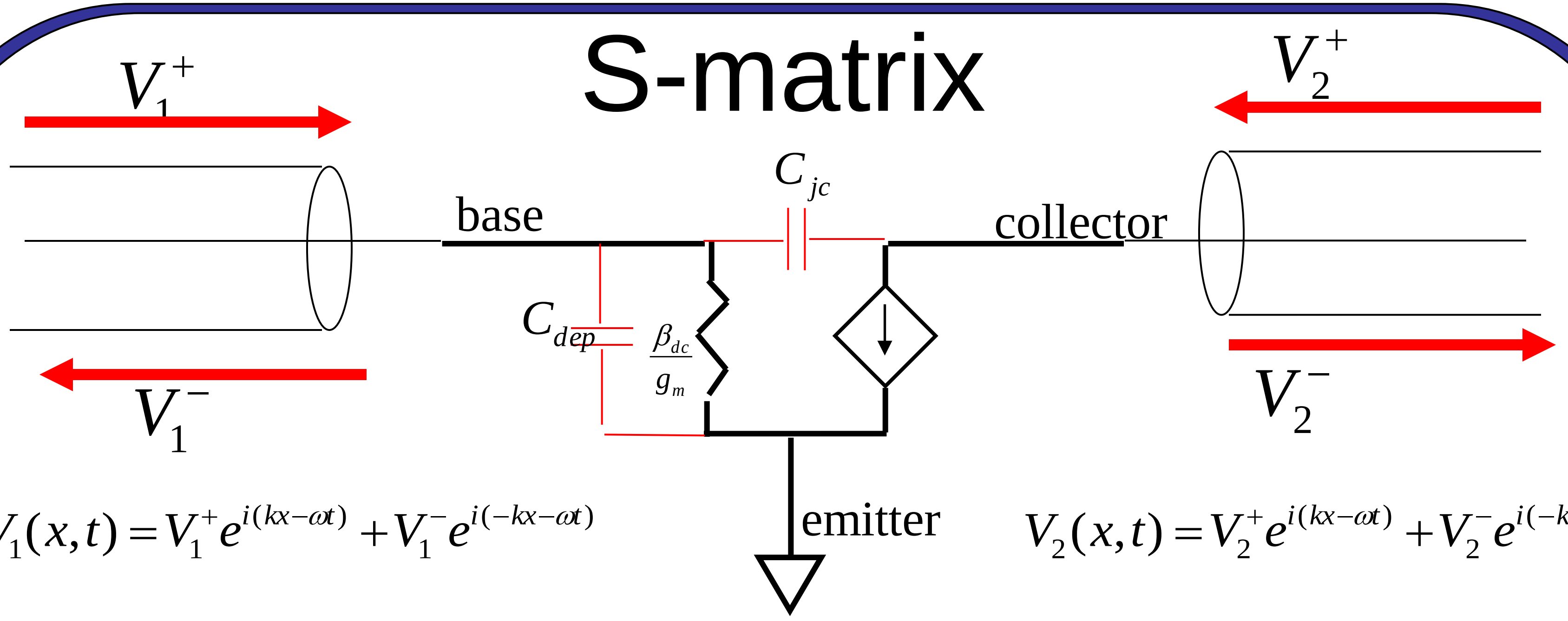
  Collector voltage changes current gain (β).
- β depends on frequency *and* collector voltage.
- How do we define frequency at which β = 1?
- At v_c=0. This *is* h_{21e}

$$i_c = h_{21e} i_b + h_{22e} v_c \rightarrow h_{21e} i_b$$

- We define f_T such that:

$$\boxed{\left| h_{21e} \right| (f_T) = 1}$$

S-matrix



$V_1(x,t) = V_1^+ e^{i(kx-\omega t)} + V_1^- e^{i(-kx-\omega t)}$

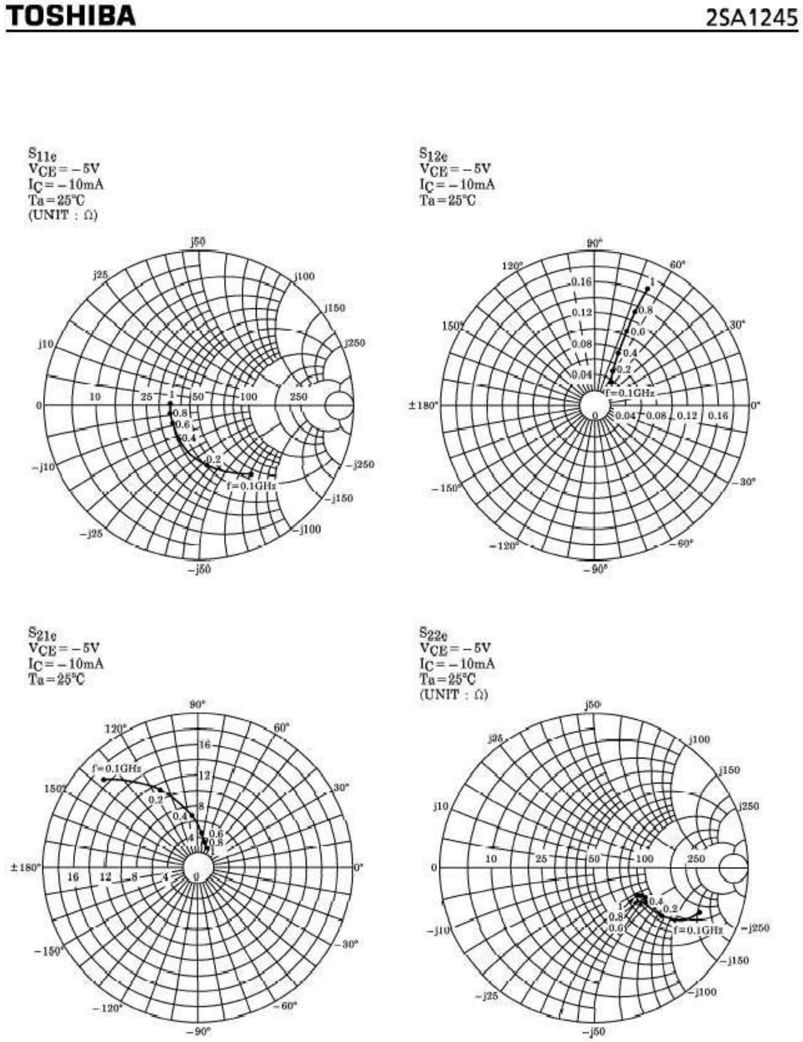
$V_2(x,t) = V_2^+ e^{i(kx-\omega t)} + V_2^- e^{i(-kx-\omega t)}$

$$\begin{pmatrix} V_1^- \\ V_2^- \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} V_1^+ \\ V_2^+ \end{pmatrix}$$

