

# Appendix I

## LIST OF SYMBOLS

Table A-1. List of symbols.

Symbol	Unit	Meaning
$A_{bulk}$	-	BSIM parameter: bulk charge effect (see chapter 3.6)
$af$	-	SPICE noise parameter: current exponent (see chapter 3.6)
$A_p$	-	Available power gain of amplifier
$C$	F (F/cm <sup>2</sup> )	Capacitance (per unit area)
$C_{box}$	F/cm <sup>2</sup>	Capacitance per unit area of buried oxide (SOI)
$C_d$	F/cm <sup>2</sup>	Depletion layer capacitance per unit area
$C_{dm}$	F/cm <sup>2</sup>	Depletion layer capacitance per unit area when the depletion layer has its maximum width $W_{dm}$
$C_{fb}$	F/cm <sup>2</sup>	Flat-band capacitance per unit area
$C_{fox}$	F/cm <sup>2</sup>	Capacitance per unit area of front gate oxide (SOI)
$C_G$	F	Gate capacitance
$C_{GS}$	F	Gate-to-source capacitance
$C_{it}$	F/cm <sup>2</sup>	Interface trap capacitance per unit area
$C_{ox}$	F/cm <sup>2</sup>	Gate oxide capacitance per unit area
$C_{Si}$	F/cm <sup>2</sup>	Capacitance per unit area of Si body (SOI)
$d$	m	Lattice constant
$D_{it}$	cm <sup>-2</sup> eV <sup>-1</sup>	Density of interface states (traps)
$E$	J, eV	Energy
$E$	V/cm	Electric field
$E_C$	eV	Conduction band edge energy
$E_{eff}$	V/cm	Effective electric field (effective vertical field in inversion layer)
$ef$	-	BSIM and SPICE noise parameter: frequency exponent (see 3.6)
$E_F$	eV	Fermi energy level

Symbol	Unit	Meaning
$E_{F,n}$	eV	Quasi-Fermi energy level for electrons
$E_{F,p}$	eV	Quasi-Fermi energy level for holes
$E_g$	eV	Band gap energy
$E_i$	eV	Intrinsic Fermi energy level
$E_T$	eV	Trap energy level
$E_V$	eV	Valence band edge energy
$F$	-	Noise factor
$f$	Hz	Frequency
$f(E)$	-	Fermi-Dirac distribution function, gives the probability that an electronic state at energy E is occupied
$f(X)$	-	Probability density function of random variable X
$FF$	-	Fano factor
$f_T$	Hz	Transition (cut-off) frequency
$f_0$	Hz	Oscillation frequency of VCO
$g$	-	Degeneracy factor
$g(\tau)$		Trap distribution function (chapter 1.3.5)
$g_{ch}$	S = A/V	Channel conductance
$g_{ch,0}$	S	Channel conductance at zero drain-source voltage
$g_m$	S	Transconductance
$h$	Js	Planck's constant (= $6.63 \times 10^{-34}$ Js)
$I$	A	Current
$i$	A	Small-signal current
$I_D$	A	Drain current
$I_{D,sat}$	A	Drain current in saturation
$I_G$	A	Gate leakage current
$i_n$	A	Noise current
$\overline{i_n^2}$	A <sup>2</sup>	Mean square of noise current
$I_S$	A	Source current
$I_0$	A	Diode saturation current
$J$	A/cm <sup>2</sup>	Current density
$k$	J/K	Boltzmann's constant (= $1.38 \times 10^{-23}$ J/K)
$k$	-	Dielectric constant (relative permittivity)
$KF$		SPICE noise parameter (see chapter 3.6)
$L$	cm	Gate length (length)
$L(\Delta f)$	dBc/Hz	Phase noise at offset $\Delta f$ from carrier
$L_{eff}$	m	BSIM parameter: effective gate length (see chapter 3.6)
$m$	-	MOSFET body-effect coefficient
$M$	-	Avalanche multiplication factor
$m^*$	kg	Electron (hole) effective mass
$N$	-	Number of carriers

