❑ gm/ID metodologija projektovanja

Kvadratna zavisnost struje drejna

$$I_D = \mu C_{ox} \frac{W}{2L} \left(V_{GS} - V_T\right)^2 \left(1 + \lambda V_{DS}\right)$$

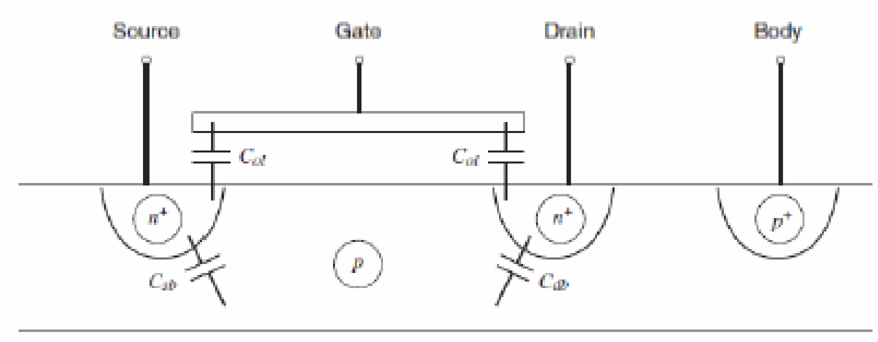
$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu C_{ox} \frac{W}{L} \left(V_{GS} - V_T\right)\left(1 + \lambda V_{DS}\right) = \frac{2 I_D}{V_{GS} - V_T}$$

$$g_{ds} = g_0 = \frac{\partial I_D}{\partial V_{DS}} = \mu C_{ox} \frac{W}{2L} \left(V_{GS} - V_T\right)^2 \left(1 + \lambda V_{DS}\right) = \mu C_{ox} \frac{W}{2L} \left(V_{GS} - V_T\right)^2 \lambda$$

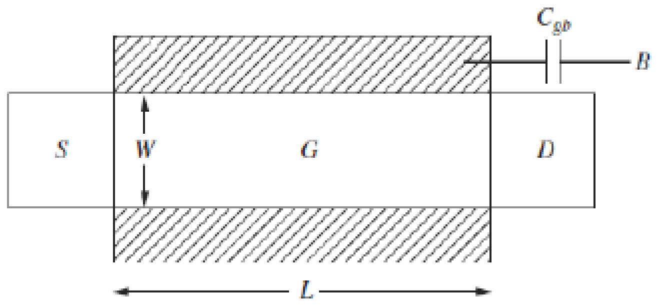
$$g_{ds} = g_0 = \frac{\partial I_D}{\partial V_{DS}} = \frac{\lambda I_D}{1 + \lambda V_{DS}}$$

- Važi samo za duge kanale i oblast jake inverzije, a model se dosta razlikuje od stvarne strujno-naponske karakteristike
- Ne postoji dovoljno precizan model za sve oblasti rada nanometarskih MOS tranzistora (EKV, ACM, ...) koji bi mogao da se koristi u “ručnim” proračunima
- Parametar koji se koristio kod tranzistora sa dugim kanalom pri “ručnim” proračunima Vod=VGS-VT, kao i napon praga nemaju više smisla jer se tranzistor može koristiti u svim oblastima inverzije, ispod napona praga i iznad napona praga

Kapacitivnosti:



(a)



(b)

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

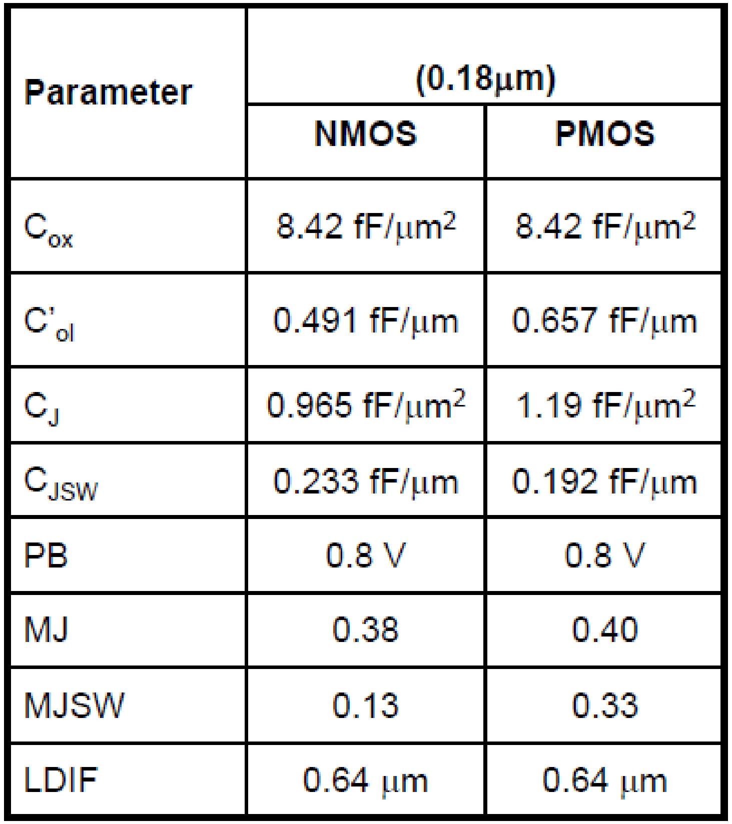
$$C_{ol} = WC'_{ol}$$

$$C_{db} = \frac{AD \cdot C_J}{\left(1+\frac{V_{DB}}{PB}\right)^{MJ}} + \frac{PD \cdot C_{JSW}}{\left(1+\frac{V_{DB}}{PB}\right)^{MJSW}}$$

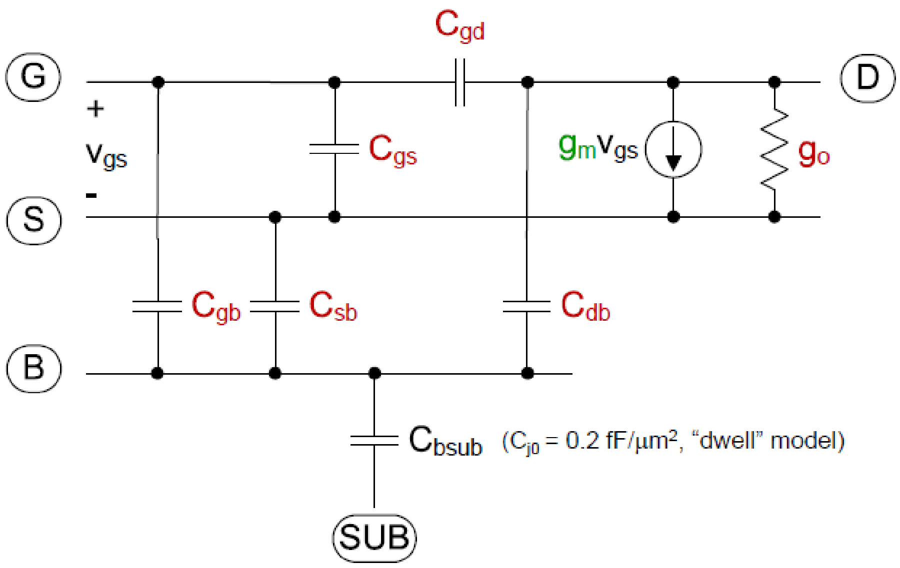
$$AD = WL_{diff}$$

$$PD = W + 2L_{diff}$$

	Subthreshold	**Triode**	**Saturation**
C_{gs}	C_{ol}	½ WLC_{ox}+ C_{ol}	$^2/_3$ WLC_{ox} + C_{ol}
C_{gd}	C_{ol}	½ WLC_{ox}+C_{ol}	C_{ov}
C_{gb}	$\left(\frac{1}{C_{js}}+\frac{1}{WLC_{ox}}\right)^{-1}$	0	0



Parameter	(0.18μm)	
	NMOS	**PMOS**
C_{ox}	8.42 fF/μm²	8.42 fF/μm²
C'_{ol}	0.491 fF/μm	0.657 fF/μm
C_J	0.965 fF/μm²	1.19 fF/μm²
C_{JSW}	0.233 fF/μm	0.192 fF/μm
PB	0.8 V	0.8 V
MJ	0.38	0.40
MJSW	0.13	0.33
LDIF	0.64 μm	0.64 μm



$$C_{gg} \triangleq C_{gs} + C_{gb} + C_{gd} \qquad C_{dd} \triangleq C_{db} + C_{gd}$$

- Ne postoji dovoljno precizan i jednostavan analitički model koji dovoljno dobro modeluje promenu kapacitivnosti sa promenom polarizacije
- Iterativne simulacije u SPICE-based okruženju daju dobre rezultate, ali su dugotrajne kada se simuliraju složenija kola

Faktori dobrote (Figure of Merit) MOS tranzistora

Efikasnost transkonduktanse (što veća transkonduktansa tranzistora za zadatu struju)

$$\frac{g_m}{I_D} = \left[\frac{2}{V_{OV}}\right]$$

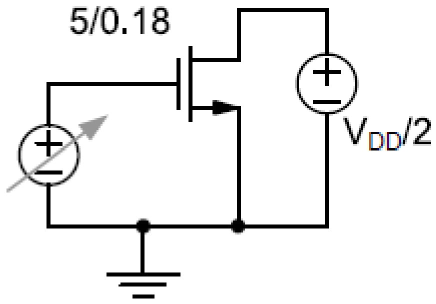
Učestanost jediničnog pojačanja

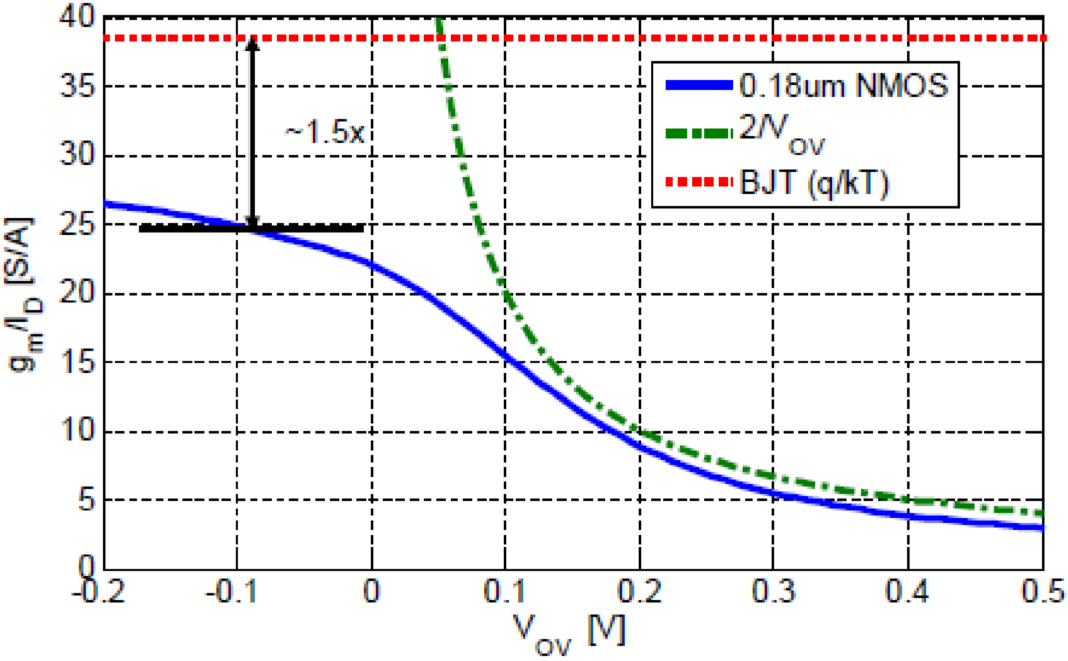
$$\frac{g_m}{C_{gg}} = \left[\frac{3}{2}\frac{\mu V_{OV}}{L^2}\right]$$