$$V_1^- = S_{11} V_1^+ + S_{12} V_2^+$$

$$V_2^- = S_{21} V_1^+ + S_{22} V_2^+$$

S-parameters



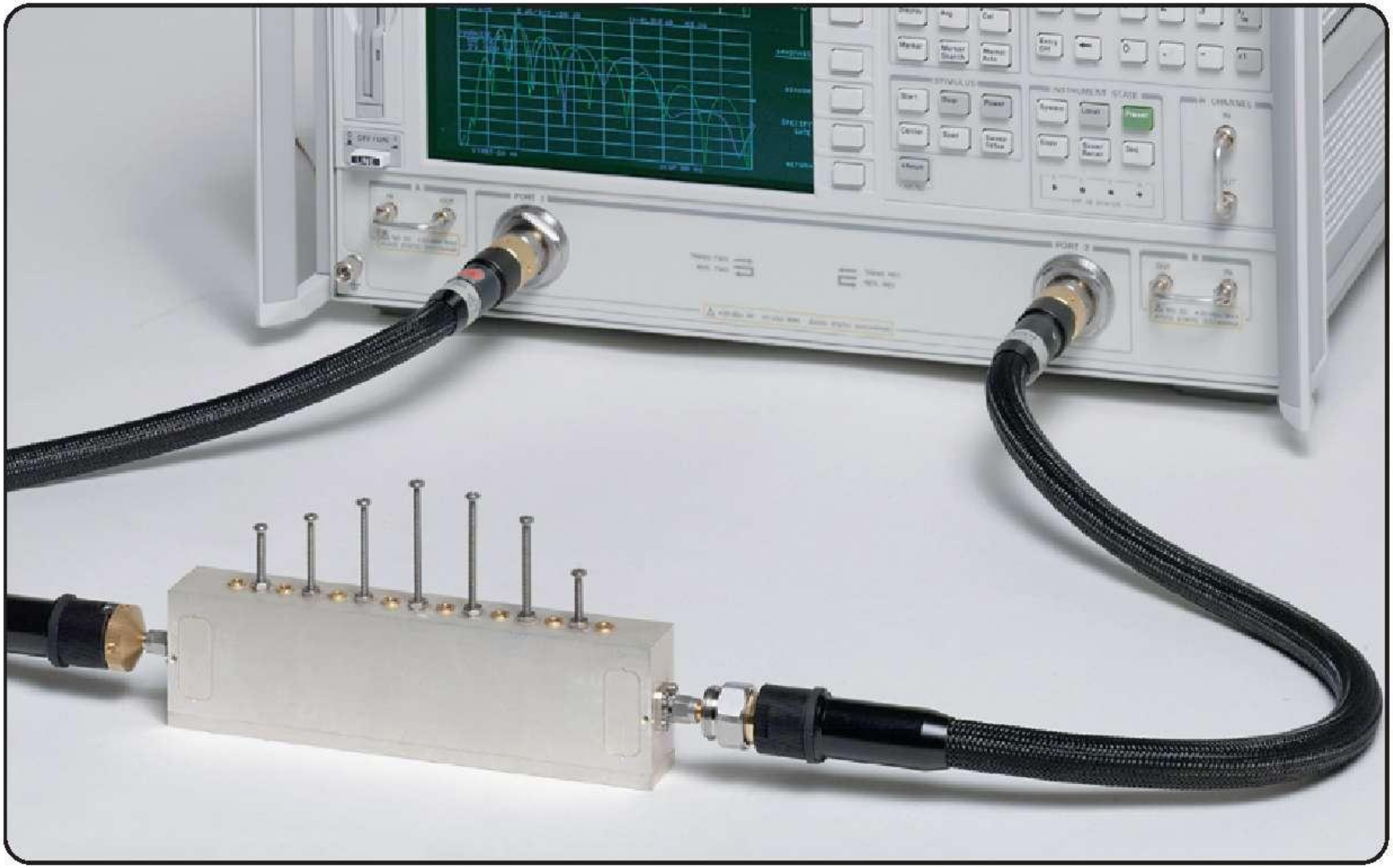
This is what you see on data sheets.
Related to input impedance, output impedanc
and gain vs. frequency.
=> Need to discuss ac performance.

Summary of parameters

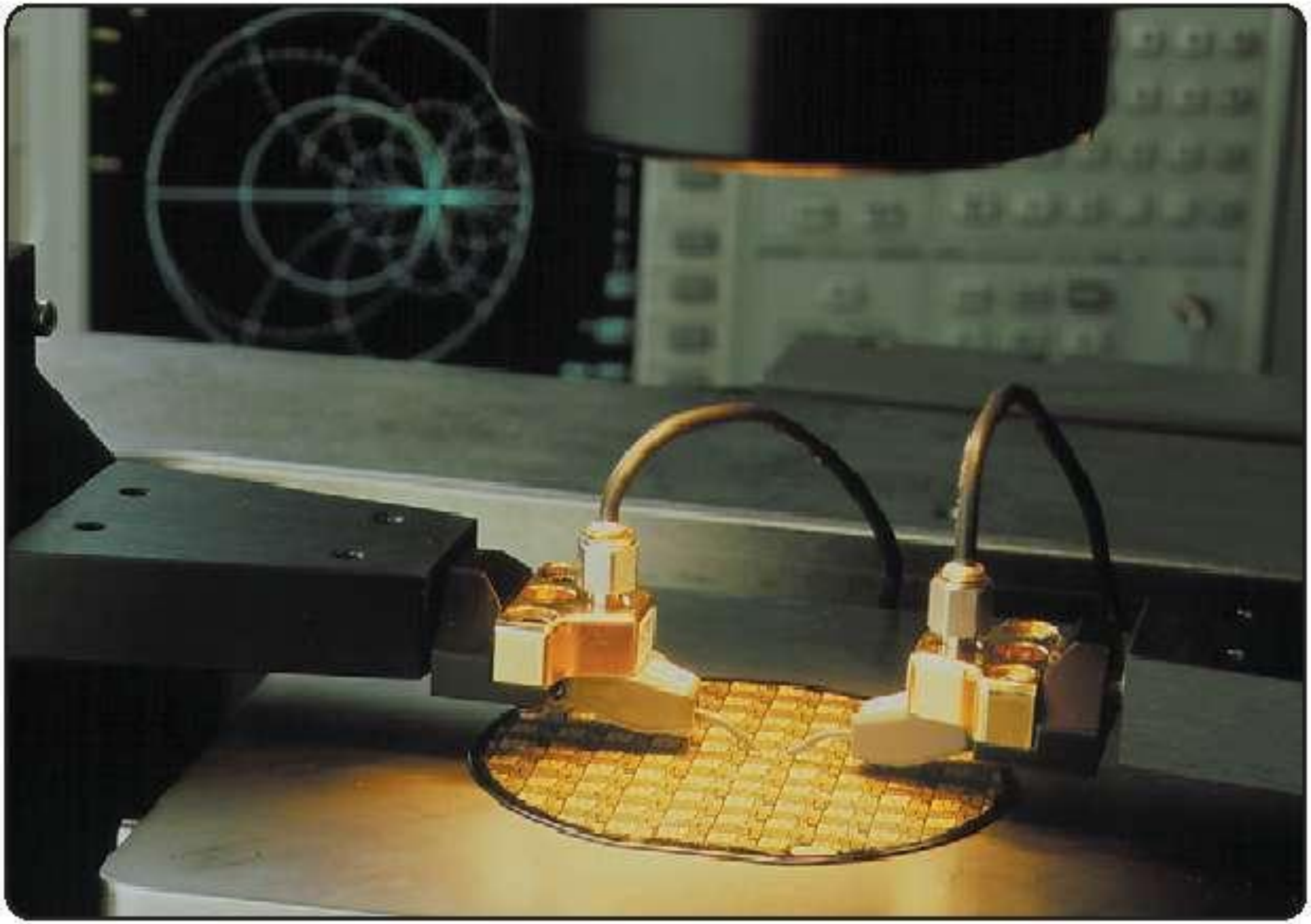
- Impedance matrix (V=IR -> V=IZ)
- Admittance matrix (I=YV)
- h-matrix (combination)
- ABCD matrix (combination)
- S-matrix (microwave reflections and transmissions)

"If you know one, then you know them all…"
See Liu, page 249 for conversions.

