EE223 Analog Integrated Circuits
Fall 2018

Lecture 5: MOS Small-Signal Model

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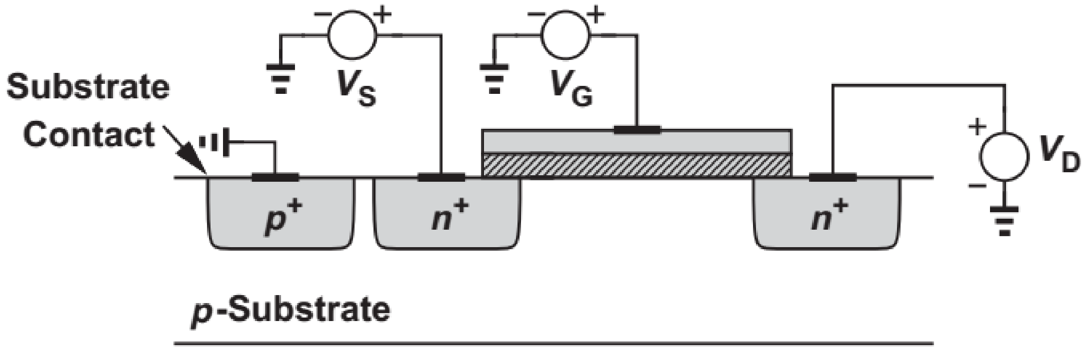
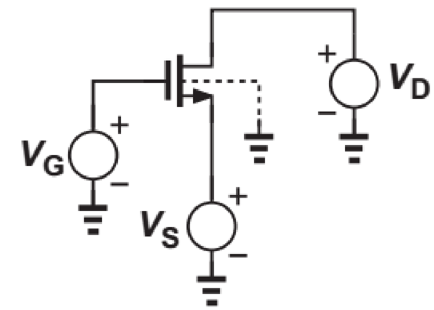
Body Effect





$$V_T = V_{T0} + \gamma\left(\sqrt{|2\Phi_F + V_{SB}|} - \sqrt{|2\Phi_F|}\right)$$

Body effect coefficient, $\gamma = \dfrac{\sqrt{2q\varepsilon_{si}N_{sub}}}{C_{ox}}$

γ typically ranges from 0.3 to 0.4V$^{1/2}$

Body (or Bulk) Transconductance, g_{mb}

The small-signal drain current changes with V_{BS} modulation due to changes in V_T

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

$$V_{TH} = V_{TH0} + \gamma\left(\sqrt{|2\Phi_F + V_{SB}|} - \sqrt{|2\Phi_F|}\right)$$

$$g_{mb} = \frac{\partial I_D}{\partial V_{BS}} = \mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})\left(-\frac{\partial V_{TH}}{\partial V_{BS}}\right)$$

$$\frac{\partial V_{TH}}{\partial V_{BS}} = -\frac{\partial V_{TH}}{\partial V_{SB}} = -\frac{\gamma}{2}(2\Phi_F + V_{SB})^{-1/2}$$