Unutrašnje pojačanje

$$\frac{g_m}{g_0} = \left[\frac{2}{\lambda V_{OV}}\right]$$

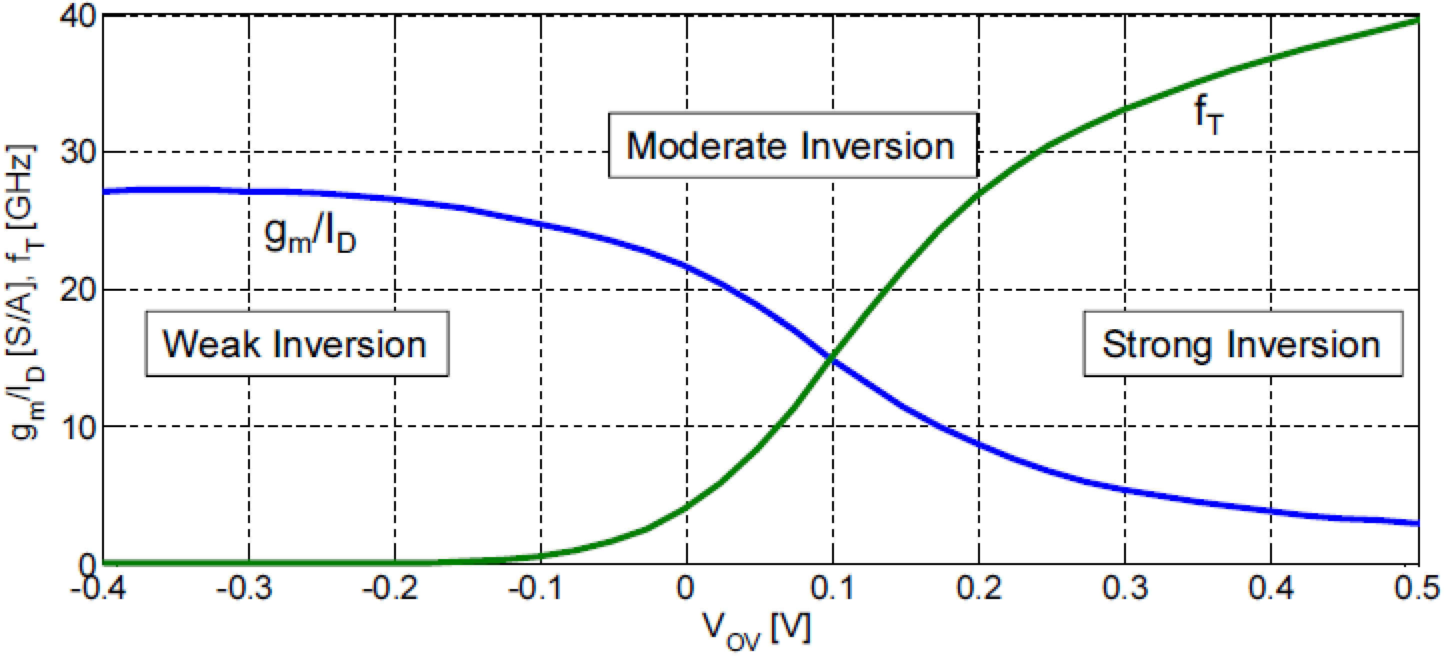
$$\frac{g_m}{I_D} = \left[\frac{2}{V_{OV}}\right]$$





$$\left(\frac{g_m}{I_D}\right)_{WI} = \frac{1}{nV_t} \qquad \left(\frac{g_m}{I_C}\right)_{BJT} = \frac{1}{V_t} \qquad n \approx 3/2$$

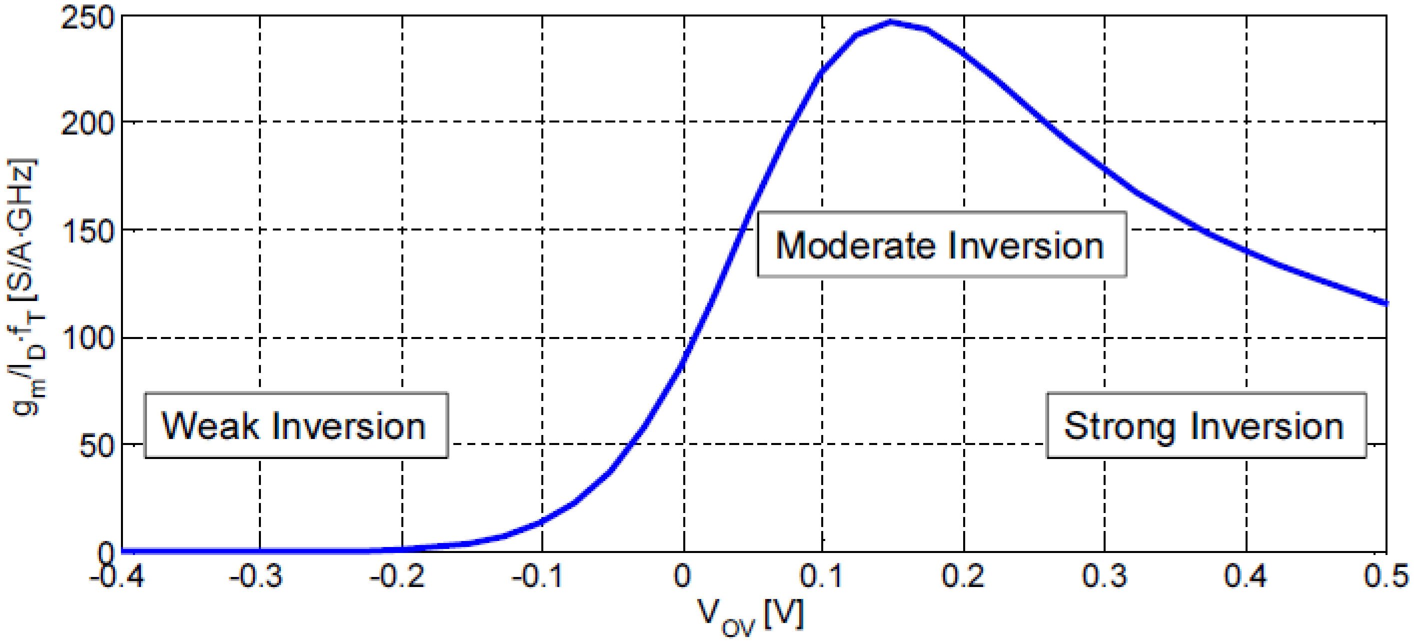
Design Tradeoff: gm/ID and fT



WI: veliki gm/ID, mali fT

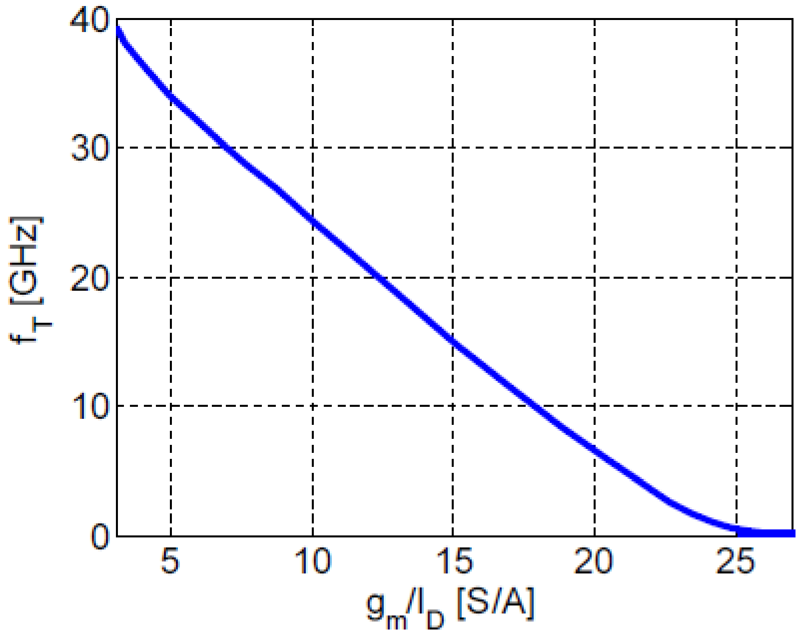
SI: veliki fT, mali gm/ID

Proizvod (gm/ID)*fT

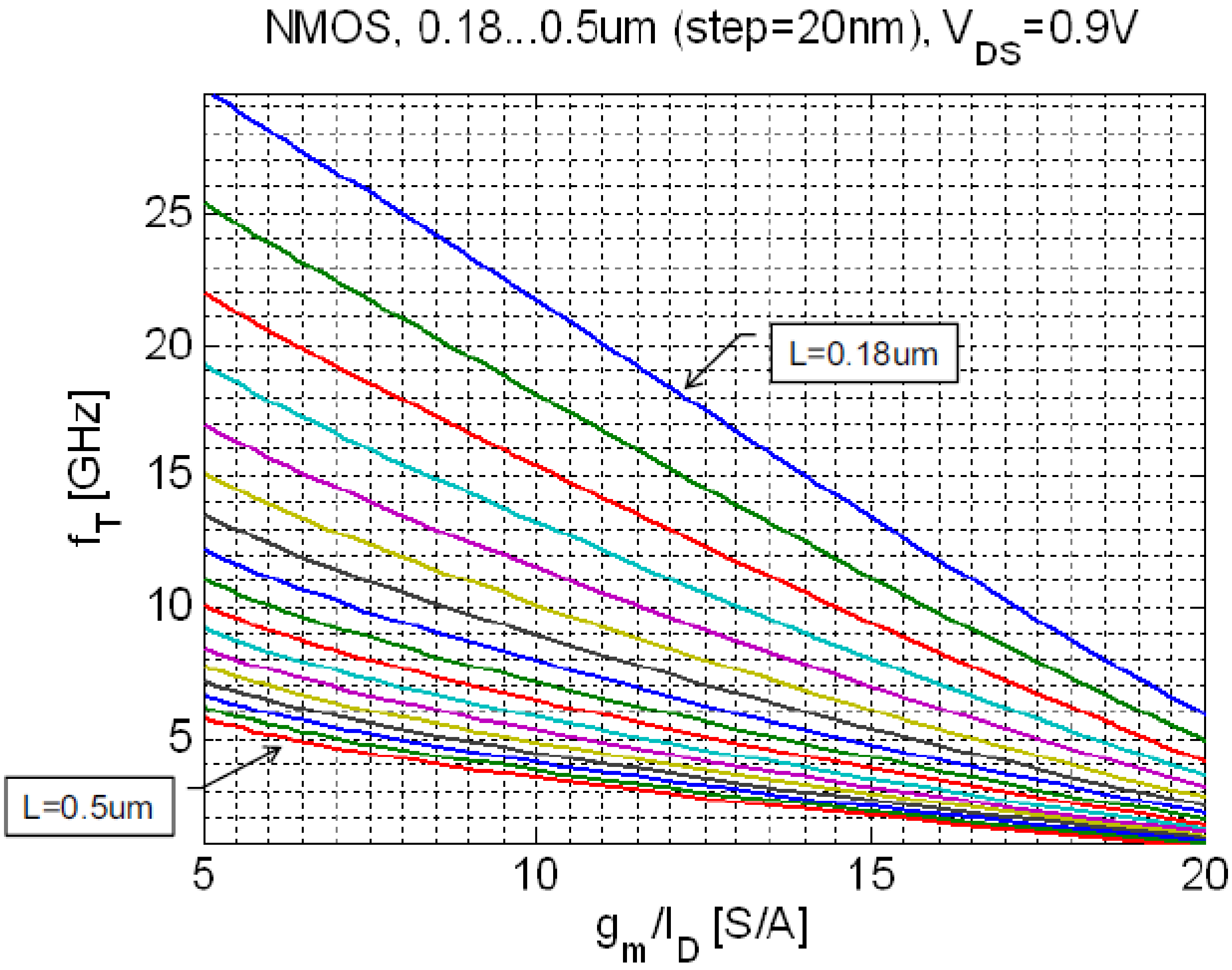


- Kada je potrebna velika brzina, sa što manjom potrošnjom, polarizacija MOS tranzistora treba da je u oblasti umerene inverzije