Measurement techniques



Measurement techniques



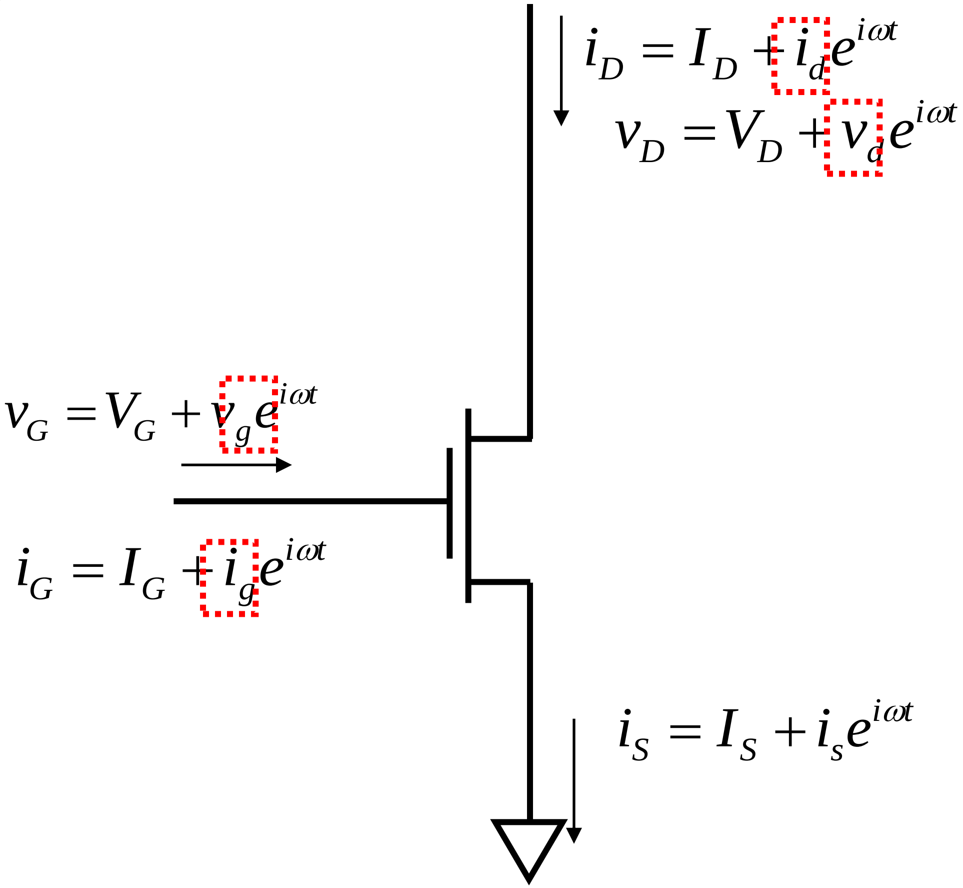
Cost (*rough* estimates)

- 10 GHz: $50,000
- 20 GHz: $70,000
- 40 GHz: $90,000
- 110 GHz: $250,000
- > 110 GHz: very expensive

For cost and difficulty reasons, parameters of transistor not always measure all the way up to f_T, but extrapolated.

These are only estimates. Contact vendor for actual prices.

AC equivalent circuit:



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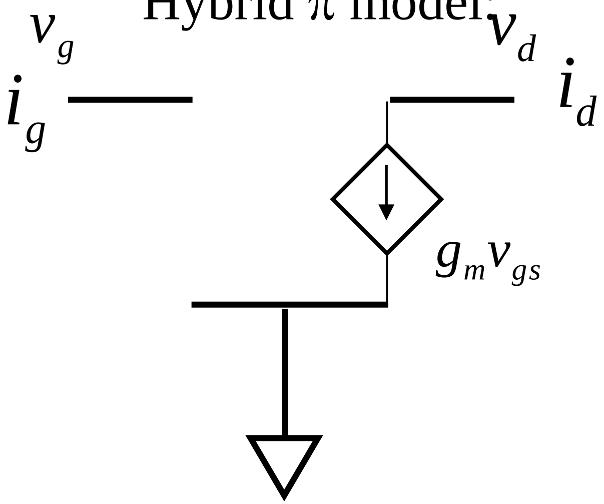
Hybrid π model:



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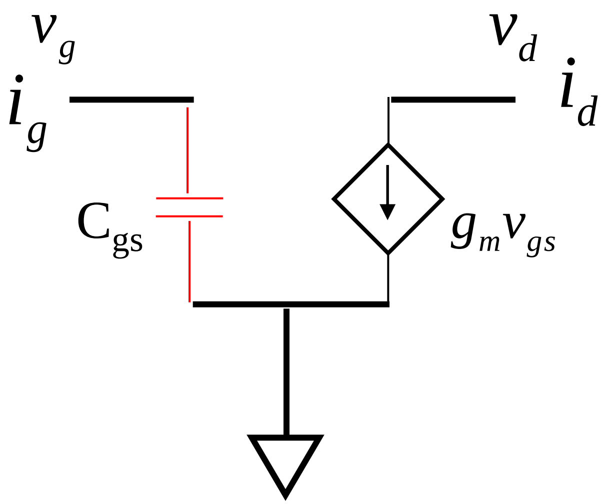
This is the common-source Y-matrix. You can get all the matrices from it.

f_T

Hybrid π model:



When current flowing through capacitor is equal to $g_m v_{gs}$

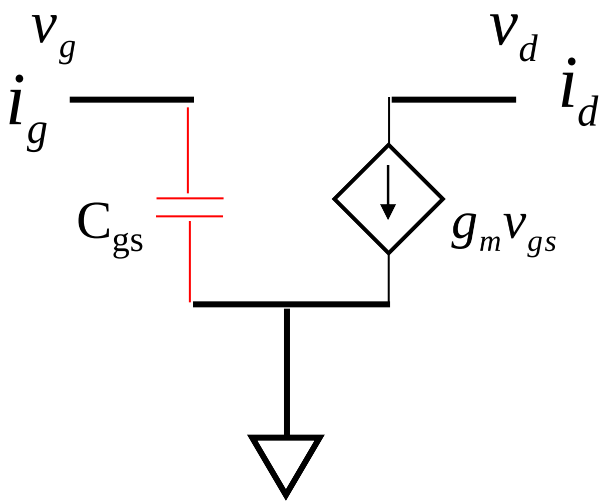
then the frequency is f_T.

$$i_g = v_{gs}(\omega C_{gs}) \qquad i_d = g_M v_{gs}$$

At f_T $$g_M v_{gs} = v_{gs}(\omega_T C_{gs})$$

$$\Rightarrow \omega_T = \frac{g_M}{C_{gs}} \Rightarrow f_T = \frac{g_M}{2\pi C_{gs}}$$

f_T



$$f_T = \frac{g_M}{2\pi C_{gs}}$$

In HW#6, you will prove for the long-channel device:

$$g_M = \frac{W\mu C_{ox}^{'}}{L}\left(V_{GS} - V_T\right)$$

$$C_{ox}^{'} \sim C_{gs}/(LW)$$

$$f_T \rightarrow \frac{1}{2\pi}\frac{\mu\left(V_{GS} - V_T\right)}{L^2}$$

For a short-channel device,

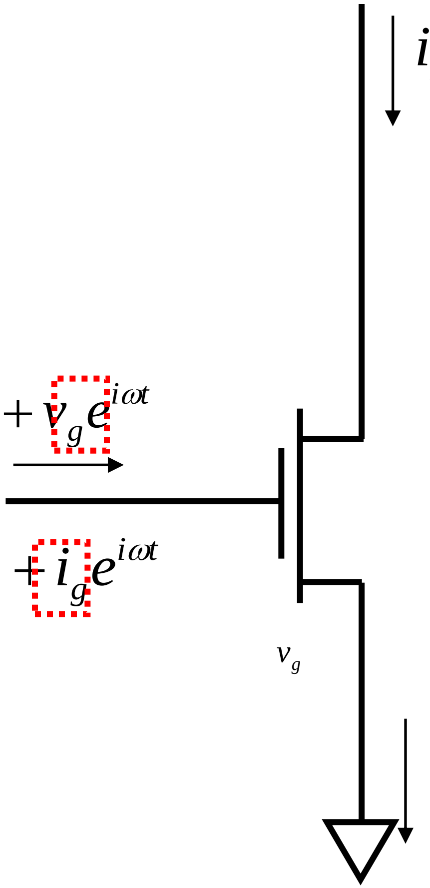
$$g_M = v_{sat} W C_{ox}^{'}$$

$$f_T \rightarrow \frac{v_{sat}}{2\pi L} = \frac{1}{2\pi\tau_{tr}}$$

Note:
(Intrinsic)
In saturation,
C_{gs} = (2/3) C_{ox} WL
C_{gd} =0
C_{sd}=0

So book model is only good for frequencies much less than f_T.