$$g_{mb} = g_m \frac{\gamma}{2\sqrt{2\Phi_F + V_{SB}}} = \eta g_m$$

Body Effect Example

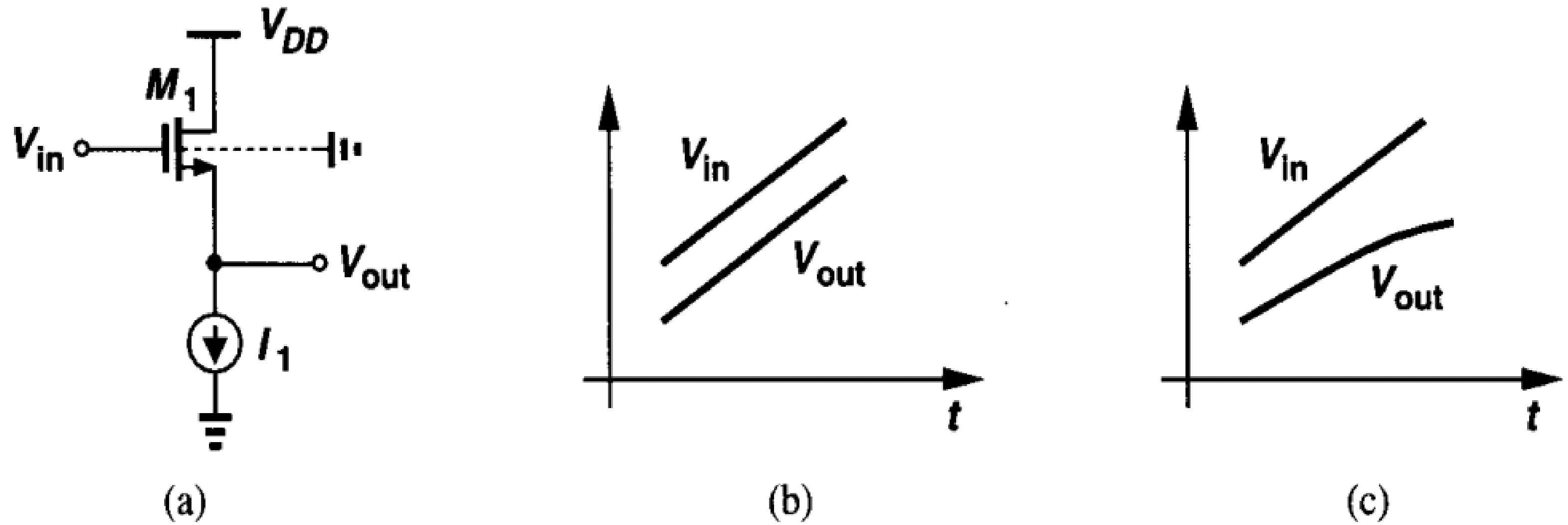
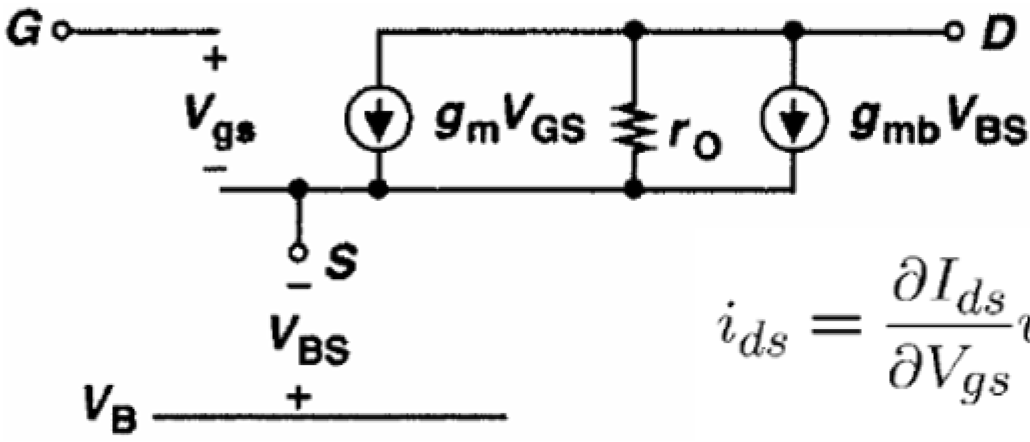


Figure 2.24 (a) A circuit in which the source-bulk voltage varies with input level, (b) input and output voltages with no body effect, (c) input and output voltages with body effect.

MOS Low-Frequency Small-Signal Model



$$i_{ds} = \frac{\partial I_{ds}}{\partial V_{gs}} v_{gs} + \frac{\partial I_{ds}}{\partial V_{bs}} v_{bs} + \frac{\partial I_{ds}}{\partial V_{ds}} v_{ds}$$

$$i_{ds} = g_m V_{gs} + g_{mb} V_{bs} + g_{ds} V_{ds}$$

$$g_m = \left.\frac{\partial i_D}{\partial v_{gs}}\right|_Q \approx \mu C_{OX} \frac{W}{L_{eff}} \left.(V_{GS} - V_T)\right|_Q$$

$$g_0 = \left.\frac{\partial i_D}{\partial v_{ds}}\right|_Q \approx \left.\left(\frac{\mu C_{OX}}{2}\right)\left(\frac{W}{L_{eff}}(V_{GS} - V_T)^2\right)\right|_Q \lambda \approx \lambda I$$

$$g_{mb} = \left.\frac{\partial i_D}{\partial v_{bs}}\right|_Q \approx \mu C_{OX} \left.\frac{W}{L_{eff}}[V_{GS} - V_T]\right|_Q * \left(-\left.\frac{\partial V_T}{\partial v_{bs}}\right|_Q\right) \cong \frac{\gamma g_m}{2\sqrt{2\phi_F + V_{SB}}} = \eta g_m$$

Transistor Models for Circuit Simulation

- SPICE (*Simulation Program with Integrated Circuit Emphasis*)
  Level 1, 2, 3, 28, 49, 57…

- BSIM (Berkeley Short-channel IGFET Model)
  BSIM4, as the extension of BSIM3 model, addresses the MOSFET physical effects into sub-100nm regime. It is a physics-based, accurate, scalable, robust and predictive MOSFET SPICE model for circuit simulation and CMOS technology development.

