CMOS Analog Design Basics: an example of transistor sizing when using the first time new techno (e.g. 1um) and we need NMOS transistor in saturation with ID=400uA and VGS bias is 1.5V

Hi,

I just got into new 1um CMOS techno so here is its transistors SPICE models:

```
* 1 um Level 3 models from the CMOS Circuit Design, Layout, and
* Simulation, Second Edtion, see cmosedu.com
*
* LTspice uses actual sizes (not scaled lengths and widths)
* Vdd=5V

.MODEL N_1u NMOS LEVEL  = 3
+ TOX    = 200E-10        NSUB   = 1E17            GAMMA  = 0.5
+ PHI    = 0.7            VTO    = 0.8             DELTA  = 3.0
+ UO     = 650            ETA    = 3.0E-6          THETA  = 0.1
+ KP     = 120E-6         VMAX   = 1E5             KAPPA  = 0.3
+ RSH    = 0              NFS    = 1E12            TPG    = 1
+ XJ     = 500E-9         LD     = 100E-9
+ CGDO   = 200E-12        CGSO   = 200E-12         CGBO   = 1E-10
+ CJ     = 400E-6         PB     = 1               MJ     = 0.5
+ CJSW   = 300E-12        MJSW   = 0.5
*
.MODEL P_1u PMOS LEVEL  = 3
+ TOX    = 200E-10        NSUB   = 1E17            GAMMA  = 0.6
+ PHI    = 0.7            VTO    = -0.9            DELTA  = 0.1
+ UO     = 250            ETA    = 0               THETA  = 0.1
+ KP     = 40E-6          VMAX   = 5E4             KAPPA  = 1
+ RSH    = 0              NFS    = 1E12            TPG    = -1
+ XJ     = 500E-9         LD     = 100E-9
+ CGDO   = 200E-12        CGSO   = 200E-12         CGBO   = 1E-10
+ CJ     = 400E-6         PB     = 1               MJ     = 0.5
+ CJSW   = 300E-12        MJSW   = 0.5
```

You can download the SPICE model here: cmosedu_models.txt .

I would like to do sizing (e.g. finding W/L) of an NMOS transistor, so this transistor is in saturation with ID = 400uA and biased with VGS=1.5V .

This is the transistor equation used for the sizing calculation:

$$I_D = \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2$$

- μ is from Spice model : `UO = 650`

- **Step 1: Cox is calculated using following formula:**

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$ where ε_{ox} is a constant: $3.9 \times 8.854 \times 10^{-12}$ F/m

and t_{ox} (units are meters[m]) is from Spice model of the transistor:

`TOX = 200E-10`

- Here is a spreadsheet to calculate Cox:

N-mos (techno data)		N-mos (calculated data)	
TOX[m]	UO [cm^^2/Vsec]	Cox[F/meter ^^2)	Cox[fF/micro meter ^^2)
2.00E-08	650	1.73E-03	1.73E+04

Or here is an Octave program that do the same Cox calculation:

```
#include <octave/oct.h>

syms ID min eox tox WdivL VGS VTH Cox min_times_Cox VDSsat R VDD


e0x = 3.9*8.854*power(10, -12) ;
```

```
tox = 200*power(10,-10)       ; % units: m

min = 650                  ;

VDD = 5                    ;


Cox = e0x/tox               ;


disp( "Cox =" ),  disp( Cox ),  disp( "units: F/m2" ) ;


Cox = (e0x/tox)*( power(10,15)/power(10,8) ) ;


disp( "or Cox =" ),  disp( Cox ),  disp( "units: fF/micro-m2" ) ;
```

Result of the Octave program run:

```
Cox =
 0.0017265
units: F/m2
or Cox =
   1.7265e+04
units: fF/micro-m2
```

- **Step 2: Calculating Cox * μ (units: F/Vsec)**
  - Here is a spreadsheet to calculate Cox * μ :

N-mos (techno data)			N-mos (calculated data)		
TOX[m]	UO [cm^^2/Vsec]		Cox[F/meter ^^2)	Cox[fF/micro meter ^^2)	Cox[F/micro meter ^^2)*UO [cm^^2/Vsec]= Cox[F/micro meter ^^2)*UO [micro meter ^^2/Vsec]*10^^4[fF/micro meter ^^2]= Cox[F/micro meter ^^2)*UO [micro meter ^^2/Vsec]*10^^4*10^^-15[F/micro meter ^^2]
2.00E-08	650		1.73E-03	1.73E+04	1.12224450E-04