AC equivalent circuit:



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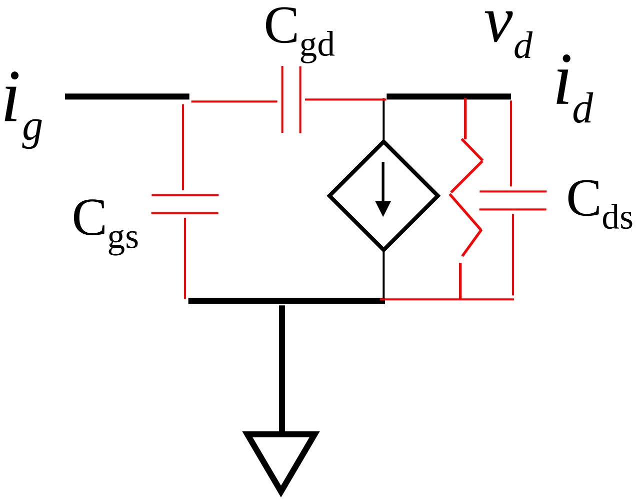
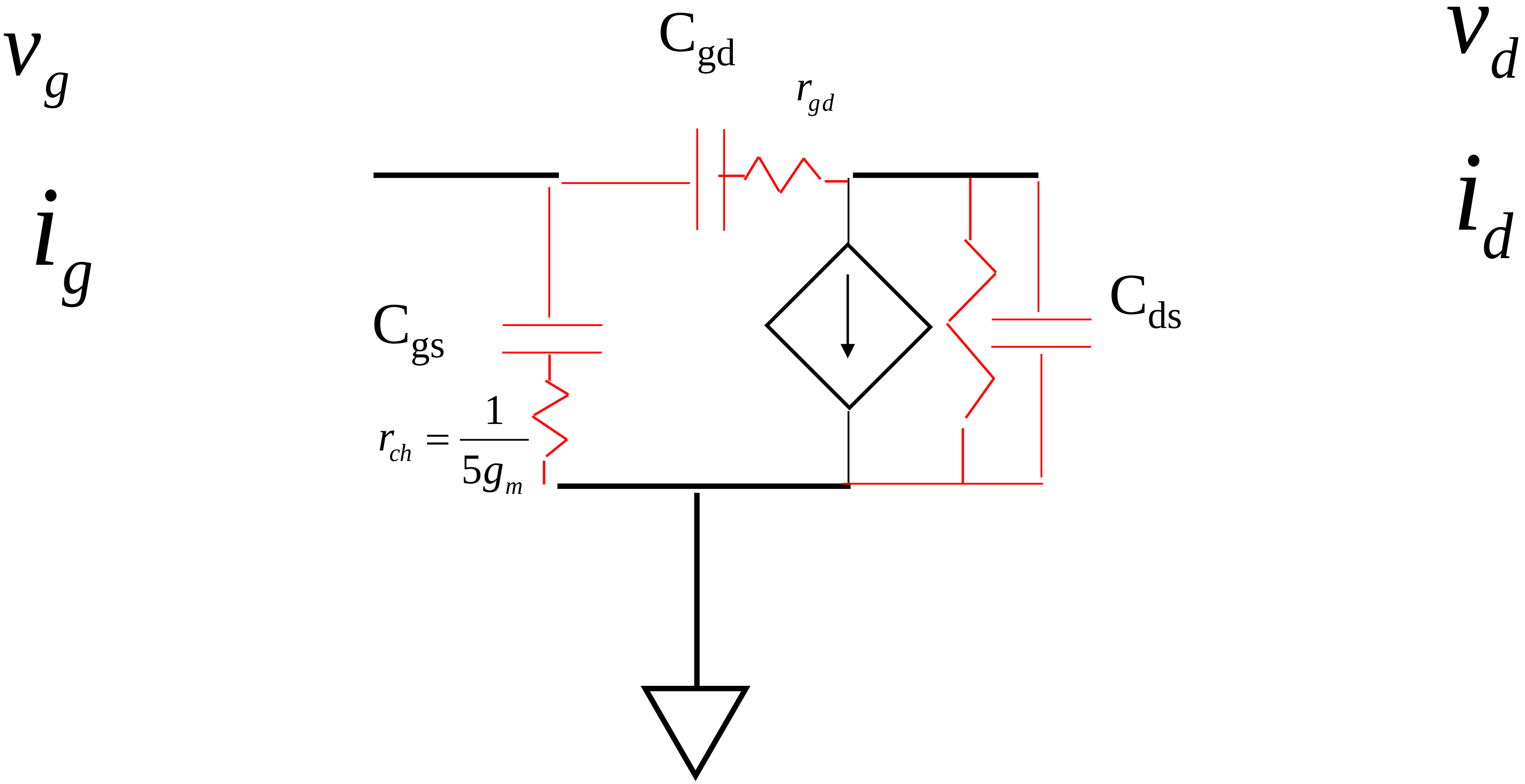
Hybrid π model:



C_{gs} dominates.

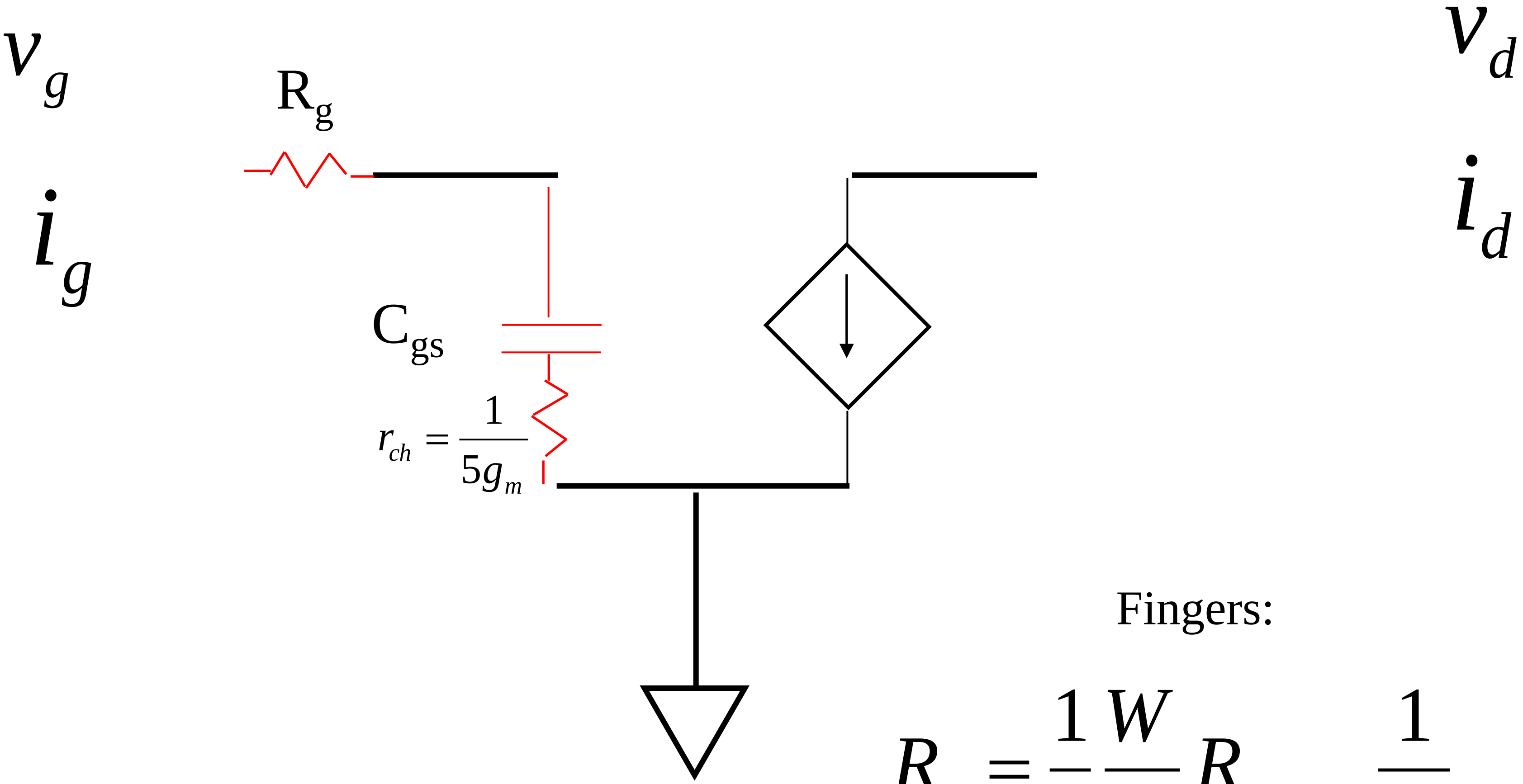
Non-quasi static model:

Hybrid π model:



Parasitics: Gate resistance:

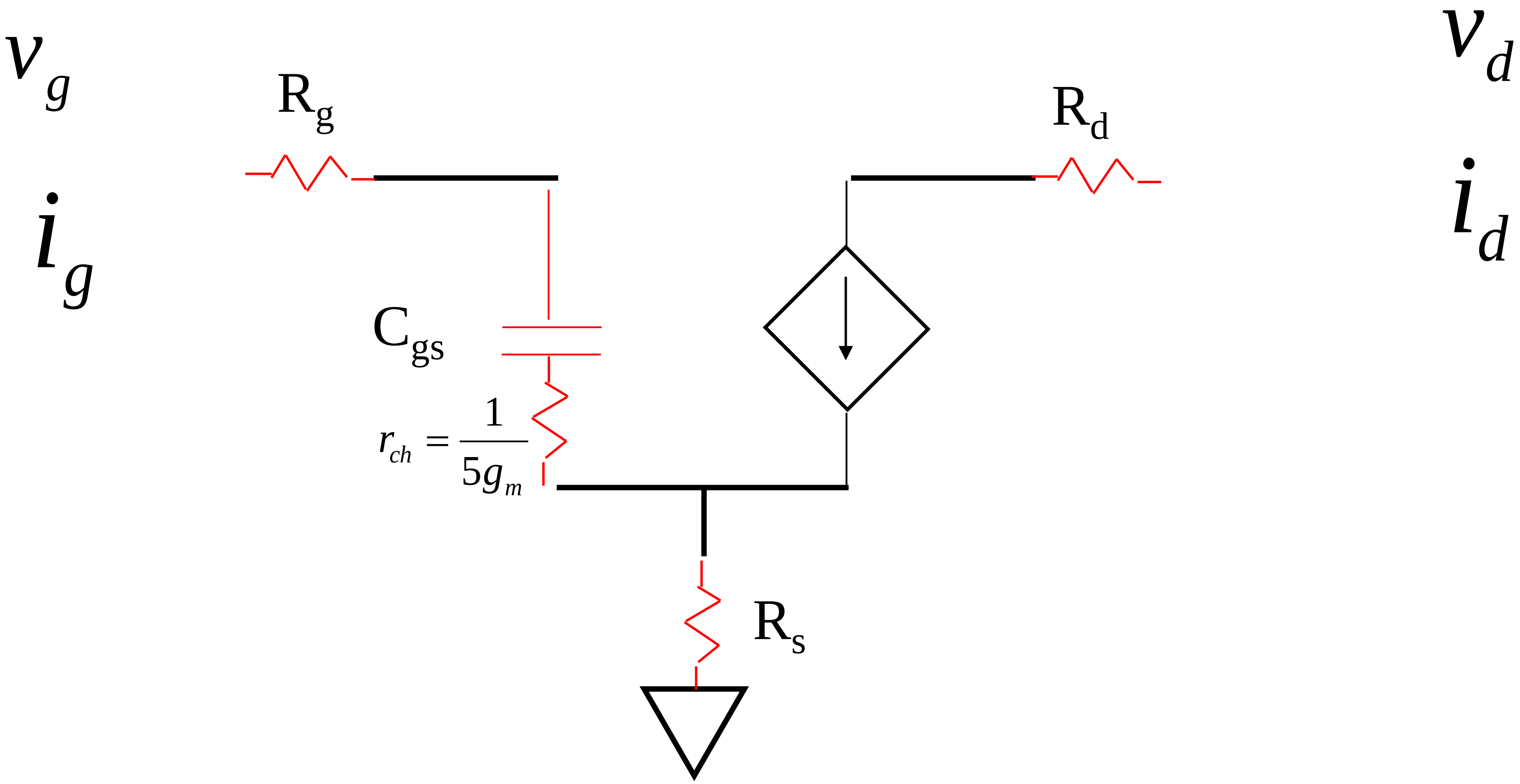
$$R_g = \frac{1}{3}\frac{W}{L}R_{square}$$



Fingers:

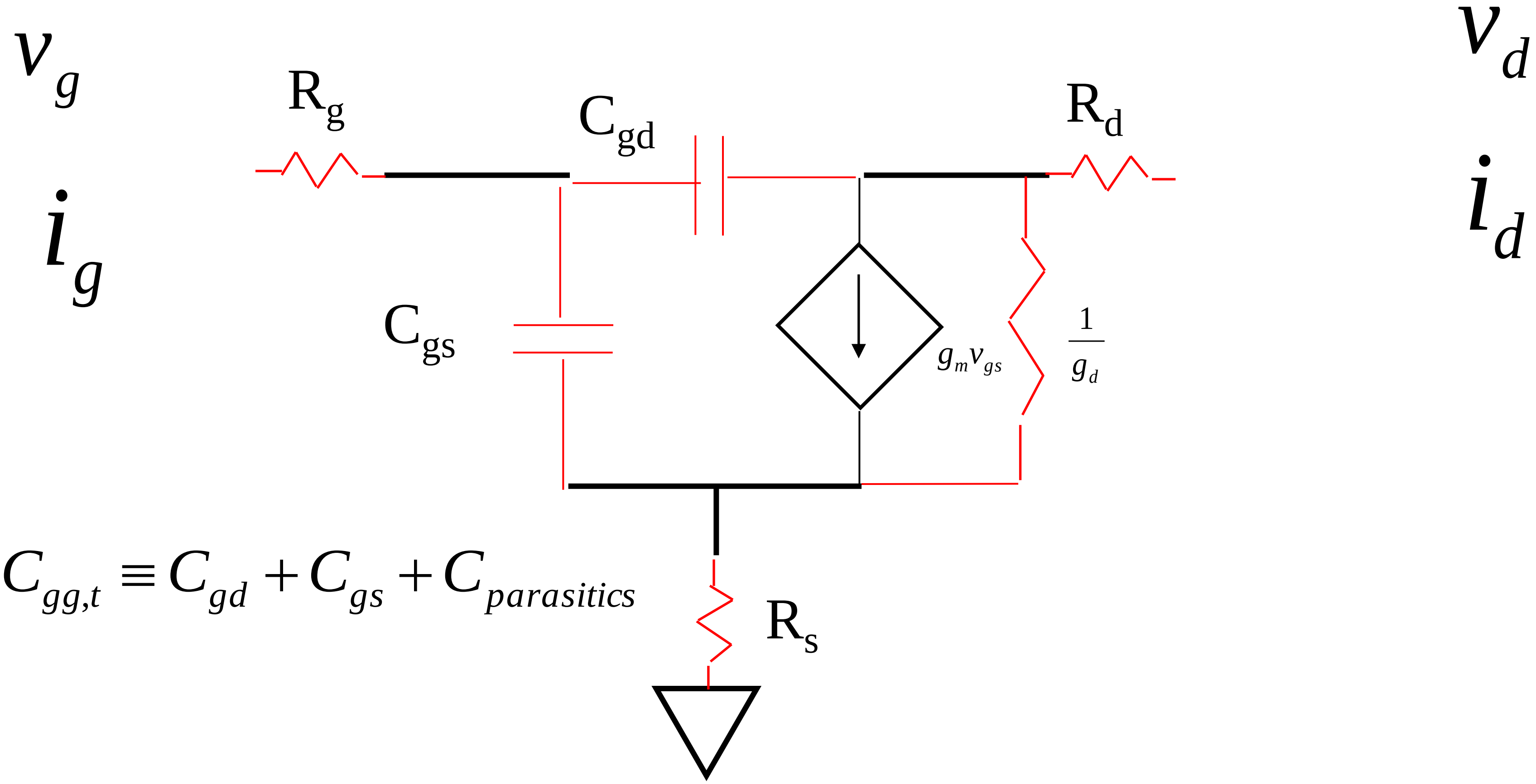
$$R_g = \frac{1}{3}\frac{W}{L}R_{square}\frac{1}{N}$$

Parasitics: Source/Draina resistance:



f_T

$$\frac{1}{2\pi f_T} = \frac{C_{gg,t}}{g_m} + \frac{C_{gg,t}}{g_m}(R_S + R_D)g_d + (R_S + R_D)C_{gd,t}$$



$$C_{gg,t} \equiv C_{gd} + C_{gs} + C_{parasitics}$$

f_{max}:

In real circuits, we do not want to short circuit the output!

Unilateral power gain: if impedance matching network is set up so that there is no reverse transmission (S_{12}=0), in that case the power gain is called the *unilateral power gain*.