Symbol	Unit	Meaning
$N^*$	$m^{-2}$	BSIM noise parameter (see chapter 3.6)
$n$	$cm^{-3}$	Electron concentration (per unit volume)
$N_a$	$cm^{-3}$	Acceptor doping concentration
$N_{body}$	$cm^{-3}$	Doping concentration in Si body of SOI substrate
$N_d$	$cm^{-3}$	Donor doping concentration
$NF$	dB	Noise figure
$n_i$	$cm^{-3}$	Intrinsic carrier concentration ( $= 1.5 \times 10^{10} cm^{-3}$ for Si at 300K)
$N_I$	$m^{-2}$	BSIM parameter: charge density at drain side (see chapter 3.6)
$NOIA$	$m^{-3}eV^{-1}$	BSIM noise parameter (see chapter 3.6)
$NOIB$	$m^{-1}eV^{-1}$	BSIM noise parameter (see chapter 3.6)
$NOIC$	$m \cdot eV^{-1}$	BSIM noise parameter (see chapter 3.6)
$N_{ox}$	$cm^{-2}$	Oxide charge density ( $= Q_{ox}/q$ )
$N_{OX}$	-	Number of oxide charges
$n_s$	$cm^{-3}$	Surface carrier concentration
$N_s$	$cm^{-2}$	Channel carrier density ( $= Q_i/q$ )
$N_{sub}$	$cm^{-3}$	Doping concentration in the substrate
$N_t$	$cm^{-3}eV^{-1}$	Oxide trap density (per unit volume)
$N_T$		Number of oxide traps
$N_0$	$m^{-2}$	BSIM parameter: charge density at source side (see chapter 3.6)
$p$	$cm^{-3}$	Hole concentration (per unit volume)
$P$	W	Power
$P$	-	Probability (chapter 1.2.2)
$P_n$	W	Available noise power
$q$	C	Electronic charge ( $= 1.602 \times 10^{-19} C$ )
$Q_d$	$C/cm^2$	Depletion charge per unit area
$Q_i$	$C/cm^2$	Inversion charge per unit area
$Q_m$	$C/cm^2$	Charge on gate per unit area
$q_{max}$	C	Maximum charge displacement of tank capacitor in VCO
$Q_{ox}$	$C/cm^2$	Oxide charge per unit area
$R$	$\Omega$	Resistance
$R(s)$		Autocorrelation function (chapter 1.2.2)
$r_{ch}$	$\Omega$	Channel resistance
$R_D$	$\Omega$	Drain series resistance
$R_{in}$	$\Omega$	Input resistance
$R_L$	$\Omega$	Load resistance
$R_n$	$\Omega$	Noise resistance (Eq. 1-12)
$r_n$	$\Omega$	Equivalent noise resistance (Eq. 2-7)
$R_S$	$\Omega$	Source series resistance
$R_{SD}$	$\Omega$	Source-drain series resistance ( $R_S + R_D$ )
$r_\pi$	$\Omega$	Dynamic resistance for pn-junction
$S$		Power spectral density