Or here is an Octave program that do the same Cox * µ calculation:

```
#include <octave/oct.h>
 syms ID min eox tox WdivL VGS VTH Cox min_times_Cox VDSsat R VDD

 e0x = 3.9*8.854*power(10, -12) ;
 tox = 200*power(10,-10)      ; % units: m
 min = 650                  ;
 VDD = 5                    ;

 Cox = e0x/tox               ;

 disp( "Cox =" ),  disp( Cox ),  disp( "units: F/m2" ) ;

 Cox = (e0x/tox)*( power(10,15)/power(10,8) ) ;

 disp( "or Cox =" ),  disp( Cox ),  disp( "units: fF/micro-m2" ) ;

 min_times_Cox = min * Cox * power(10,4) * power(10,-15) ;
 disp ( "min * Cox =" ), disp( min_times_Cox ), disp( "units: F/Vsec" ) ;
```

Result of the Octave program run:

```
Cox =
 0.0017265
units: F/m2
or Cox =
   1.7265e+04
units: fF/micro-m2
min * Cox =
   1.1222e-04
units: F/Vsec
```

- **Step 3: Calculating W/L**
  - Summary:
    - Reminder, this is the equation we are using:

$$I_D = \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{GS}\text{-}V_{TH})^2$$

    - We know that we want:
      - ID = 400μA
    - We know we will bias the transistor with :
      - VGS = 1.5V
    - From techno, meaning from SPICE model, the value of Vth[V] is:

```
VTO      = 0.8
```

- We already calculated Cox * μ [F/Vsec] : 1.1222 * 10^^-4

=> W/L = 14.548 or approx. 15

Here is an Octave program that do the same W/L calculation:

```
#include <octave/oct.h>

 syms ID min eox tox WdivL VGS VTH Cox min_times_Cox VDSsat R VDD
```

```
e0x = 3.9*8.854*power(10, -12) ;

tox = 200*power(10,-10)       ; % units: m

min = 650                    ;

VDD = 5                      ;


Cox = e0x/tox                ;


disp( "Cox =" ),  disp( Cox ),  disp( "units: F/m2" ) ;


Cox = (e0x/tox)*( power(10,15)/power(10,8) ) ;


disp( "or Cox =" ),  disp( Cox ),  disp( "units: fF/micro-m2" ) ;


min_times_Cox = min * Cox * power(10,4) * power(10,-15) ;

disp ( "min * Cox =" ), disp( min_times_Cox ), disp( "units: F/Vsec" ) ;



f = -ID + (1/2)*min_times_Cox*(WdivL)*power((VGS-VTH),2)



% Substitute in values that are known

newf = subs(f, [ID VGS VTH], [( 400*power(10, -6) ), 1.5, 0.8]);



% Solve the resulting symbolic expression for x
```

```
result = solve(newf == 0, WdivL)
```

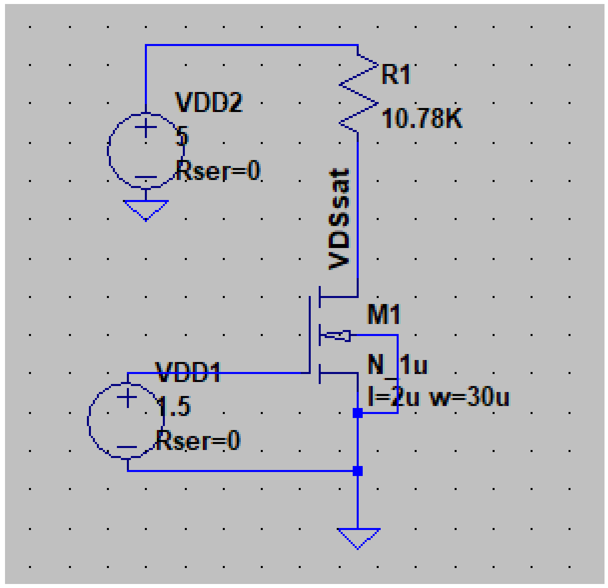
```
% And if you need a numeric (rather than symbolic) result

double(result)
```

Result of the Octave program run:

```
Cox =
 0.0017265
units: F/m2
or Cox =
   1.7265e+04
units: fF/micro-m2
min * Cox =
   1.1222e-04
units: F/Vsec
f = (sym)

                                  2
        7·WdivL·(VGS - VTH)
  -ID + ————————————————————
               124750

result = (sym)

  4990
  ————
  343

ans =  14.548
```

- **Step 4: Verifying that when we have an NMOS (in the techno used) with W/L = 15 and we bias it with VGS=1.5V and alim. for this techno is VDD=5V, then the transistor shoud be in saturation with ID = 400µA**

  - For this verification I will use LTSpice simulation of following schematic:



Here is how I calculated R1 = 10.77K in this schematic:

Step 4.1: to calculate R1 we would need VDSsat because R1= (VDD -VDSsat)/IDS

- R1= (5V -VDSsat)/400µA

- A friendly reminder: we are still using the same equation:

$$I_D = \frac{1}{2} \mu C_{ox} \frac{W}{L} (V_{GS}-V_{TH})^2$$

  - We know that we want:
    - ID = 400µA

  - We already calculated Cox * µ [F/Vsec] : 1.1222 * 10^^-4

  - We already calculated (under assumption that VGS = 1.5 V and knowing from the techno, meaning from SPICE model, that the value of Vth[V] is:

```
VTO      = 0.8
```