"It can be shown that…"

$$U = \frac{\left|z_{21} - z_{12}\right|^2}{4\left[\mathrm{Re}(z_{11})\,\mathrm{Re}(z_{22}) - \mathrm{Re}(z_{12})\,\mathrm{Re}(z_{21})\right]}$$

"It can be shown that…"

$$f_{\max} = \sqrt{\frac{f_T}{8\pi r_g C_{gd}}}$$

Note r_{gate} dependence.

OR:

$$f_{\max} = \frac{1}{2} f_T \sqrt{\frac{r_o}{r_g}}$$

f_{MAX}

$$f_{MAX} = \sqrt{\frac{f_T}{8\pi R_G C_{gd,t}\left[1+\left(\frac{2\pi f_T}{C_{gd,t}}\right)\Psi\right]}}$$

$$\Psi \equiv (R_S + R_D)\frac{C_{gg,t}{}^2 g_d^2}{g_m^2} + (R_S + R_D)\frac{C_{gd,t}C_{gg,t}g_d}{g_m} + \frac{C_{gg,t}{}^2 g_d}{g_m^2}$$

f_{max} helped by fingers.
f_T not helped by fingers.
fMax sometimes larger, sometimes smaller than f_T.

Example

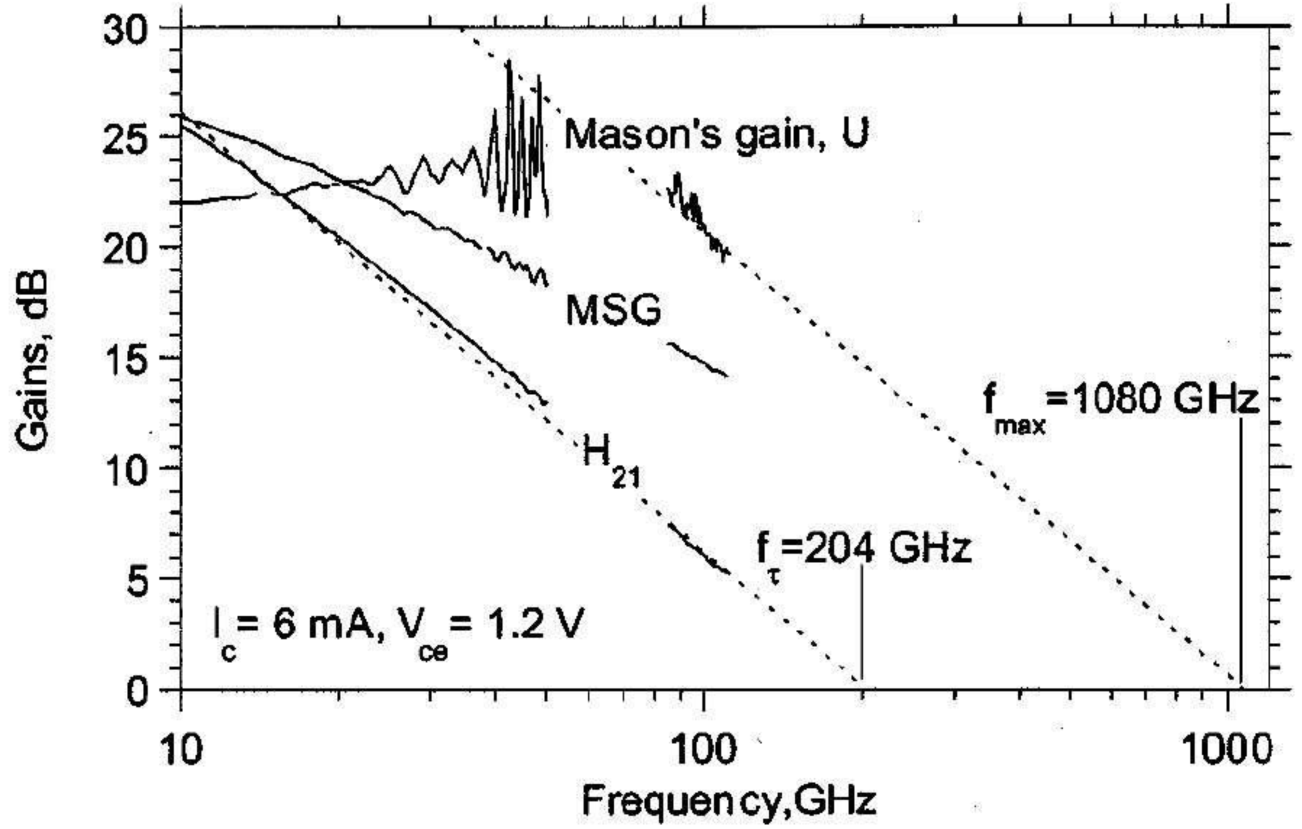


Fig. 14. Gains of a 0.4 μm × 6 μm emitter and 0.7 μm × 10 μm collector HBT fabricated using electron-beam lithography. Theoretical −20 dB/decade (H_{21}, U) gain slopes are indicated. The device exhibits an *extrapolated* 1.08 THz $f_{\max}$.

From Rodwell, et al, TRANSACTIONS ON ELECTRON DEVICES 48 (11): 2606-2624 IEEE NOV 2001

RF/AMS

Table RFAMS1 RF and Analog Mixed-Signal CMOS Technology Requirements

Year of Production	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*
Performance RF/Analog [1]																
Supply voltage (V) [2]	**1.1**	**1.05**	**1.05**	**1.05**	**1**	**0.95**	**0.95**	**0.95**	**0.85**	**0.85**	**0.85**	**0.85**	**0.75**	**0.75**	**0.75**	**0.75**
T_{ox} (nm) [2]	**1.2**	**1.2**	**1.2**	**1.2**	**1.10**	**1.10**	**1.10**	**1.10**	**1.10**	**1.00**	**1.00**	**0.90**	**0.90**	**0.80**	**0.80**	**0.70**
Gate Length (nm) [2]	**38**	**38**	**32**	**29**	**27**	**22**	**18**	**17**	**15**	**14**	**13**	**12**	**11**	**9.7**	**8.9**	**8.1**
g_m/g_{ds} at 5·$L_{min\text{-}digital}$ [3]	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
1/f-noise ($\mu V^2\cdot\mu m^2$/Hz) [4]	**100**	**90**	**80**	**70**	**70**	**60**	**50**	**50**	**40**	**40**	**40**	**30**	**30**	**30**	**20**	**20**
σ V_{th} matching (mV·µm) [5]	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**4**	**4**	**4**	**4**	**4**
I_{ds} (µA/µm) [6]	**9**	**9**	**8**	**7**	**7**	**6**	**5**	**4**	**4**	**3**	**3**	**3**	**2**	**2**	**2**	**2**
Peak F_t (GHz) [7]	**240**	**240**	**280**	**310**	**340**	**400**	**480**	**520**	**570**	**630**	**680**	**750**	**820**	**890**	**970**	**1060**
Peak F_{max} (GHz) [8]	**290**	**290**	**340**	**380**	**420**	**510**	**610**	**670**	**740**	**820**	**900**	**990**	**1090**	**1200**	**1320**	**1450**
NF_{min} (dB) [9]	**0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**	**<0.2**
Precision Analog/RF Driver [1]																
Supply voltage (V)	**2.5**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
T_{ox} (nm) [10]	**5**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**
Gate Length (nm) [10]	**250**	**180**	**180**	**180**	**180**	**180**	**180**	**180**	**180**	**180**	**130**	**130**	**130**	**130**	**130**	**130**
g_m/g_{ds} at 10·$L_{min\text{-}digital}$ [11]	**220**	**160**	**160**	**160**	**160**	**160**	**160**	**160**	**160**	**160**	**110**	**110**	**110**	**110**	**110**	**110**
1/f Noise ($\mu V^2\cdot\mu m^2$/Hz) [4]	**1000**	**360**	**360**	**360**	**360**	**360**	**360**	**360**	**360**	**360**	**270**	**270**	**270**	**270**	**270**	**270**
σ V_{th} matching (mV·µm) [5]	**9**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**5**	**5**	**5**	**5**	**5**	**5**
Peak F_t (GHz) [7]	**40**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**70**	**70**	**70**	**70**	**70**	**70**
Peak F_{max} (GHz) [8]	**70**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**90**	**120**	**120**	**120**	**120**	**120**	**120**
Availability of optional analog / High-voltage FETs	**limited**	**limited**	**common**	**common**	**wide**	**wide**	**wide**	**wide**	**wide**	**wide**	**wide**	**wide**	**wide**	**wide**	**wide**	**wide**
							switch to UTB FD or									