- EKV Model
  Developed by C. C. Enz, F. Krummenacher and E. A. Vittoz (hence the initials EKV). Unlike simpler models like the Quadratic Model, the EKV Model is accurate even when the MOSFET is operating in the subthreshold region in submicrometer CMOS IC design.

SPICE Level-3 MOS Model

```
* 1 um Level 3 models
* Don't forget the .options scale=1u if using an Lmin of 1
* 1<L<200 and 10<W<10000 Vdd=5V

.MODEL NMOS 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 PMOS 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
```

BSIM4 Model

[2] BSIM4 is a fourth generation MOSFET model developed at the University of California, Berkeley. The acronym stands for Berkeley Short-channel IGFET (insulated gate FET) Model. For more information see: http://www-device.eecs.berkeley.edu

```
* 50nm BSIM4 models
*
* Don't forget the .options scale=50nm if using an Lmin of 1
* 1<Ldrawn<200   10<Wdrawn<10000 Vdd=1V
*
.model      nmos      nmos       level = 54
+binunit = 1          paramchk= 1        mobmod  = 0
+capmod  = 2          igcmod  = 1        igbmod  = 1        geomod  = 1
+diomod  = 1          rdsmod  = 0        rbodymod= 1        rgatemod= 1
+permod  = 1          acnqsmod= 0        trnqsmod= 0

+tnom    = 27         toxe    = 1.4e-009 toxp    = 7e-010   toxm    = 1.4e-009
+epsrox  = 3.9        wint    = 5e-009   lint    = 1.2e-008
+ll      = 0          wl      = 0        lln     = 1        wln     = 1
+lw      = 0          ww      = 0        lwn     = 1        wwn     = 1
+lwl     = 0          wwl     = 0        xpart   = 0        toxref  = 1.4e-009

+vth0    = 0.22       k1      = 0.35     k2      = 0.05     k3      = 0
+k3b     = 0          w0      = 2.5e-006 dvt0    = 2.8      dvt1    = 0.52
+dvt2    = -0.032     dvt0w   = 0        dvt1w   = 0        dvt2w   = 0
+dsub    = 2          minv    = 0.05     voffl   = 0        dvtp0   = 1e-007
+dvtp1   = 0.05       lpe0    = 5.75e-008 lpeb   = 2.3e-010 xj      = 2e-008
+ngate   = 5e+020     ndep    = 2.8e+018 nsd     = 1e+020   phin    = 0
+cdsc    = 0.0002     cdscb   = 0        cdscd   = 0        cit     = 0
+voff    = -0.15      nfactor = 1.2      eta0    = 0.15     etab    = 0
+vfb     = -0.55      u0      = 0.032    ua      = 1.6e-010 ub      = 1.1e-017
+uc      = -3e-011    vsat    = 1.1e+005 a0      = 2        ags     = 1e-020
+a1      = 0          a2      = 1        b0      = -1e-020  b1      = 0
+keta    = 0.04       dwg     = 0        dwb     = 0        pclm    = 0.18
+pdiblc1 = 0.028      pdiblc2 = 0.022    pdiblcb = -0.005   drout   = 0.45
+pvag    = 1e-020     delta   = 0.01     pscbe1  = 8.14e+8  pscbe2  = 1e-007
+fprout  = 0.2        pdits   = 0.2      pditsd  = 0.23     pditsl  = 2.3e+006
+rsh     = 3          rdsw    = 150      rsw     = 150      rdw     = 150
+rdswmin = 0          rdwmin  = 0        rswmin  = 0        prwg    = 0
+prwb    = 6.8e-011   wr      = 1        alpha0  = 0.074    alpha1  = 0.005
+beta0   = 30         agidl   = 0.0002   bgidl   = 2.1e+009 cgidl   = 0.0002
+egidl   = 0.8

+aigbacc = 0.012      bigbacc = 0.0028   cigbacc = 0.002
+nigbacc = 1          aigbinv = 0.014    bigbinv = 0.004    cigbinv = 0.004
+eigbinv = 1.1        nigbinv = 3        aigc    = 0.017    bigc    = 0.0028
+cigc    = 0.002      aigsd   = 0.017    bigsd   = 0.0028   cigsd   = 0.002
+nigc    = 1          poxedge = 1        pigcd   = 1        ntox    = 1

+xrcrg1  = 12         xrcrg2  = 5
+cgso    = 6.238e-010 cgdo    = 6.238e-010 cgbo  = 2.56e-011 cgdl   = 2.495e-10
+cgsl    = 2.495e-10  ckappas = 0.02     ckappad = 0.02     acde    = 1
+moin    = 15         noff    = 0.9      voffcv  = 0.02

+kt1     = -0.21      kt1l    = 0.0      kt2     = -0.042   ute     = -1.5
+ua1     = 1e-009     ub1     = -3.5e-019 uc1    = 0        prt     = 0
+at      = 53000

+fnoimod = 1          tnoimod = 0

+jss     = 0.0001     jsws    = 1e-011   jswgs   = 1e-010   njs     = 1
+ijthsfwd= 0.01       ijthsrev= 0.001    bvs     = 10       xjbvs   = 1
+jsd     = 0.0001     jswd    = 1e-011   jswgd   = 1e-010   njd     = 1
+ijthdfwd= 0.01       ijthdrev= 0.001    bvd     = 10       xjbvd   = 1
+pbs     = 1          cjs     = 0.0005   mjs     = 0.5      pbsws   = 1
+cjsws   = 5e-010     mjsws   = 0.33     pbswgs  = 1        cjswgs  = 3e-010
+mjswgs  = 0.33       pbd     = 1        cjd     = 0.0005   mjd     = 0.5
+pbswd   = 1          cjswd   = 5e-010   mjswd   = 0.33     pbswgd  = 1
+cjswgd  = 5e-010     mjswgd  = 0.33     tpb     = 0.005    tcj     = 0.001
+tpbsw   = 0.005      tcjsw   = 0.001    tpbswg  = 0.005    tcjswg  = 0.001
+xtis    = 3          xtid    = 3

+dmcg    = 0e-006     dmci    = 0e-006   dmdg    = 0e-006   dmcgt   = 0e-007
+dwj     = 0.0e-008   xgw     = 0e-007   xgl     = 0e-008

+rshg    = 0.4        gbmin   = 1e-010   rbpb    = 5        rbpd    = 15
+rbps    = 15         rbdb    = 15       rbsb    = 15       ngcon   = 1
```