Symbol	Unit	Meaning
$S_I$	A <sup>2</sup> /Hz	Power spectral density of current fluctuations
$S_{I_D}$	A <sup>2</sup> /Hz	Power spectral density of drain current noise
$S_{I_{D, ch}}$	A <sup>2</sup> /Hz	Power spectral density of drain current noise in the channel
$S_{I_{D, th}}$	A <sup>2</sup> /Hz	Power spectral density of drain current thermal noise
$S_{I_{D, 1/f}}$	A <sup>2</sup> /Hz	Power spectral density of drain current 1/ <i>f</i> noise
$S_{I_G}$	A <sup>2</sup> /Hz	Power spectral density of gate current noise
$S_{I_{R_D}}$	A <sup>2</sup> /Hz	Power spectral density of current noise generated in $R_D$
$S_{I_{R_S}}$	A <sup>2</sup> /Hz	Power spectral density of current noise generated in $R_S$
$S_{I_{R_{SD}}}$	A <sup>2</sup> /Hz	Power spectral density of current noise generated in $R_{SD}$
$S_{lim}$	A <sup>2</sup> /Hz	BSIM noise parameter (see chapter 3.6)
$S_N$	1/Hz	Power spectral density of carrier number fluctuations
$S_{Q_{ox}}$	C <sup>2</sup> /cm <sup>4</sup> Hz	Power spectral density of oxide charge density fluctuations
$S_R$	Ω <sup>2</sup> /Hz	Power spectral density of resistance fluctuations
$S_V$	V <sup>2</sup> /Hz	Power spectral density of voltage fluctuations
$S_{V_{fb}}$	V <sup>2</sup> /Hz	Power spectral density of flat-band voltage noise
$S_{V_G}$	V <sup>2</sup> /Hz	Power spectral density of equivalent input gate voltage noise
$S_{wi}$	A <sup>2</sup> /Hz	BSIM noise parameter (see chapter 3.6)
$SS$	V/decade	Subthreshold slope
$T$	K	Absolute temperature
$T$	s	Time (constant)
$t$	s	Time
$t_{box}$	cm	Thickness of buried oxide (SOI)
$t_{EOT}$	cm	Equivalent oxide thickness
$T_n$	K	Noise temperature (Eq. 1-11)
$t_{ox}$	cm	Gate oxide thickness
$t_{Si}$	cm	Thickness of Si body in SOI substrate
$T_0$	K	Standard noise temperature (= 290 K)
$V$	cm <sup>3</sup>	Volume
$V$	V	Voltage
$v$	V	Small-signal voltage
$V_B$	V	Substrate voltage (Bulk terminal voltage)
$V_{BS}$	V	Substrate-to-source voltage
$v_d$	cm/s	Carrier drift velocity
$V_d$	V	Applied voltage across pn-junction
$V_{DD}$	V	Power supply voltage
$V_{DS}$	V	Drain-to-source voltage
$V_{DS, sat}$	V	MOSFET drain-to-source saturation voltage
$V_{fb}$	V	Flat-band voltage
$V_G$	V	Gate voltage

Symbol	Unit	Meaning
$V_{GS}$	V	Gate-to-source voltage
$V_{GT}$	V	Gate voltage overdrive ( $=  V_{GS} - V_T $ )
$v_i$	cm/s	Individual carrier drift velocity
$V_{max}$	V	Maximum voltage swing over tank capacitor in VCO
$v_n$	V	Noise voltage
$\overline{v_n^2}$	V <sup>2</sup>	Mean square of noise voltage
$v_{n,rms}$	V	RMS noise voltage
$V_T$	V	Threshold voltage
$v_{th}$	cm/s	Thermal velocity of electrons
$W$	cm	Gate width
$W_d$	cm	Depletion layer width
$W_{dm}$	cm	Maximum depletion layer width
$W_{eff}$	m	BSIM parameter: effective gate width (see chapter 3.6)
$Y_S$	S	Source admittance
$z$	cm	Distance in a direction vertical to the channel
$Z_S$	$\Omega$	Source impedance
$z_t$	cm	Trap distance from gate oxide/channel interface
$\alpha$	Vs/C	Scattering parameter of the correlated mobility fluctuations
$\alpha_C$	Vs/C	Coulomb scattering parameter
$\alpha_H$	-	Hooge parameter
$\alpha_{H,a}$	-	Hooge parameter of $1/f$ noise generated in scattering processes other than surface roughness scattering.
$\alpha_{H,ph}$	-	Hooge parameter of $1/f$ noise generated in the phonon scattering
$\alpha_{H,sr}$	-	Hooge parameter of $1/f$ noise generated in the surface roughness scattering
$\delta$	m	Skin depth (Eq. 2-1)
$\Delta f$	Hz	Frequency separation from the oscillating frequency of a VCO
$\Delta L_{clm}$	m	BSIM parameter: channel length reduction (see chapter 3.6)
$\Delta x$ or $\delta x$		Fluctuation in $x$
$\epsilon_{ox}$	F/cm	Permittivity of SiO <sub>2</sub> ( $= 3.45 \times 10^{-13}$ F/cm)
$\epsilon_{Si}$	F/cm	Silicon Permittivity ( $= 1.04 \times 10^{-12}$ F/cm)
$\Phi_B$	J, eV	Energy barrier height
$\phi_{ms}$	V	Work-function difference between the gate material and the substrate material
$\gamma$	-	Frequency exponent
$\gamma$	-	MOSFET thermal noise coefficient
$\eta$	-	Electric field parameter (in Eq. 3-66)
$\eta_v$	-	MOSFET parameter describing the relative degree of drain saturation (in Eqs. 3-21 and 3-22)
$\kappa_D$	-	Gate leakage current partitioning coefficient at drain side