RF CMOS

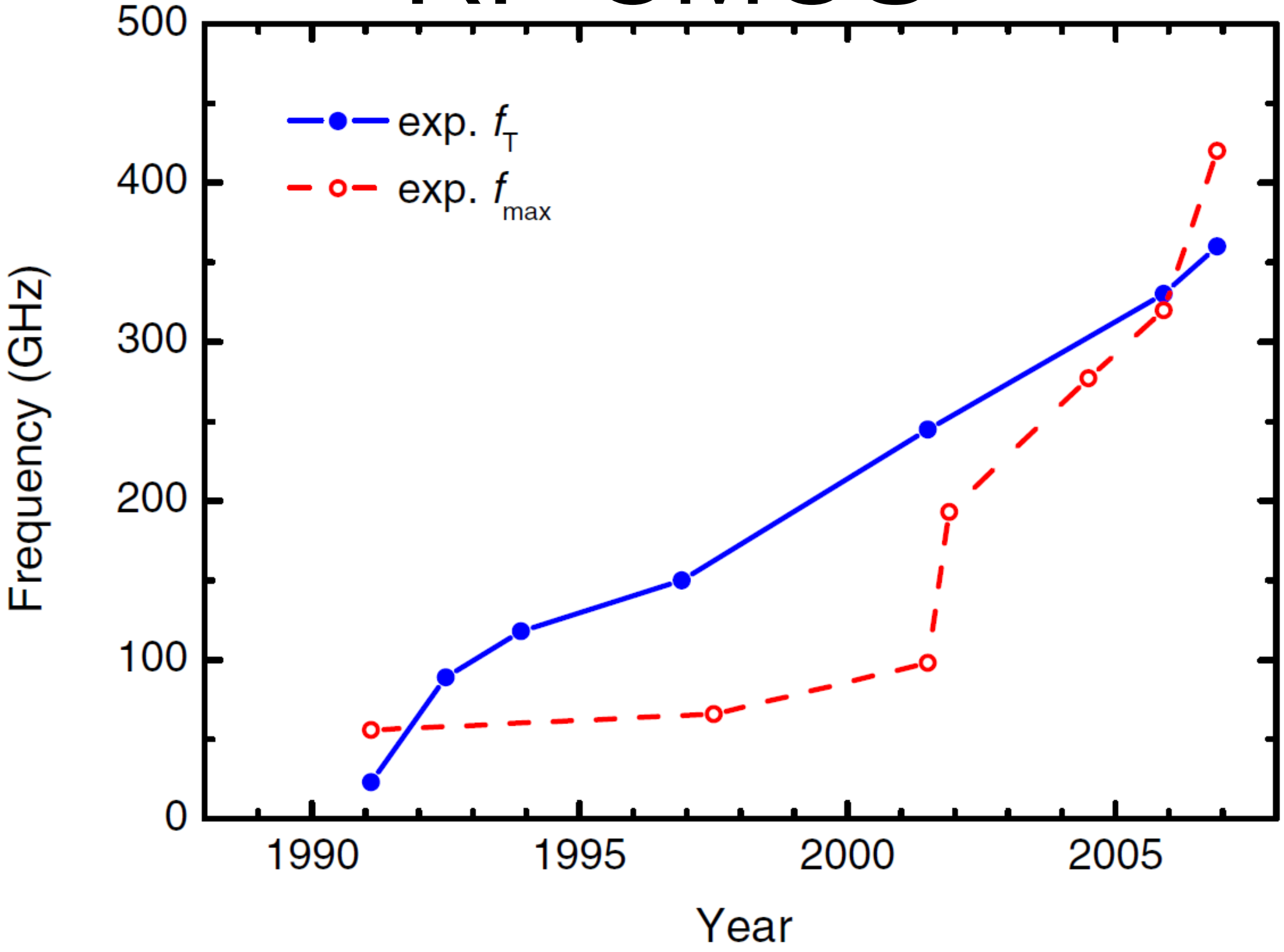
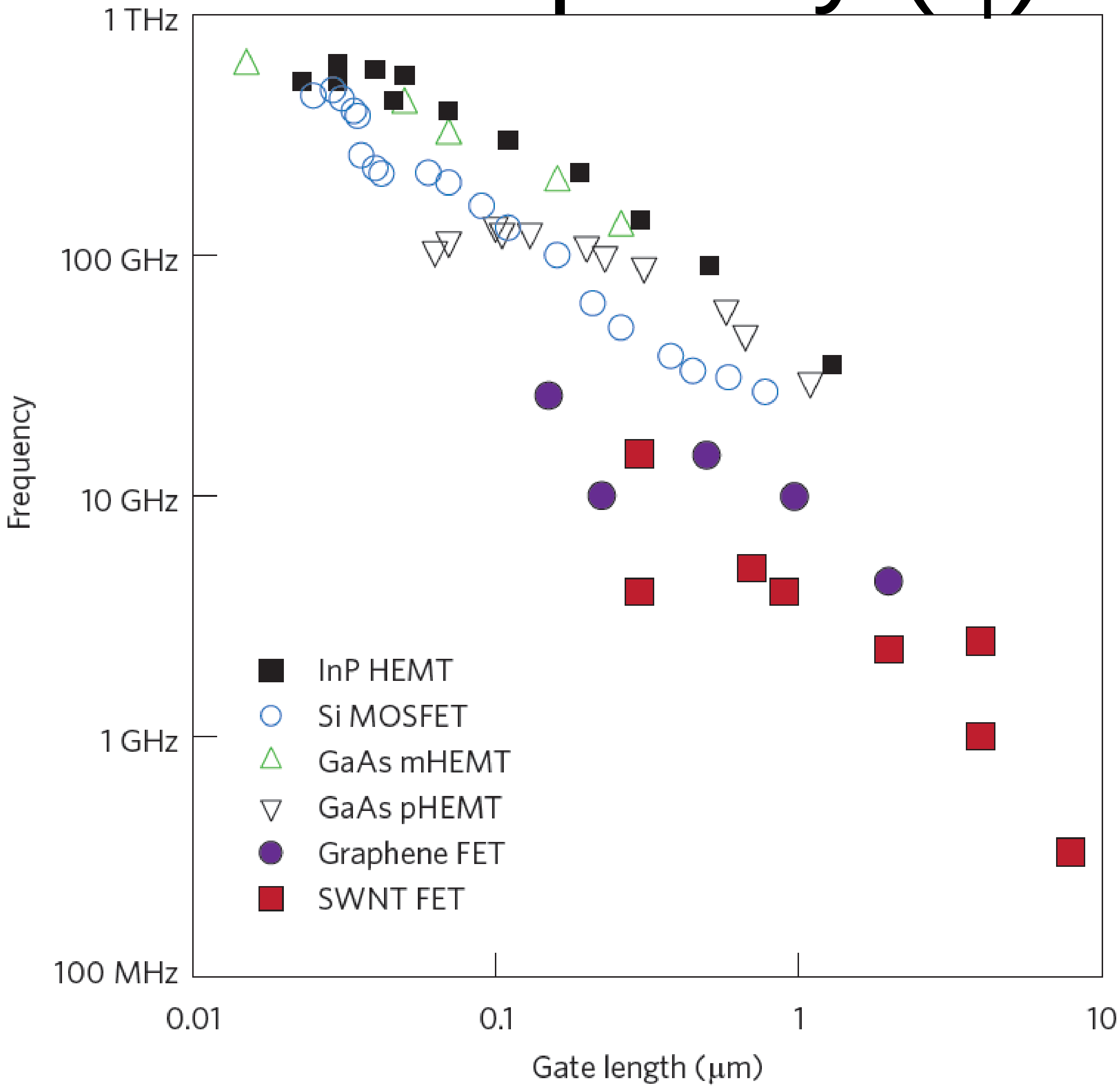


Fig. 1. Evolution of the record cutoff frequency f_T and the record maximum frequency of oscillation f_{max} of RF Si MOSFETs versus time.