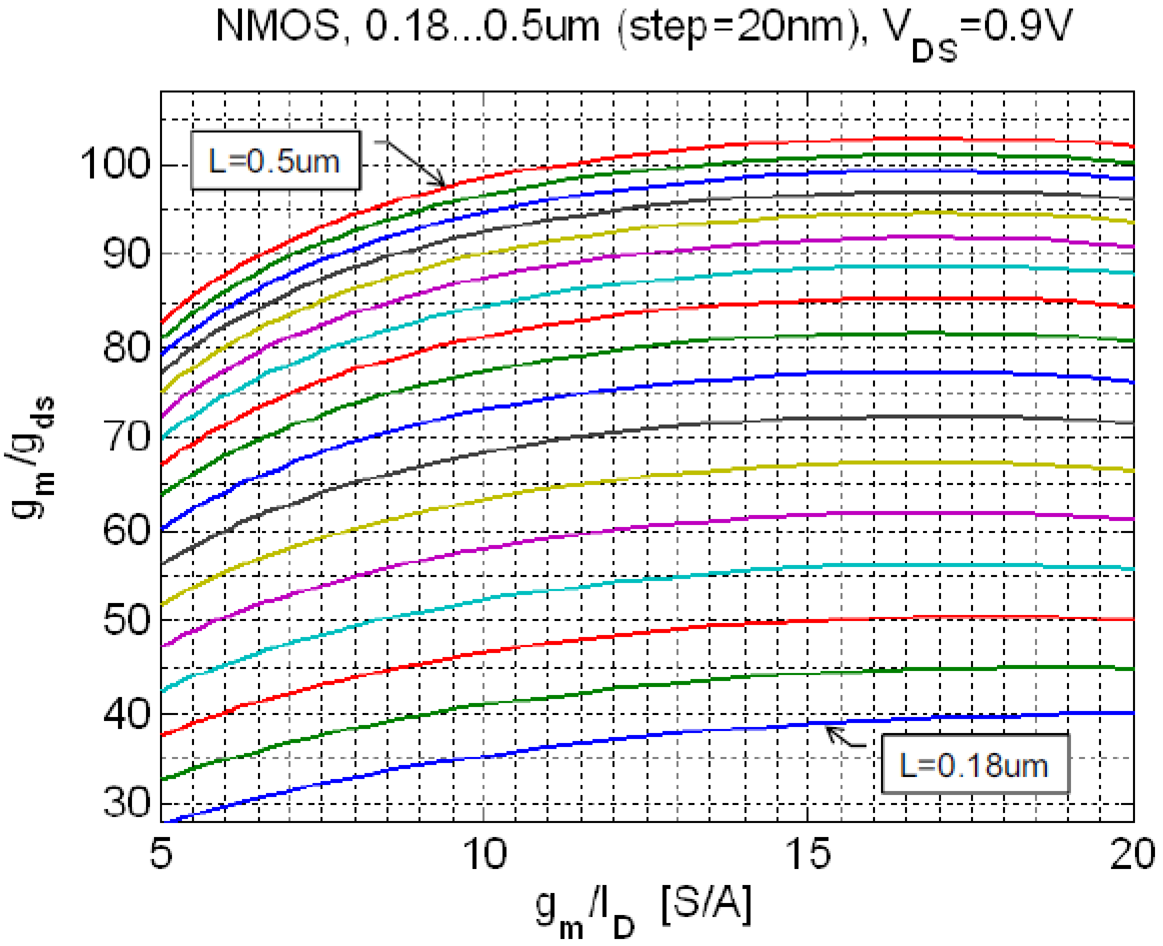
$$f_T = f\left(\frac{g_m}{I_D}\right)$$



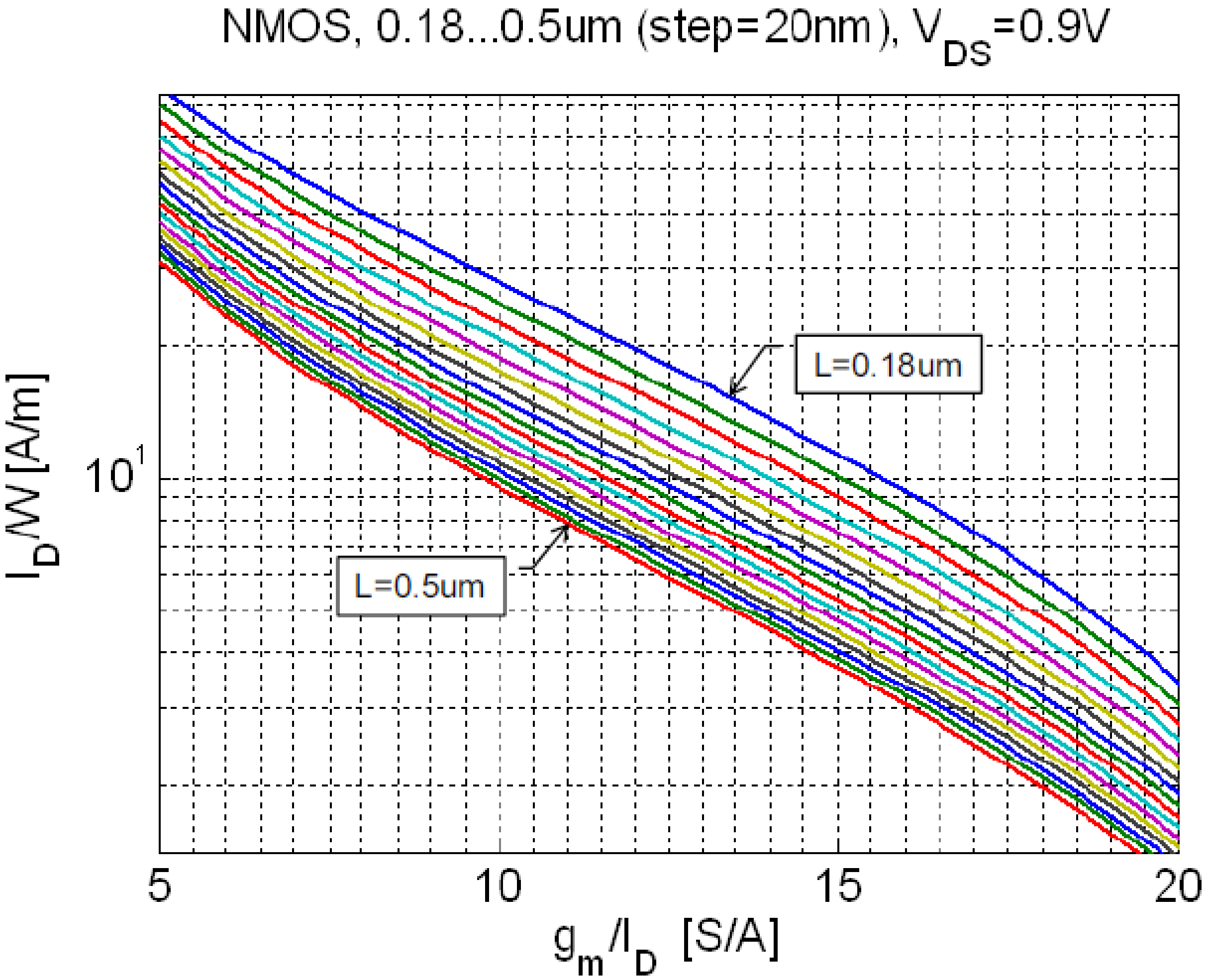
$$f_T = f\left(\frac{g_m}{I_D}\right)$$



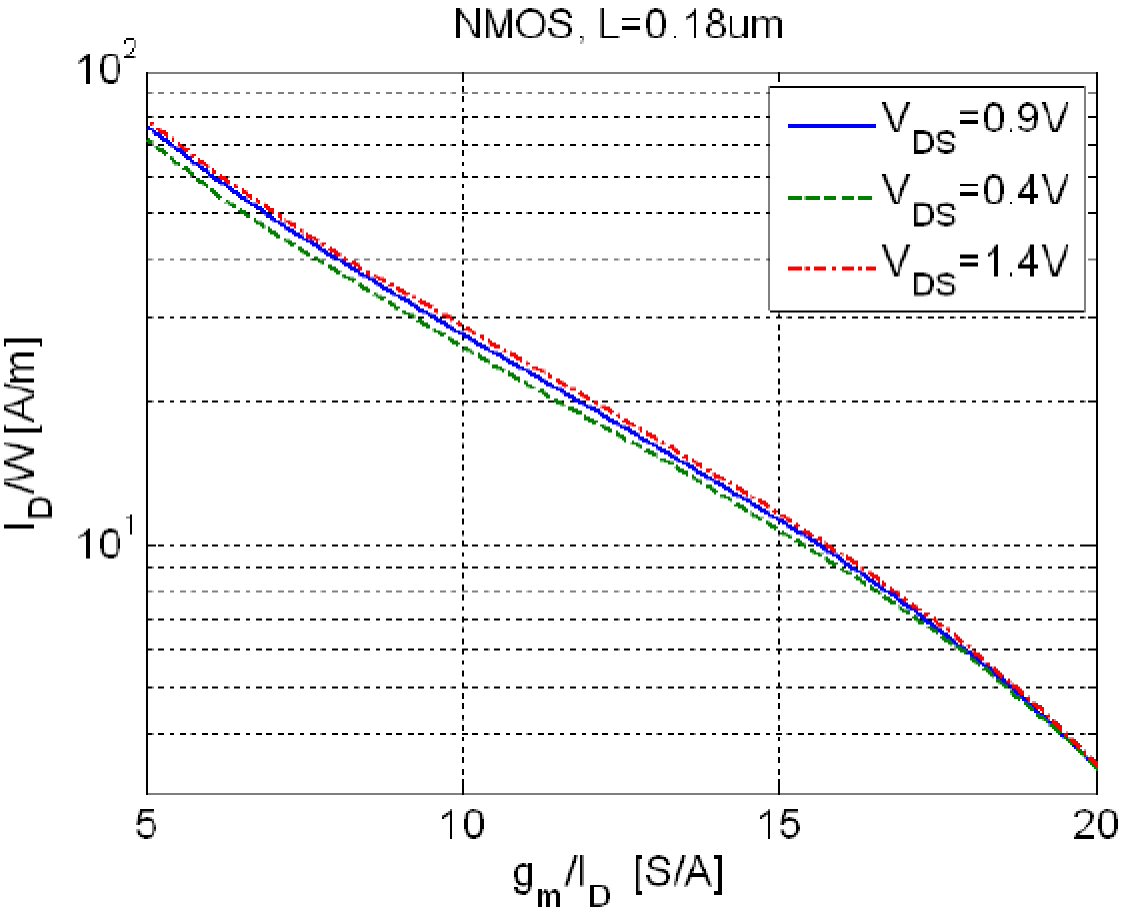
$$a_i = \frac{g_m}{g_{ds}} = g\left(\frac{g_m}{I_D}\right)$$