=> W/L = approx. 15

Note*: We expect VDSsat minimum to be VGS - Vth = 1.5 - 0.8 = 0.7V

Here is a Octave program to calculate VDSsat:

```
#include <octave/oct.h>
 syms ID min eox tox WdivL VGS VTH Cox min_times_Cox VDSsat R VDD

 e0x = 3.9*8.854*power(10, -12) ;
 tox = 200*power(10,-10)       ; % units: m
 min = 650                    ;
 VDD = 5                      ;

 Cox = e0x/tox                  ;

 disp( "Cox =" ),  disp( Cox ),  disp( "units: F/m2" ) ;

 Cox = (e0x/tox)*( power(10,15)/power(10,8) ) ;

 disp( "or Cox =" ),  disp( Cox ),  disp( "units: fF/micro-m2" ) ;

 min_times_Cox = min * Cox * power(10,4) * power(10,-15) ;
 disp ( "min * Cox =" ), disp( min_times_Cox ), disp( "units: F/Vsec" ) ;


f = -ID + (1/2)*min_times_Cox*(WdivL)*power((VGS-VTH),2)


% Substitute in values that are known
 newf = subs(f, [ID VGS VTH], [( 400*power(10, -6) ), 1.5, 0.8]);


% Solve the resulting symbolic expression for x
 result = solve(newf == 0, WdivL)

% And if you need a numeric (rather than symbolic) result
double(result)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%
```

```
f = -ID + (1/2)*min_times_Cox*(WdivL)*power(VDSsat,2)

% Substitute in values that are known
  newf = subs(f, [ID WdivL] , [( 400*power(10, -6) ), 15 ]);

  % Solve the resulting symbolic expression for x
  result = solve(newf == 0,VDSsat)

  % And if you need a numeric (rather than symbolic) result
double(result)
```

Result of the Octave program run:

```
Cox =
 0.0017265
units: F/m2
or Cox =
   1.7265e+04
units: fF/micro-m2
min * Cox =
   1.1222e-04
units: F/Vsec
f = (sym)

                                  2
          7·WdivL·(VGS - VTH)
  -ID + ─────────────────────────
                124750

result = (sym)



  4990
  ────
  343

ans =  14.548
```

```
f = (sym)

                 2
        7·VDSsat  ·WdivL
  -ID + ───────────────
            124750

result = (sym 2×1 matrix)

  ⎡-√20958 ⎤
  ⎢────────⎥
  ⎢  210   ⎥
  ⎢        ⎥
  ⎢ √20958 ⎥
  ⎢ ────── ⎥
  ⎣  210   ⎦

ans =

  -0.68938
   0.68938
```

Source code of Octave program is here: https://docs.google.com/document/d/14I43zrIZxGM7f2o_nSRhpw2w8WisVjJJfqztLpO0uGI/edit?usp=sharing

Step 4.2:

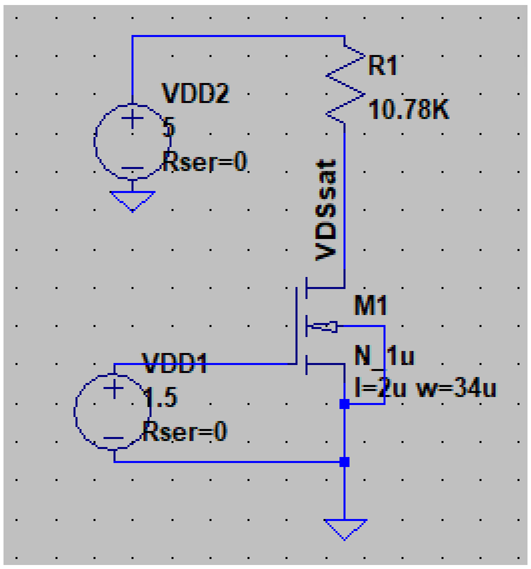
- A friendly reminder from previous step: R1= (5V -VDSsat)/400µA
  => R1 = (5V -0.68938)/400µA
  => R1 = 1.0777e+04 = approx. 10.78KΩ

  LTspice simulation showed: IDS = 354 µA (expected 400 µA) and VDSsat= 1.18V (expected result: 689mV)

Name: m1
Model: n_1u
Id: 3.54e-04
Vgs: 1.50e+00

Vds: 1.18e+00
Vbs: 0.00e+00
Vth: 8.39e-01
Vdsat: 5.59e-01

Finally, by fine adjusting of W/L from 15 to 17, LTspice simulation showed: IDS = approx. 398 µA (expected 400 µA) and VDSsat= approx. 711mV (expected result: 689mV)



Name: m1
Model: n_1u
Id: 3.98e-04
Vgs: 1.50e+00
Vds: 7.11e-01
Vbs: 0.00e+00
Vth: 8.39e-01
Vdsat: 5.60e-01