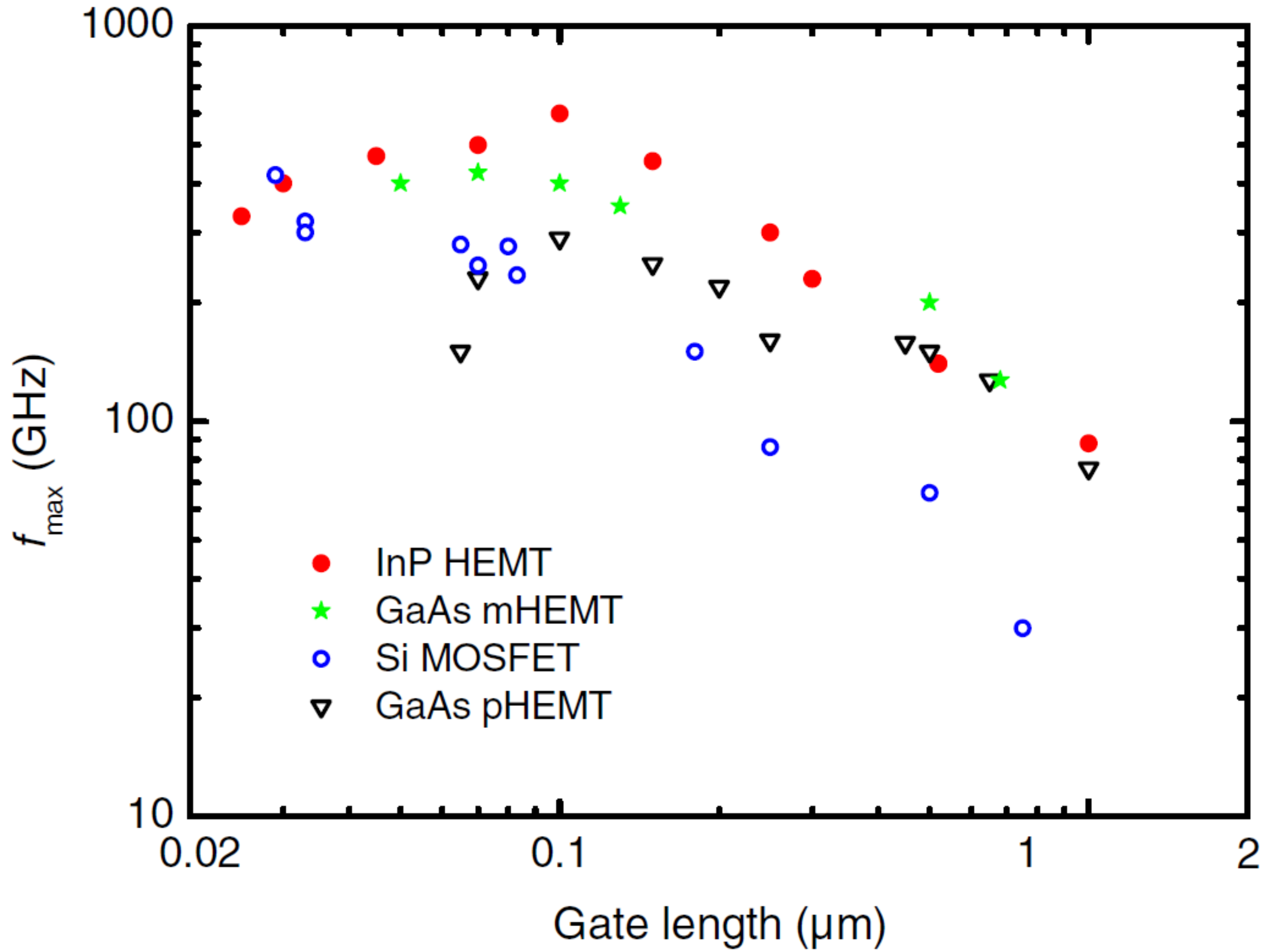
F. Schwierz and J. J. Liou, "RF Transistors: Recent Developments and Roadmap toward Terahertz Applications", *Solid-State Electronics*, ***51, 1079-1091, (2007).***

Cutoff frequency (f_T)



C. Rutherglen, D. Jain and P. Burke, "Nanotube Electronics for Radiofrequency Applications", *Nature Nanotechnology*, ***4, 811-819, (2009).***

III-V f_{Max}



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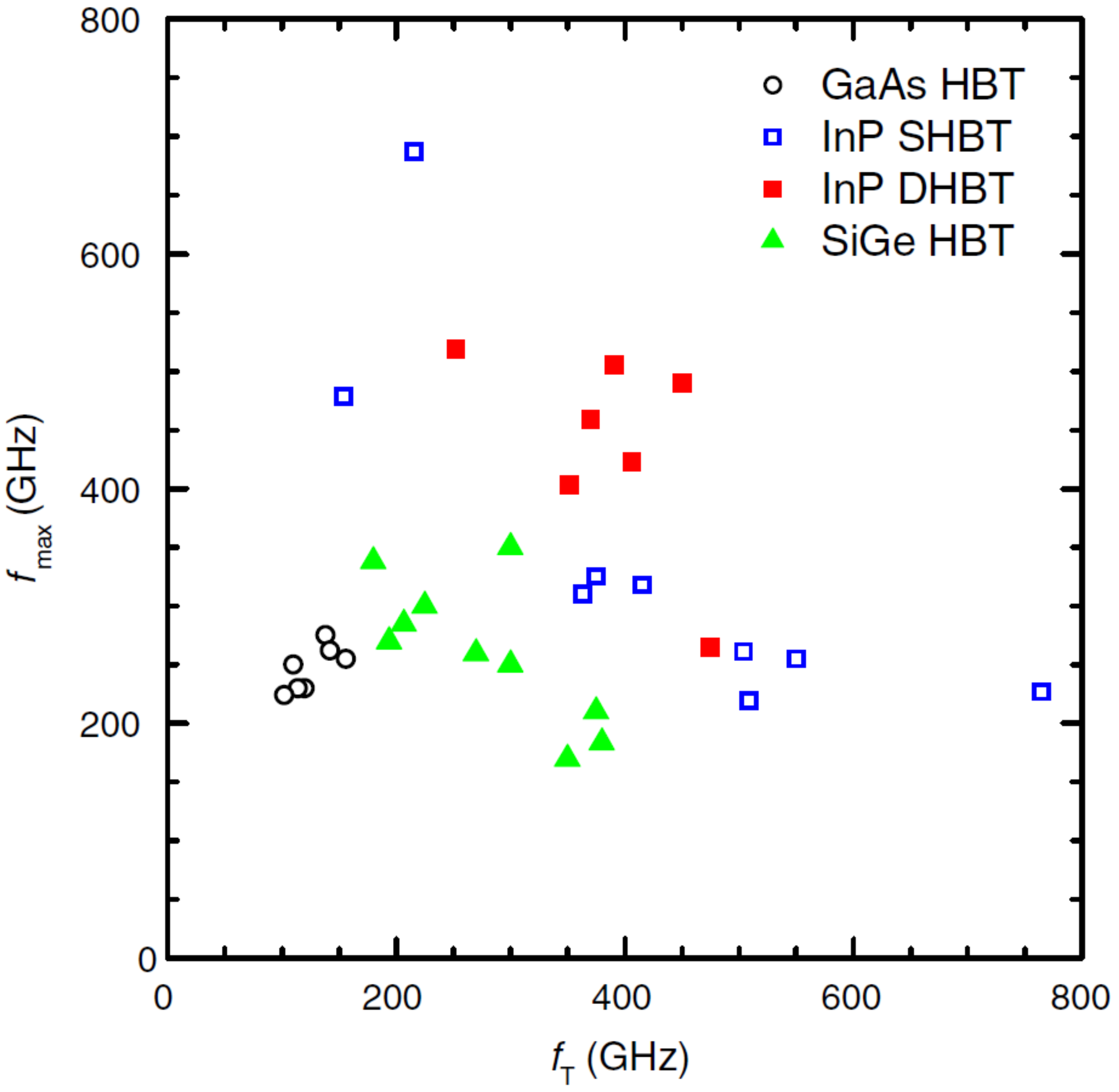
f_T vs f_{Max}



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