$$\frac{I_D}{W} = h\left(\frac{g_m}{I_D}\right)$$

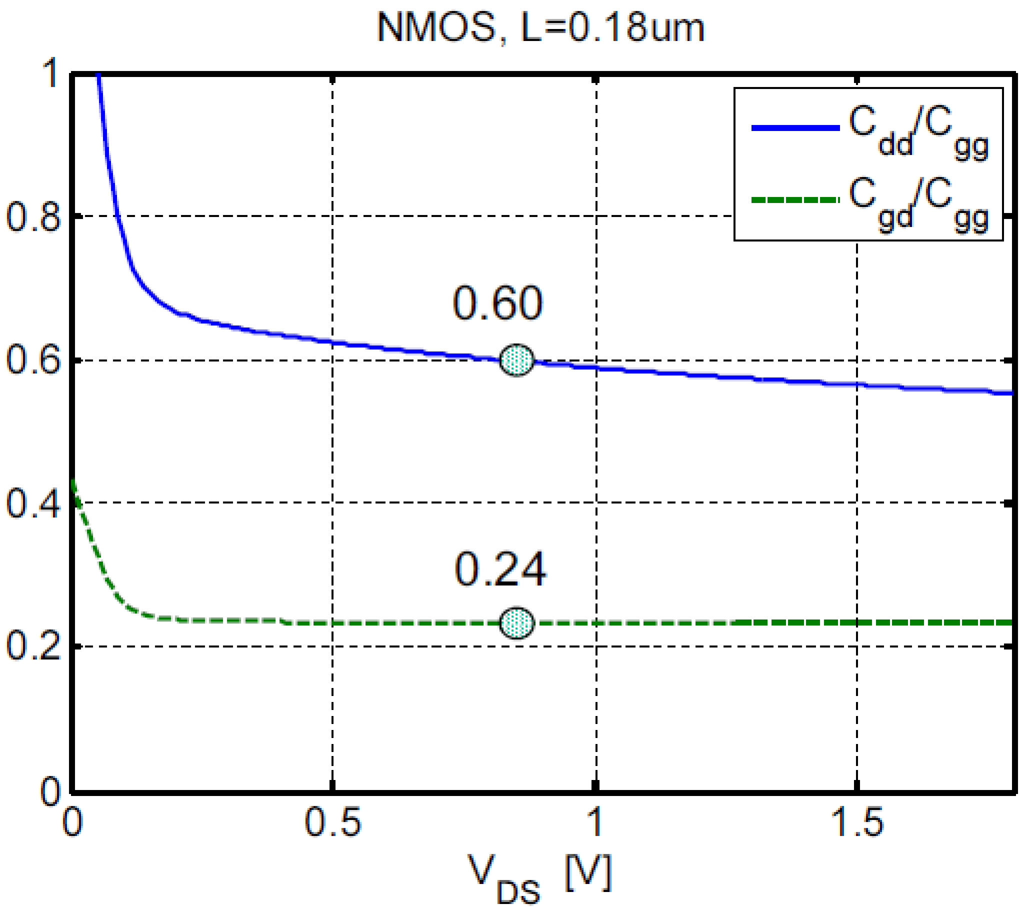


$$\frac{I_D}{W} = h\left(\frac{g_m}{I_D}\right)\bigg|_{V_{DS}=const}$$



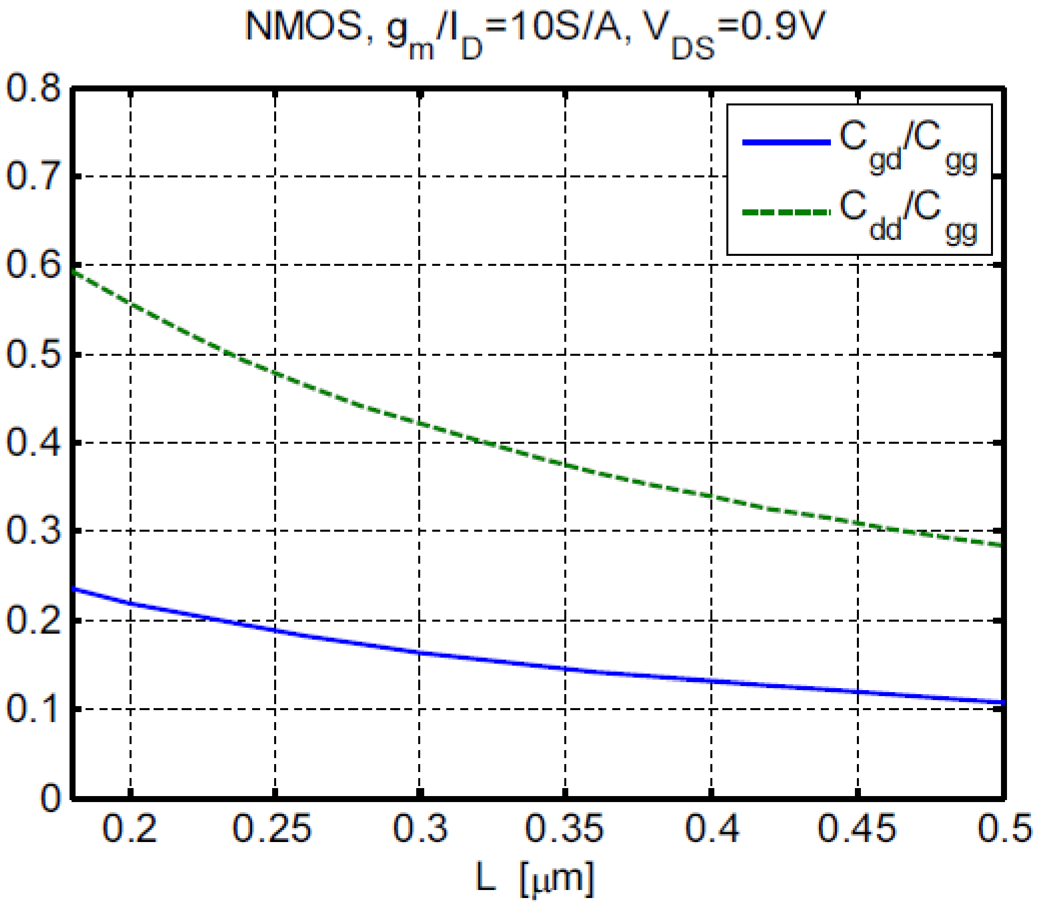
- Aproksimativno se može koristiti karakteristika pri VDS=VDD/2=0.9V

$$\frac{C_{dd}}{C_{gg}} = f_1(V_{DS}) \qquad \frac{C_{gd}}{C_{gg}} = f_2(V_{DS})$$

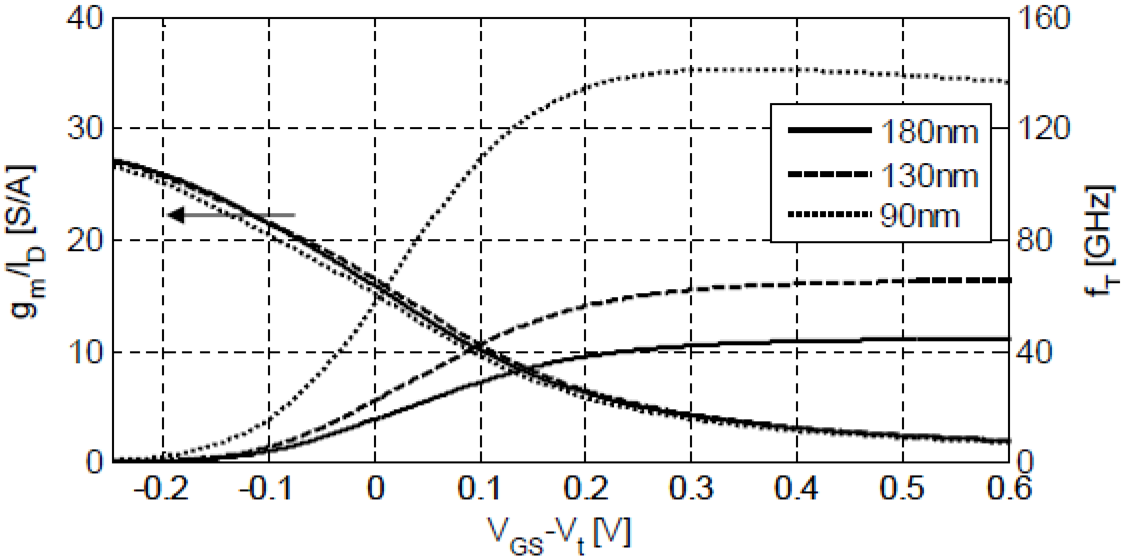


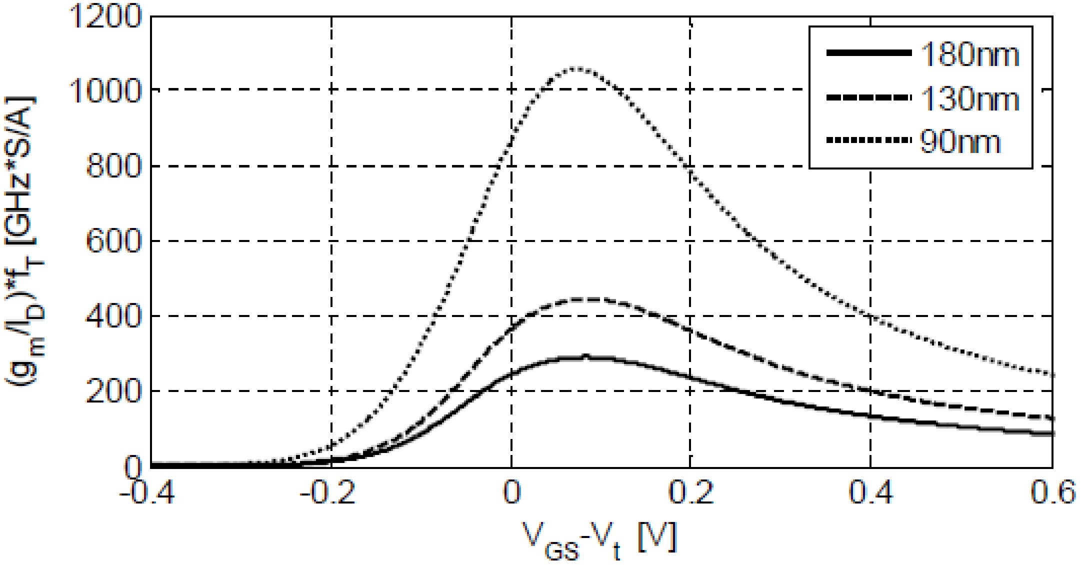
- Aproksimativno se mogu uzeti vrednosti pri VDS=VDD/2=0.9V