NMOS Id-Vgs Characteristics

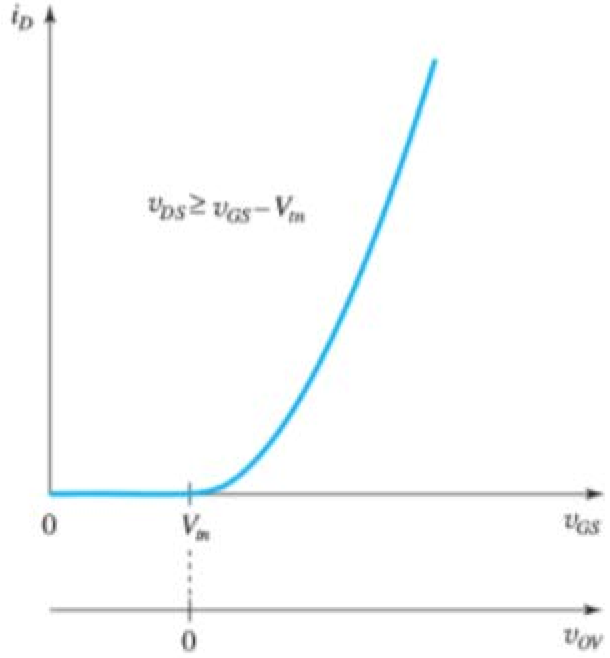
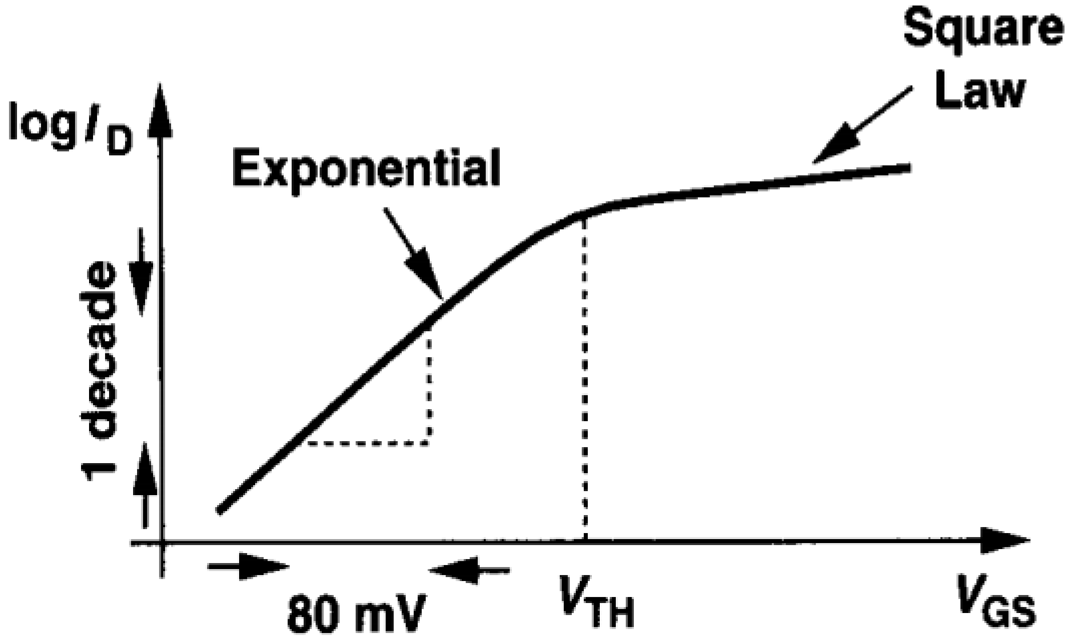


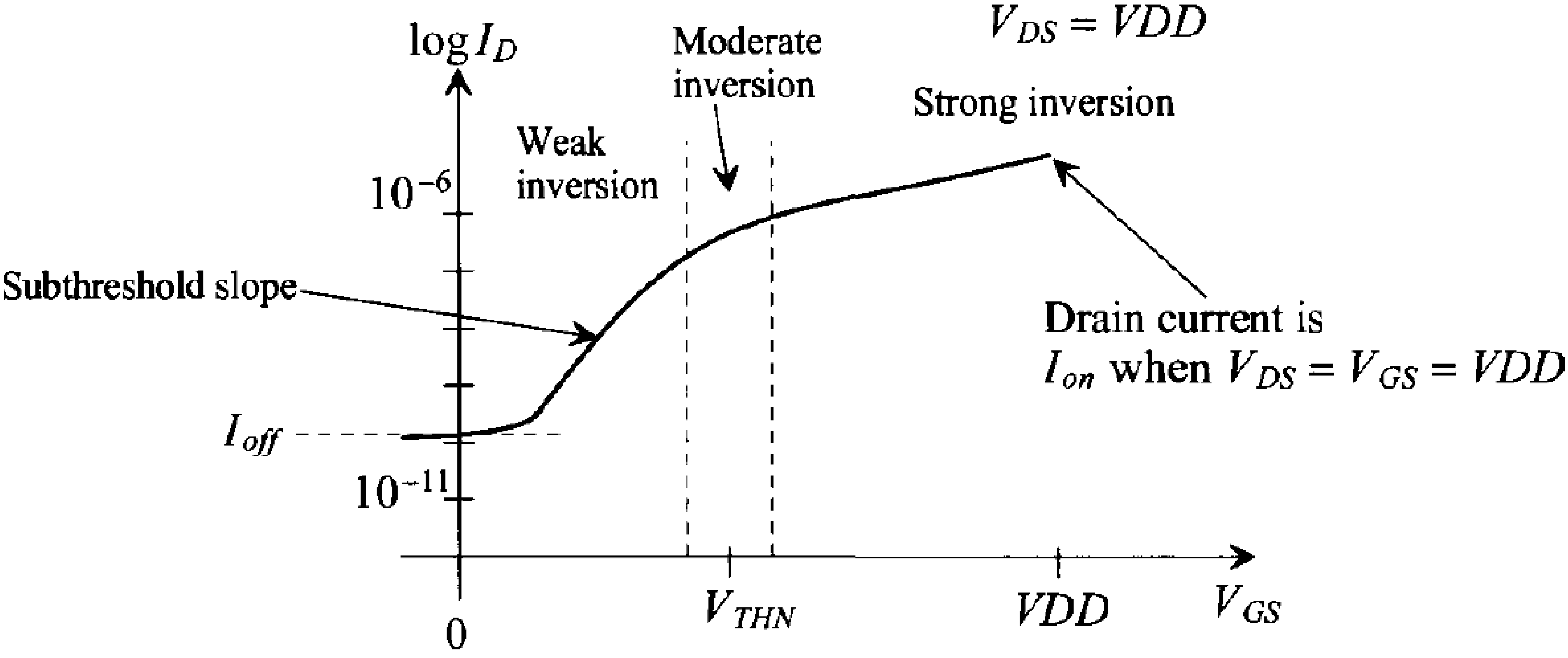
Figure 5.14 The i_D–v_{GS} characteristic of an NMOS transistor operating in the saturation region. The i_D–v_{OV} characteristic can be obtained by simply relabeling the horizontal axis, that is, shifting the origin to the point $v_{GS} = V_{tn}$.

