Oxide Breakdown

For reliable device operation, the maximum electric field across a device gate oxide should be limited to 10 MV/cm. This translates into 1V / 10 Å of gate oxide. A device with t_{ox} of 20 Å should limit the applied gate voltages to 2 V for reliable long-term operation.

Drain-Induced Barrier Lowering

Drain-induced barrier lowering (DIBL, pronounced "dibble") causes a threshold voltage reduction with the application of a drain-source voltage. The positive potential at the drain terminal helps to attract electrons under the gate oxide and thus increase the surface potential V_s. In other words V_{DS} helps to invert the channel on the drain side of the device, causing a reduction in the threshold voltage. Since V_{THN} decreases with increasing V_{DS}, the result is an increase in drain current and thus a decrease in the MOSFET's output resistance.

Gate-Induced Drain Leakage

Gate-Induced Drain Leakage (GIDL, pronounced "giddle") is a term used to describe a component of the drain to substrate leakage current. When the device is in accumulation (e.g. the gate of an NMOS device is at ground) the surface and substrate potentials are nearly the same. In this situation there can be a dramatic increase in avalanche multiplication or band-to-band tunneling when the drain is at a higher potential. Minority carriers underneath the gate are swept to the substrate creating the leakage current.

Gate Tunnel Current

As the oxide thickness scales downwards, the probability of carriers directly tunneling through the gate oxide increases. For oxide thicknesses less than 15 Å, this gate current can be significant. To reduce the tunnel current, various sandwiches of dielectrics are being explored. Figure 16.67 later in the book presents some results showing values for direct tunnel currents under various operating conditions.

6.5.3 SPICE Models for Our Short-Channel CMOS Process

Section 6.4 presented some SPICE models for the long-channel CMOS process used in this book. In this section we give the BSIM4[2] models for the 50 nm process we use in the book with *VDD* = 1 V, see also Table 5.2. The model listing is given below.

BSIM4 Model Listing (NMOS)

```
* 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  = 0
+diomod  = 1            rdsmod  = 0         rbodymod= 1         rgatemod= 1
```

[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

```
+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  = 5e-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    = 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
```

BSIM4 Model Listing (PMOS)

```
.model        pmos      pmos       level = 54

+binunit = 1            paramchk= 1            mobmod  = 0
+capmod  = 2            igcmod  = 1            igbmod  = 1             geomod  = 0
+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      = 0.39         k2      = 0.05          k3      = 0
+k3b    = 0            w0      = 2.5e-006     dvt0    = 3.9           dvt1    = 0.635
+dvt2   = -0.032        dvt0w   = 0            dvt1w   = 0             dvt2w   = 0
+dsub   = 0.7           minv    = 0.05         voffl   = 0             dvtp0   = 0.5e-008
+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   = 0.000258      cdscb   = 0            cdscd   = 6.1e-008      cit     = 0
+voff   = -0.15         nfactor = 2            eta0    = 0.15          etab    = 0
+vfb    = 0.55          u0      = 0.0095       ua      = 1.6e-009      ub      = 8e-018
+uc     = 4.6e-013      vsat    = 90000        a0      = 1.2           ags     = 1e-020
+a1     = 0             a2      = 1            b0      = -1e-020       b1      = 0
+keta   = -0.047        dwg     = 0            dwb     = 0             pclm    = 0.55
+pdiblc1 = 0.03         pdiblc2 = 0.0055       pdiblcb = 3.4e-008      drout   = 0.56
+pvag   = 1e-020        delta   = 0.014        pscbe1  = 8.14e+08      pscbe2  = 9.58e-07
+fprout  = 0.2          pdits   = 0.2          pditsd  = 0.23          pditsl  = 2.3e+006
+rsh    = 3             rdsw    = 250          rsw     = 160           rdw     = 160
+rdswmin = 0            rdwmin  = 0            rswmin  = 0             prwg    = 3.22e-008
+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    = 0.69          bigc    = 0.0012
+cigc   = 0.0008        aigsd   = 0.0087       bigsd   = 0.0012        cigsd   = 0.0008
+nigc   = 1             poxedge = 1            pigcd   = 1             ntox    = 1

+xrcrg1  = 12           xrcrg2  = 5
+cgso   = 7.43e-010     cgdo    = 7.43e-010    cgbo    = 2.56e-011     cgdl    = 1e-014
+cgsl   = 1e-014        ckappas = 0.5          ckappad = 0.5           acde    = 1
+moin   = 15            noff    = 0.9          voffcv  = 0.02

+kt1    = -0.19         kt1l    = 0            kt2     = -0.052        ute     = -1.5
+ua1    = -1e-009       ub1     = 2e-018       uc1     = 0             prt     = 0
+at     = 33000

+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 = 5e-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 = 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

Simulation Results

Figure 6.19 shows 10/1 PMOS and NMOS device simulation results using the topologies seen in Figs. 6.11–6.13. The actual device sizes are 500 nm (width) by 50 nm (length). From the information in this figure and knowing *VDD* is 1 V, we can estimate the on currents for the MOSFETs. For the NMOS device

$$I_{on,n} \approx 300\ \mu A/(W \cdot scale) = 600\ \mu A/\mu m \qquad (6.60)$$

For the PMOS device

$$I_{on,p} \approx 150\ \mu A/(W \cdot scale) = 300\ \mu A/\mu m \qquad (6.61)$$

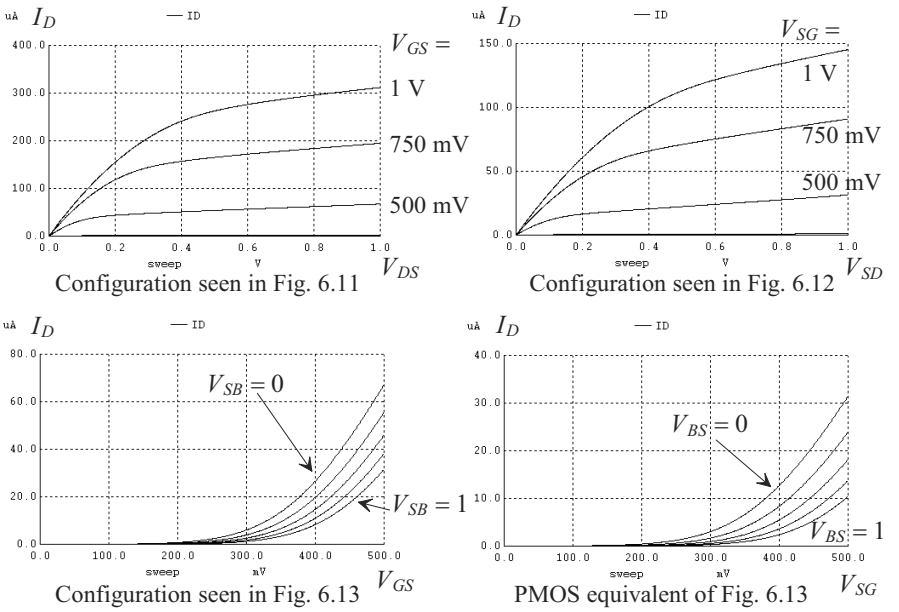

Figure 6.19 Current-voltage characteristics for 50 nm MOSFETs.