$$\frac{C_{gd}}{C_{gg}} = g_1(L) \qquad \frac{C_{dd}}{C_{gg}} = g_2(L)$$



gm/ID i fT trend sa promenom tehnologije





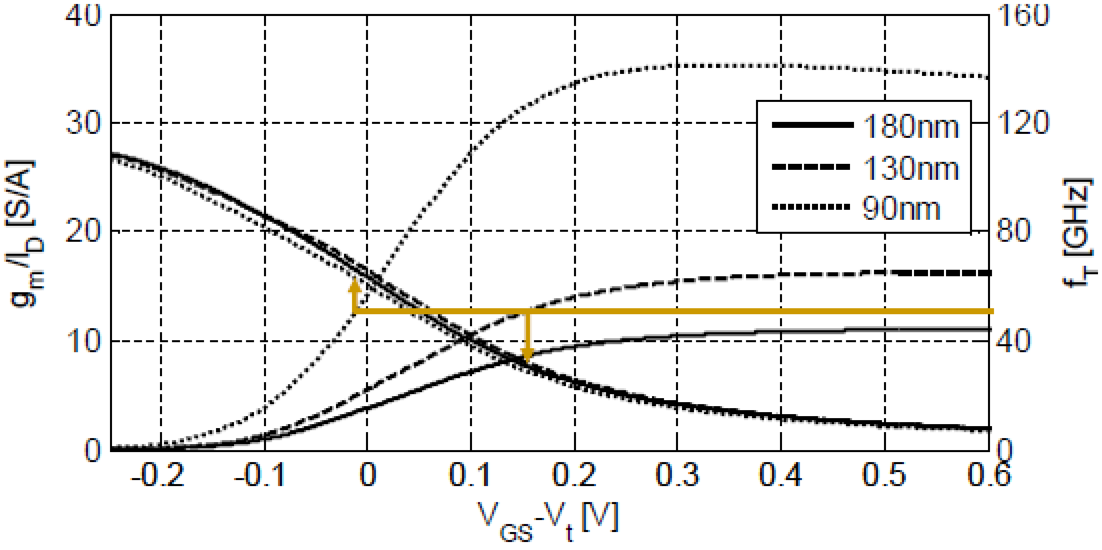
FOM sa uticajem šuma

$$P \propto V_{DD} \cdot I_D \qquad BW \propto \frac{g_m}{C} \qquad DR \propto \frac{Swing^2}{kT/C}$$

$$\boxed{\frac{BW \cdot DR}{P} \propto V_{DD} \cdot \left(\frac{Swing}{V_{DD}}\right)^2 \cdot \frac{g_m}{I_D}}$$

- Smanjenje napona napajanja smanjuje FOM, ali on zavisi i od odnosa swing/VDD:

$$ADC: \left.\frac{Swing}{V_{DD}}\right|_{0.5\text{um}} = \frac{2}{5} \qquad ADC: \left.\frac{Swing}{V_{DD}}\right|_{90\text{nm}} = \frac{0.5}{1}$$



$$\frac{g_m}{I_D} = ?$$

f_T = 50GHz, 130nm: g_m/I_D = 8S/A,

90nm: g_m/I_D = 16S/A

Dijagram toka gm/ID algoritma

1. Izabrati vrednost transkonduktanse gm prema željenom dizajnu
2. Izabrati vrednost dužine kanala
    - sa kraćim kanalima veća je fT (high speed)
    - duži kanali omogućuju veća unutrašnja pojačanja ai

3. Izabrati gm/ID, ili fT
    - veće gm/ID se koristi u kolima sa manjom disipacijom i većim opsegom signala na izlazu (VDSsat je manje)

$$\mathrm{LCH, SI:}\, V_{DSsat} = V_{GS} - V_T$$

$$\frac{g_m}{I_D} = \frac{2}{V_{GS} - V_T} \Rightarrow V_{DSsat} = \frac{2}{g_m / I_D}$$

$$\mathrm{LCH, WI:}\, I_D = I_{D0} e^{\frac{V_{GS}}{nV_t}} \left(1 - e^{-\frac{V_{DS}}{V_t}} \right) \qquad V_{DSsat} \approx 3V_t$$

$$\frac{g_m}{I_D} = \frac{1}{nV_t} \Rightarrow \frac{2}{g_m / I_D} = 2nV_t \approx 3V_t$$

Dobra aproksimacija: $V_{DSsat} = \dfrac{2}{g_m / I_D}$

- manje gm/ID je potrebno u bržim kolima sa većim fT

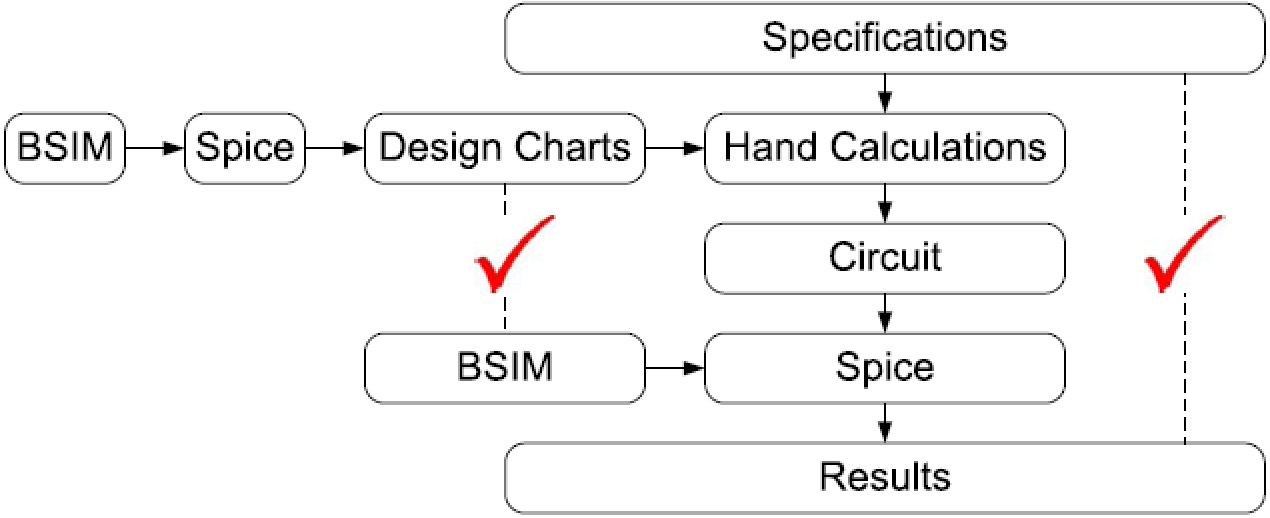
4. Na osnovu gm i gm/ID odrediti jednosmernu struju drejna

$$I_D = \frac{g_m}{(g_m / I_D)}$$

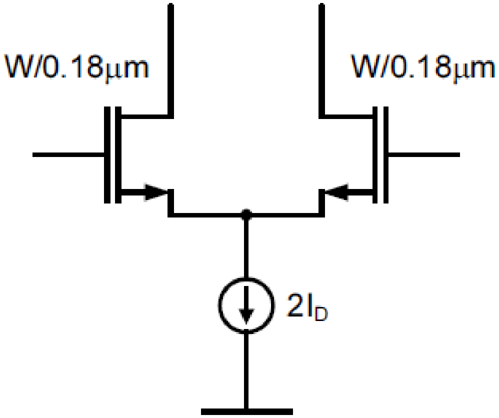
5. Na osnovu struje drejna odrediti širinu kanala tranzistora

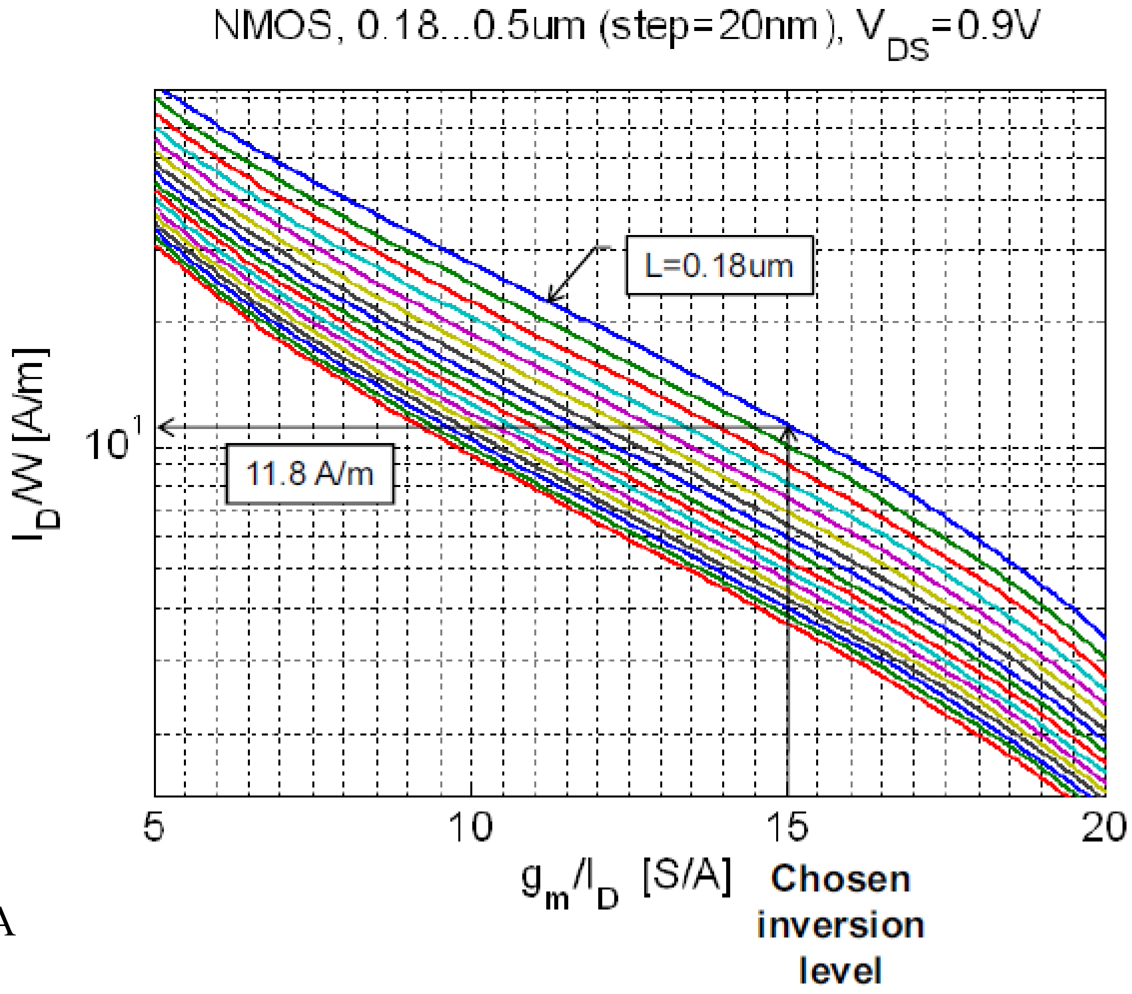
$$W = \frac{I_D}{(I_D / W)}$$

Dijagram toka:



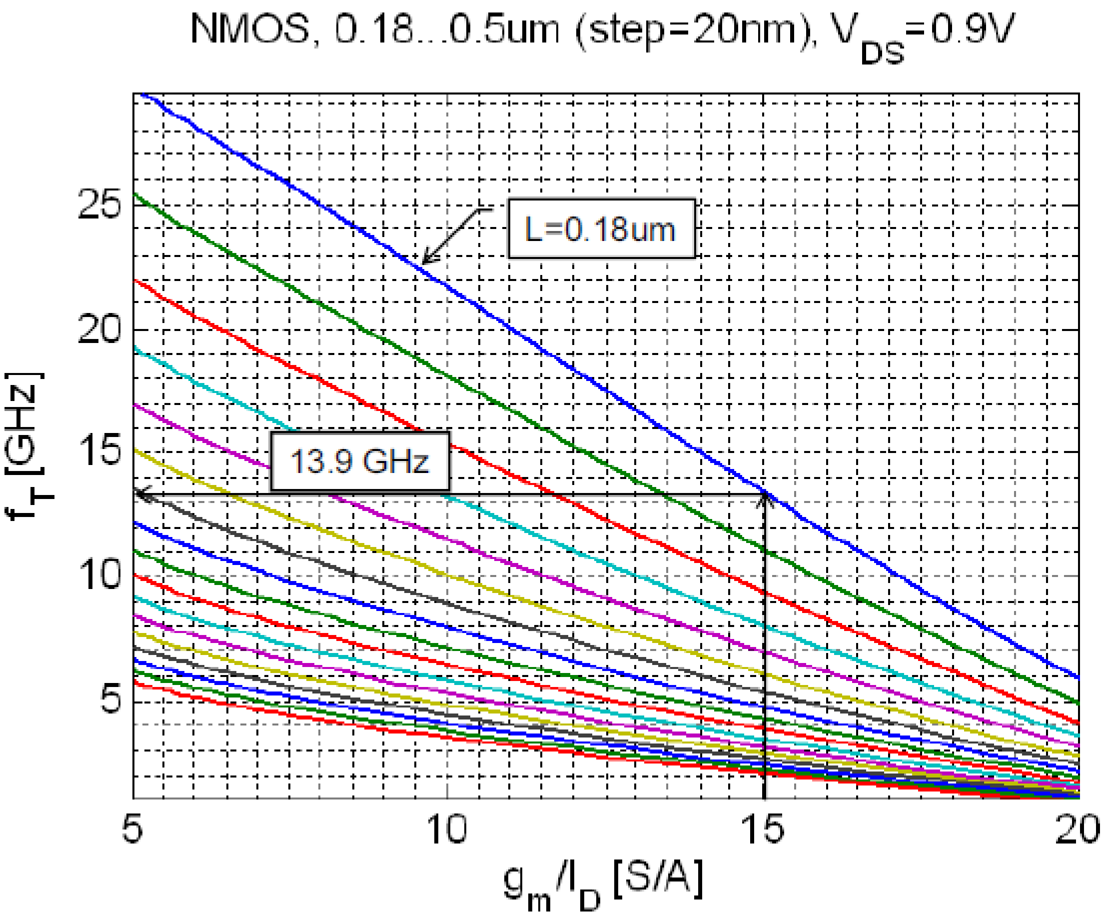
Primer: Odrediti širinu kanala tranzistora u diferencijalnom pojačavaču tako da je gm=10mS. Dimenzionisati tranzistore za tri vrednosti gm/ID: 15, 25 i 5.





$$I_D = \frac{g_m}{\left(g_m / I_D\right)} = \frac{10}{15}\,\text{mA} = 0.67\,\text{mA}$$

$$W = \frac{I_D}{\left(I_D / W\right)} = \frac{g_m / \left(g_m / I_D\right)}{\left(I_D / W\right)} = \frac{\left(2/3\right)\text{mA}}{11.8\,\mu\text{A}/\mu\text{m}} = \frac{670}{11.8}\,\mu\text{m} = 56{,}6\,\mu\text{m}$$



$$f_T = \frac{g_m}{2\pi C_{gg}} \Rightarrow C_{gg} = \frac{g_m}{2\pi f_T}$$

$$C_{gg} = \frac{10}{2\pi \cdot 13.9} \cdot 1000\ \text{fF} = 114\ \text{fF}$$

$$C_{gd} = \left(\frac{C_{gd}}{C_{gg}}\right) C_{gg} = 0.24 C_{gg} = 27.4\ \text{fF}$$

$$C_{gs} + C_{gb} = C_{gg} - C_{gd} = C_{gg}\left(1 - \left(\frac{C_{gd}}{C_{gg}}\right)\right) = 0.76 C_{gg} = 86.6\ \text{fF}$$

$$C_{dd} = \left(\frac{C_{dd}}{C_{gg}}\right) C_{gg} = 0.60 C_{gg} = 68.4\ \text{fF}$$

$$C_{db} = C_{dd} - C_{gd} = \left[\left(\frac{C_{dd}}{C_{gg}}\right) - \left(\frac{C_{gd}}{C_{gg}}\right)\right] C_{gg} = (0.60 - 0.24) C_{gg} \approx 41\ \text{fF}$$

Sumirani proračun za tri vrednosti gm/ID (slaba, umerena i jaka inverzija) je dat u sledećoj tabeli

Gm/ID	**25**	**15**	**5**
gm[mS]	10	10	10
ID[mA]	0.4	0.67	2
ID/W[uA/um]	0.12	11.8	83.3
W[um]	3243	56.7	24
fT[GHz]	0.37	13.9	32.3
Cgg[fF]	4346	114	49

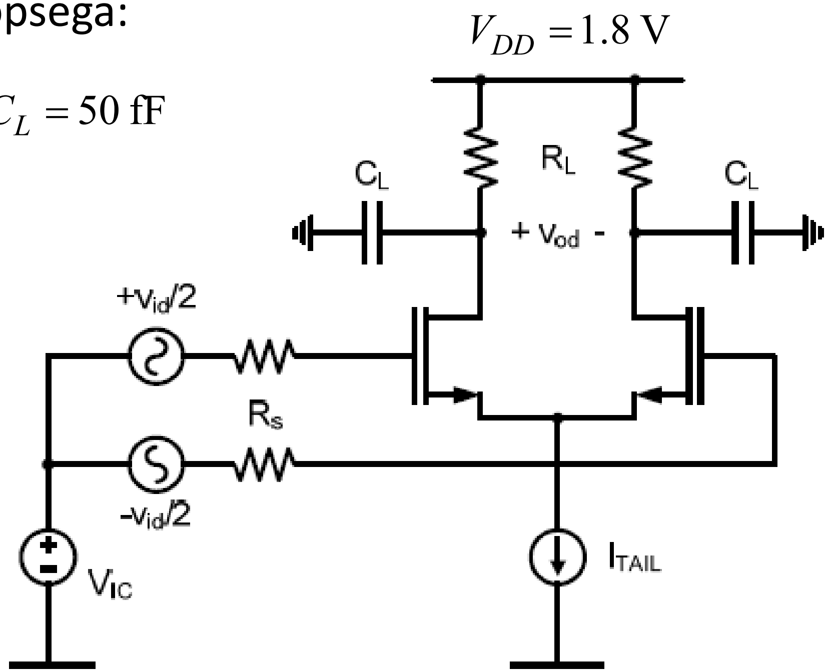
WI: mala struja drejna, velike dimenzije transistora i velike kapacitivnosti
SI: velika struja drejna, male dimenzije tranzistora I male kapacitivnosti
MI: dobar kompromis između WI i SI

Matlab Script

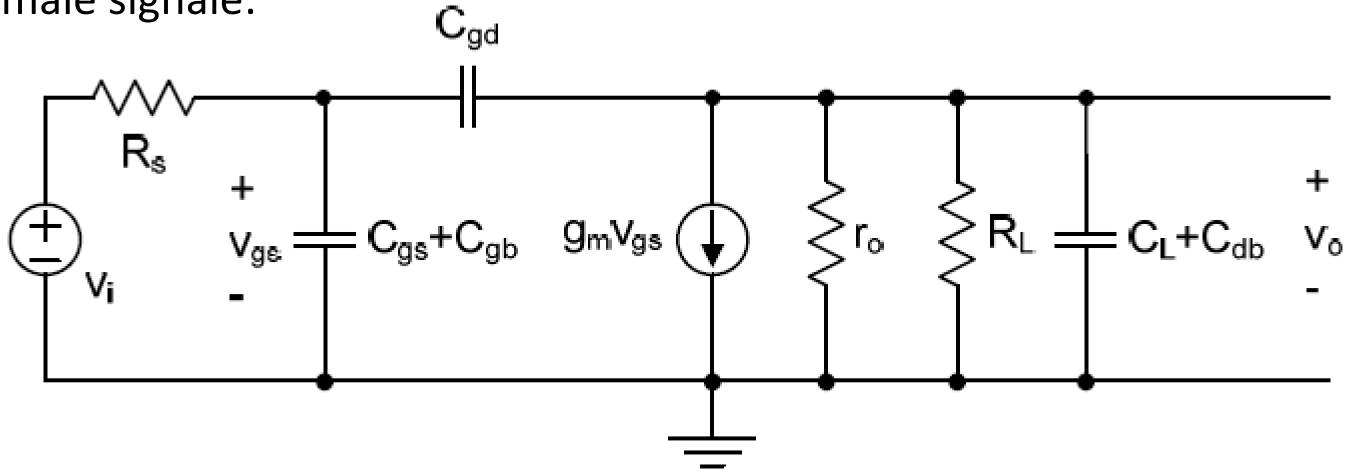
```
% basic sizing example
clear all;
close all;

load 180nch.mat;

% Specification
gm = 10e-3;
% Chosen inversion levels and resulting drain current
gm_id = [25 15 5]';
ID = gm./gm_id

% Current density and width
JD = lookup(nch, 'ID_W', 'GM_ID', gm_id)
W = ID./JD

% Transit frequency and Cgg
wT = lookup(nch, 'GM_CGG', 'GM_ID', gm_id);
Cgg = gm./wT
```

Procena propusnog opsega:

$R_S = 50\,\Omega, R_L = 500\,\Omega, C_L = 50\text{ fF}$



Šema za male signale:



$$A(s) = A_{PO}\frac{1+s/\omega_z}{1+b_1 s+b_2 s^2} \qquad \omega_z = \frac{g_m}{C_{gd}} >> \omega_T$$

$$b_1 = R_S\left[C_{gs}+C_{gb}+C_{gd}\left(1+\left|A_{PO}\right|\right)\right]+R_L\left(C_L'+C_{gd}\right) \qquad C_L' = C_L + C_{db}$$

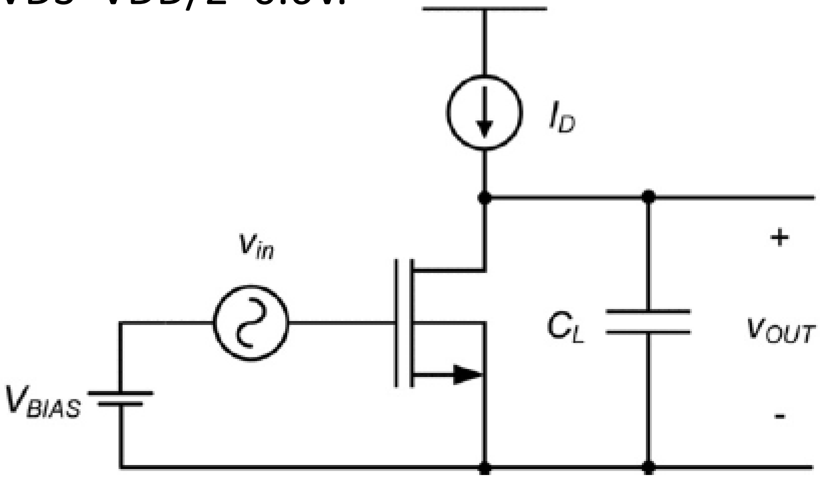
$$b_2 = R_S R_L\left(C_{gs}C_L'+C_{gs}C_{gd}+C_L'C_{gd}\right)$$