Subthreshold Conduction

$$I_D = I_0 \exp \frac{V_{GS}}{\zeta V_T}$$



Subthreshold Conduction



Subthreshold Slope

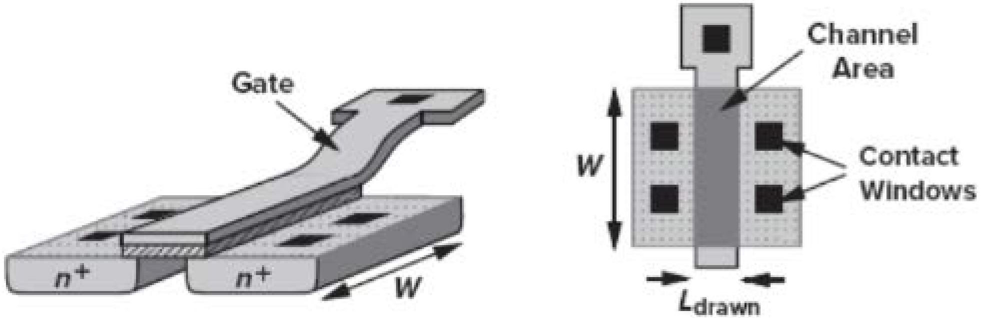
$$I_D = I_{D0} \cdot \frac{W}{L} \cdot e^{q(V_{GS} - V_{THN})/(n \cdot kT)}$$

$$\log I_D = \log \frac{W}{L} + \log I_{D0} + -\frac{V_{THN}}{nV_T} \cdot \log e + \overbrace{\left[\frac{1}{V_T \cdot n} \cdot \log e \right]}^{\text{subthreshold slope}} \cdot V_{GS}$$

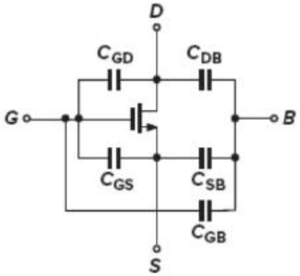
$$\text{Subthreshold slope}^{-1} = \frac{V_T \cdot n}{\log e} \text{ (mV/decade)}$$

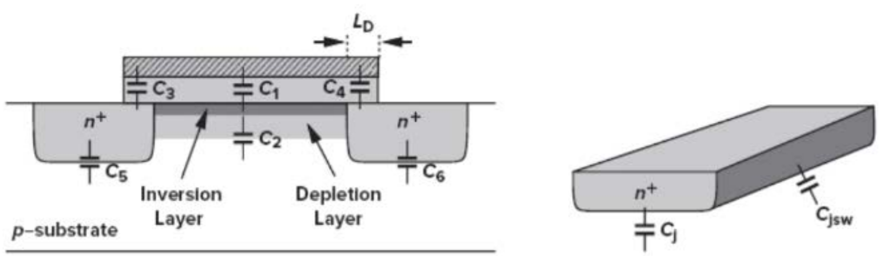
If $kT/q = 0.026\ \text{V} = V_T$ and n (the slope parameter) = 1, the reciprocal of the subthreshold slope is 60 mV/decade (it can be said the subthreshold slope is 60 mV/decade and it is understood it is actually one over the slope). In bulk CMOS n is around 1.6 and the subthreshold slope is 100 mV/decade at room temperature.

MOS Capacitances



(a) (b)





(a) (b)