Pojačanje u propusnom opsegu $A_{PO} = g_m R_L = 5$

Dominantni pol određuje propusni opseg pojačavača : $f_{3dB} = f_{p1} = \frac{\omega_{p1}}{2\pi} = \frac{1}{2\pi}\frac{1}{b_1}$

gm/ID	**25**	**15**	**5**
f3dB	662.2kHz	25.1MHz	58.1MHz

Primer 2: Odrediti širinu kanala tranzistora tako da učestanost jediničnog pojačanja funkcije prenosa naponskog pojačanja bude fu=1GHz kada je CL=1pF. Smatrati da je L=60nm, gm/ID=15 i VDS=VDD/2=0.6V.



$$A(s) = A_{PO}\frac{1}{1+s/\omega_p} \qquad \omega_p = \frac{g_{ds}}{C_L + C_{db} + C_{gd}} \approx \frac{g_{ds}}{C_L}$$

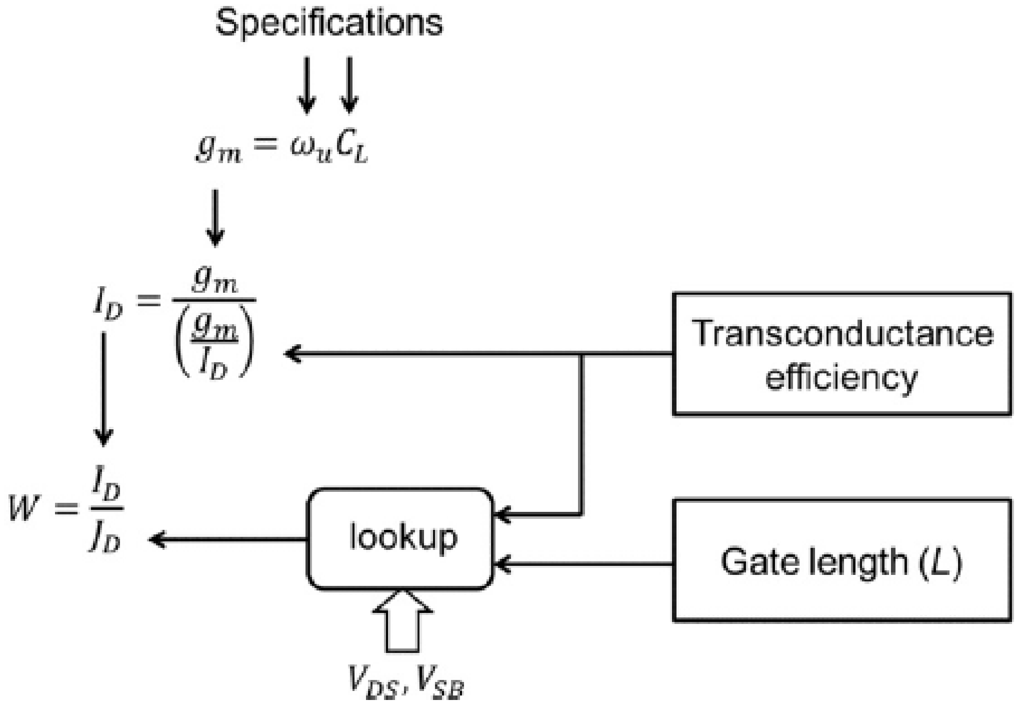
$$\left|A(j\omega_u)\right| = 1 \Rightarrow A_{PO}\frac{1}{\sqrt{1+(\omega_u/\omega_p)^2}} = 1 \Rightarrow \omega_u \approx A_{PO}\omega_p = \frac{g_m}{g_{ds}}\frac{g_{ds}}{C_L} = \frac{g_m}{C_L}$$

Fan-out:

$$FO = \frac{C_{out}}{C_{in}} = \frac{C_L}{C_{gs}+C_{gb}+C_{gd}} = \frac{C_L}{C_{gg}}$$

$$\frac{\omega_T}{\omega_u} = \frac{g_m/C_{gg}}{g_m/C_L} = FO$$

gm/ID algoritam:



$$g_m = 2\pi f_u C_L = 6{,}28\ \text{mS}$$

$$I_D = \frac{g_m}{\left(g_m / I_D\right)} = \frac{6{,}28}{15}\ \text{mA}=419\ \mu\text{A}$$

Gustina struje se određuje pomoću lookup tabele

JD=lookup(nch,’ID_W’,’GM_ID’,gm_ID,’VDS’,VDS,’VSB’,VSB,’L’,L)

$$J_D = 10.05\ \mu\text{A}/\mu\text{m}$$

$$W = \frac{I_D}{\left(I_D / W\right)} = 41{,}72\ \mu\text{m}$$

Napon polarizacije spoja gejt-sors:

VGS =lookupVGS(nch,’GM_ID’,gm_ID,’VDS’,VDS,’VSB’,VSB,’L’,L);

$$V_{GS} = 468.3\ \text{mV}$$

Sada se pomoću lookup tabele može odrediti i unutrašnje pojačanje tranzistora:

Av0 = - lookup(nch,’GM_GDS’,’GM_ID’,gm_ID,’VDS’,VDS,’VSB’,VSB,’L’,L)

$$A\text{v}0 = -10.25$$

odnosno učestanost jediničnog pojačanja:

fT =lookup(nch,’GM_CGG’,’GM_ID’,gm_ID,’VDS’,VDS,’VSB’,VSB, ’L’,L)/2/pi

$$f_T = 26.46\ \text{GHz}$$

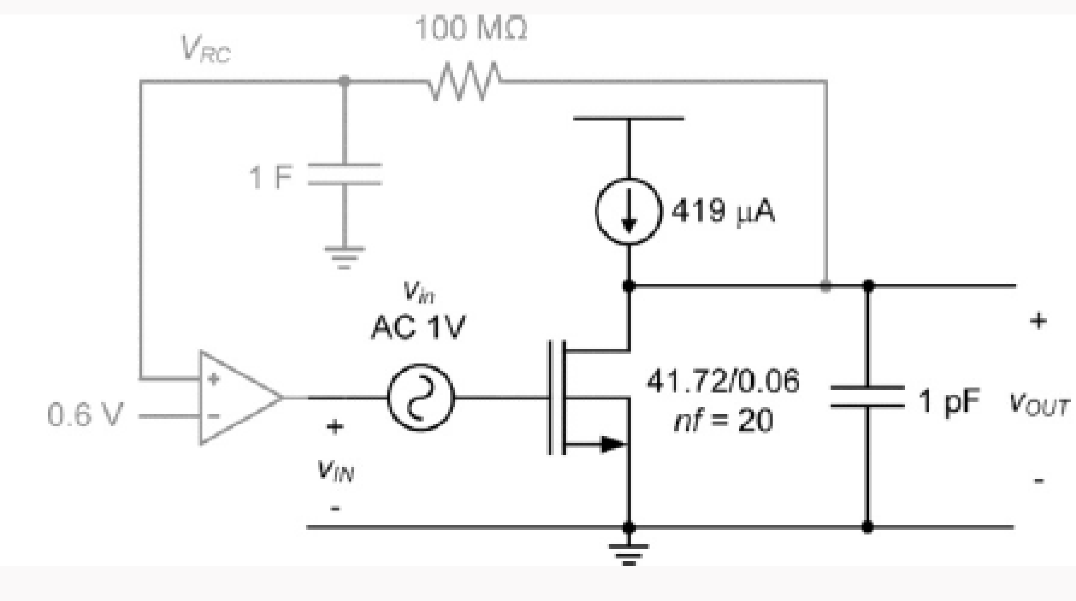
Fan-out:

$$FO = \frac{f_T}{f_u} = 26.46$$

Earlyjev napon:

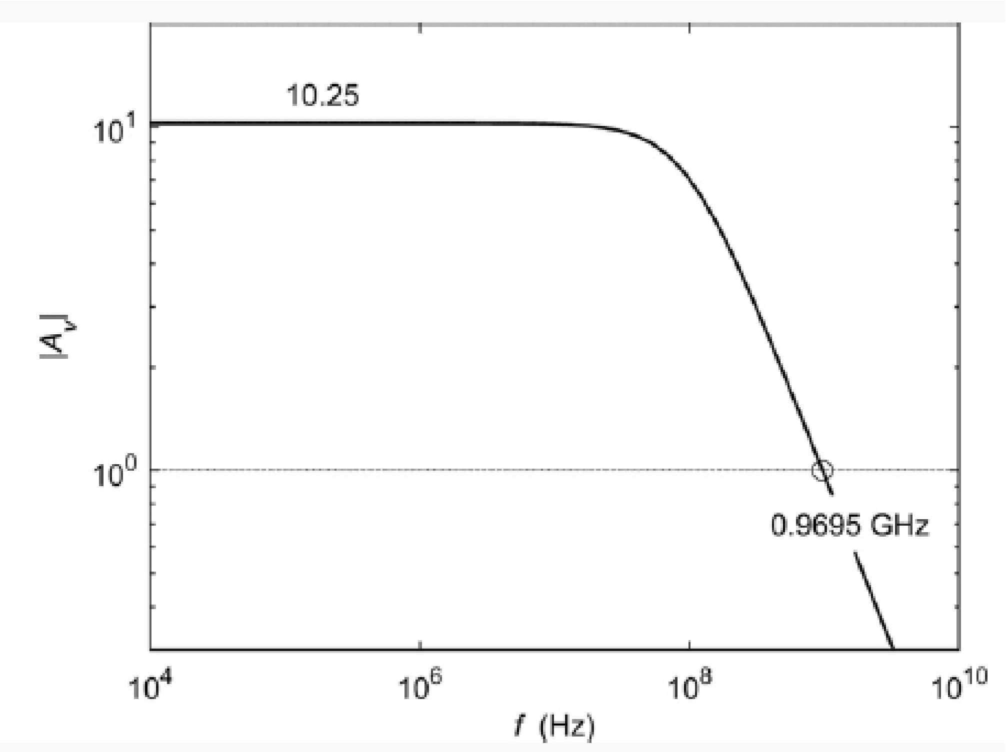
$$V_A = \frac{I_D}{g_{ds}} = \frac{\left(\frac{g_m}{g_{ds}}\right)}{\left(\frac{g_m}{I_D}\right)} = \frac{10.25}{15} = 0.683\ \text{V}$$

Kolo za verifikaciju proračuna:



$$V_{GS} = 468.119\ \text{mV}$$
$$V_{DS} = 600.468\ \text{mV}$$
$$I_D = 419.004\ \mu\text{A}$$
$$g_m = 6.28284\ \text{mS}$$
$$g_{ds} = 612.939\ \mu\text{S}$$

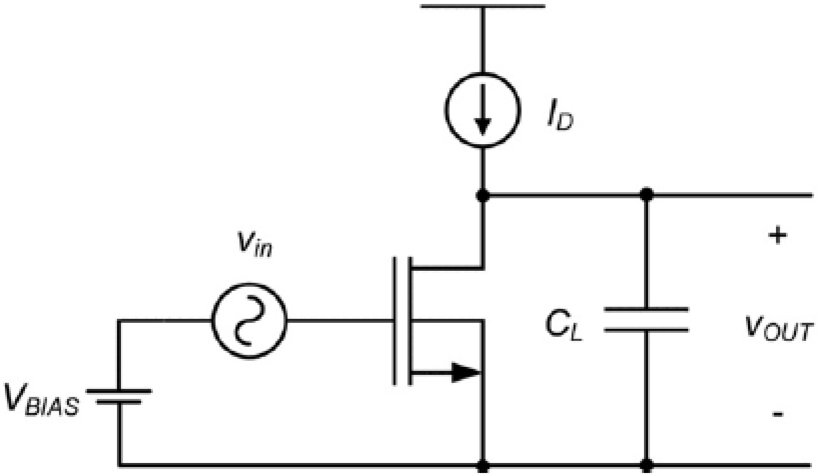
AC sweep:



Greška aproksimacije GBW-a je 3% i posledica je zanemarenih kapacitivnosti Cgd i Cdb

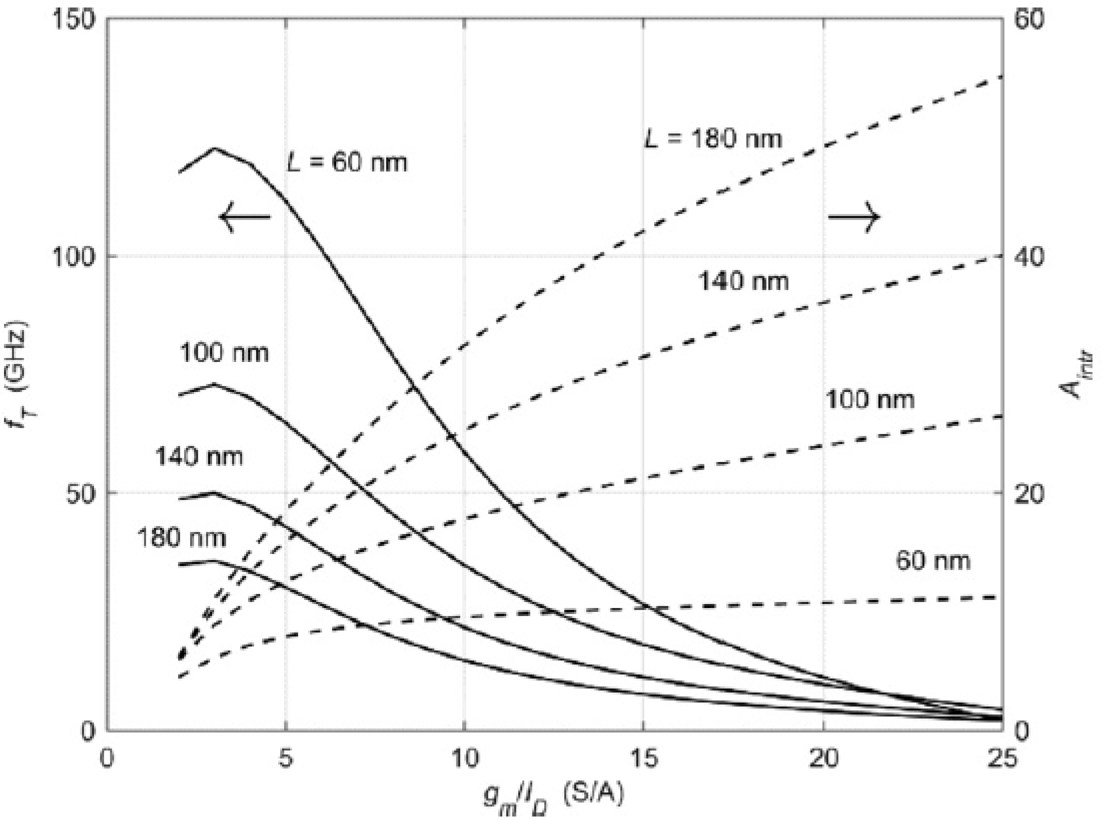
$$GBW = f_u = 969.5\ \text{MHz}$$

Primer 3: Odrediti dimenzije tranzistora tako da učestanost jediničnog pojačanja funkcije prenosa naponskog pojačanja bude fu=100 MHz kada je CL=1pF. Smatrati da je gm/ID=15 i VDS=VDD/2=0.6V.

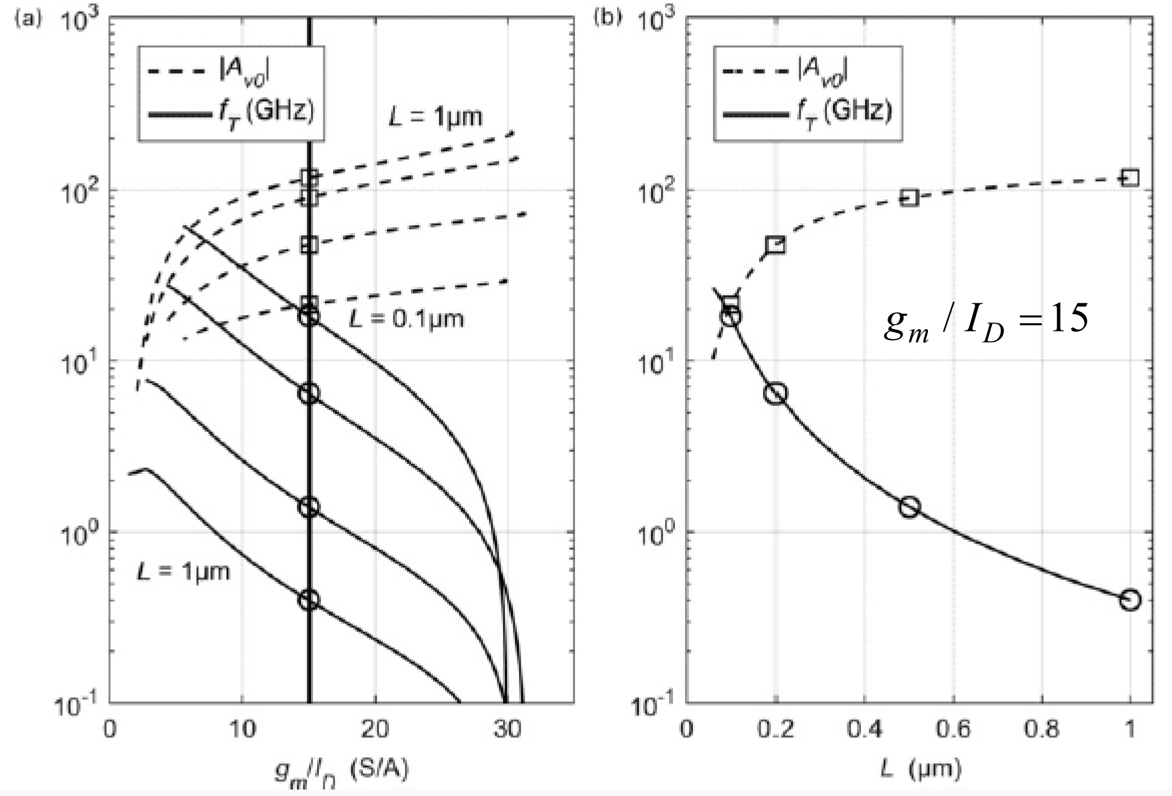


Koristeći lookup tabele mogu se nacrtati zavisnosti unutrašnjeg pojačanja i učestanosti jediničnog pojačanja u funkciji gm/ID

```
Avo = lookup(nch,’GM_GDS’,’GM_ID’,gmID,’L’,L);
fT = lookup(nch,’GM_CGG’,’GM_ID’,gmID,’L’,L)/(2*pi);
```



- Kompromisni zahtevi za velikim unutrašnjim pojačanjem i učestanošću jediničnog pojačanja fT
- Učestanost fT ima maksimalnu vrednost za određenu vrednost gm/ID, odnosno ID/W
- Zumiranje grafika oko vrednosti gm/ID=15



$$g_m \,/\, I_D = 15$$

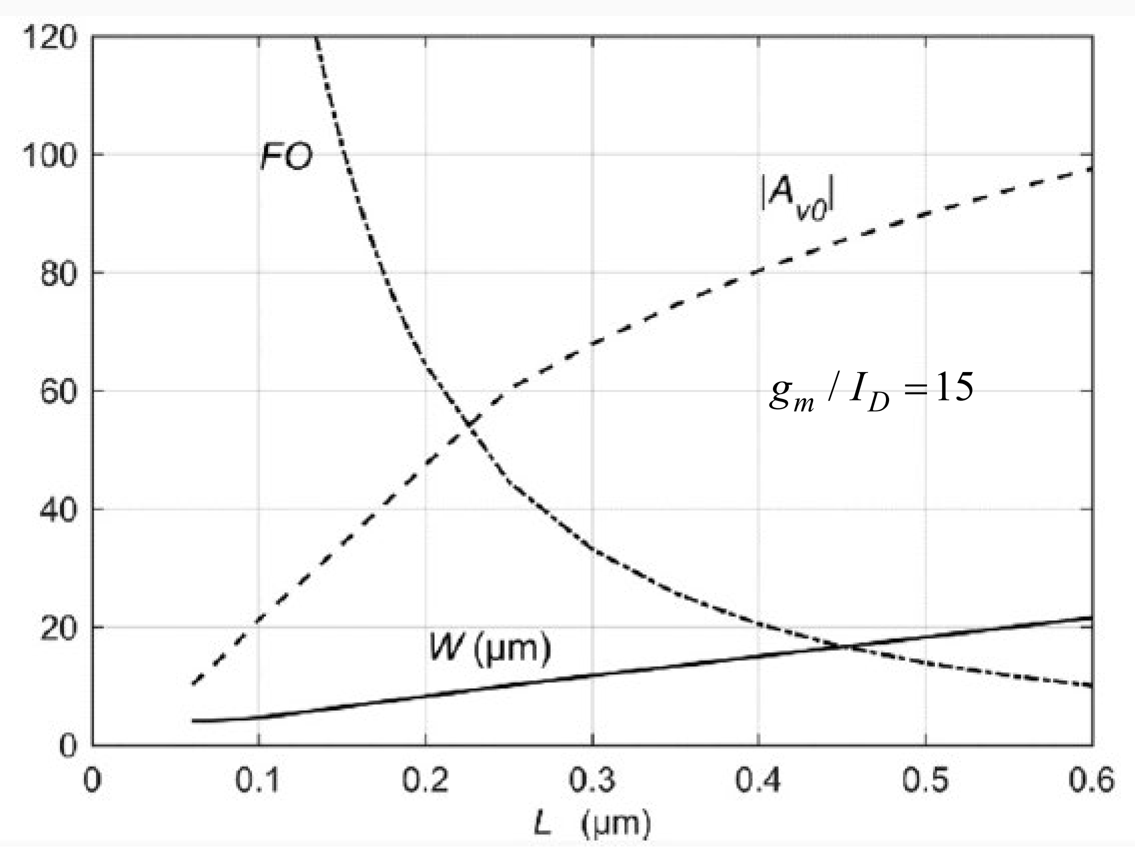
$$g_m = 2\pi f_u C_L = 628\,\mu\text{S}$$

$$I_D = \frac{g_m}{15} = \frac{628}{15}\,\mu\text{A} = 41.9\,\mu\text{A}$$

$$f_T \geq 10 f_u \Rightarrow f_{T\,\min} = 1\,\text{GHz}$$

$$\Rightarrow L = L_{\max} = 0.6\,\mu\text{m}$$

$$\Rightarrow L = L_{\max} = 0.6\,\mu\text{m}$$


120
100
80
60
40
20
0
0
0.1
0.2
0.3
0.4
0.5
0.6
L (μm)
FO
|A_{v0}|
$g_m / I_D = 15$
W (μm)