Symbol	Unit	Meaning
$\kappa_S$	-	Gate leakage current partitioning coefficient at source side
$\lambda$	cm	Tunneling attenuation length
$\lambda_e$	m	Phonon mean free path
$\mu$	cm <sup>2</sup> /Vs	Carrier mobility
$\mu_a$	cm <sup>2</sup> /Vs	Carrier mobility limited by other mechanisms than surface roughness scattering
$\mu_{ac}$	cm <sup>2</sup> /Vs	Mobility limited by scattering with surface acoustic phonons
$\mu_b$	cm <sup>2</sup> /Vs	Mobility limited by scattering with bulk phonons
$\mu_C$	cm <sup>2</sup> /Vs	Mobility limited by Coulomb scattering
$\mu_{C,imp}$	cm <sup>2</sup> /Vs	Mobility limited by Coulomb scattering from impurities
$\mu_{C,ox}$	cm <sup>2</sup> /Vs	Mobility limited by Coulomb scattering from oxide charges
$\mu_{C0}$	cm/Vs	Screened Coulomb scattering parameter
$\mu_{eff}$	cm <sup>2</sup> /Vs	Effective mobility in MOSFET inversion layer
$\mu_i$	cm <sup>2</sup> /Vs	Individual carrier mobility
$\mu_{ph}$	cm <sup>2</sup> /Vs	Mobility limited by scattering with phonons, both bulk phonons and surface acoustic phonons.
$\mu_r$		Relative permeability (in Eq. 2-1)
$\mu_{sr}$	cm <sup>2</sup> /Vs	Mobility limited by surface roughness scattering
$\mu_0$	cm <sup>2</sup> /Vs	Low-field mobility (Eq. 3-78)
$\mu_0$	H/m	Permeability of free space (= $4\pi \times 10^{-7}$ H/m), used in Eq. (2-1)
$\theta$	rad	Phase
$\theta$	V <sup>-1</sup>	Mobility attenuation coefficient (in Eq. 3-78)
$\rho_{1,2}$	-	Correlation coefficient
$\sigma$	$\Omega^{-1}\text{cm}^{-1}$	Conductivity
$\sigma$		Standard deviation (in Eq. 1-5)
$\sigma_e$	cm <sup>2</sup>	Capture cross section for electrons
$\sigma_h$	cm <sup>2</sup>	Capture cross section for holes
$\sigma_{N_t}$	cm <sup>0.5</sup> eV <sup>0.5</sup>	Relative standard deviation of the trap density
$\tau$	s	CMOS inverter delay
$\tau$	s	Time constant of g-r noise
$\tau_c$	s	Capture time for electrons (holes)
$\tau_e$	s	Emission time for electrons (holes)
$\tau_h$	s	Time in high level of two-state RTS
$\tau_l$	s	Time in low level of two-state RTS
$\tau_{ph-ph}$	s	Relaxation time for phonon-phonon scattering
$\tau_{th}$	s	Time constant of thermally activated traps
$\tau_0$	s	Tunneling time constant (usually taken as $10^{-10}$ s)
$\omega_0$	rad/s	Angular frequency of oscillation
$\psi_B$	V	Difference between Fermi level and intrinsic level potentials
$\psi_s$	V	Surface potential

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

$$1 \text{ \AA} = 10^{-10} \text{ m}$$

**log** means logarithm function in base 10

**ln** means natural logarithm (base  $e$ )

## Appendix II

### LIST OF ACRONYMS

*Table A-2. List of Acronyms.*

Acronym	Meaning
ALD	Atomic layer deposition
B	Bulk
BSIM	Berkeley short channel IGFET model
CMOS	Complementary metal-oxide-semiconductor
CVD	Chemical vapour deposition
D	Drain
DC	Direct current
DCR	Direct conversion receiver
DIBL	Drain-induced barrier lowering
DT	Dynamic threshold
DUT	Device-under-test
EOT	Equivalent oxide thickness
FD	Fully depleted
FFT	Fast Fourier Transform
FOM	Figure-of-merit
FUSI	Fully silicided
G	Gate
g-r	Generation-recombination
HF-clean	Clean in Hydrofluoric acid
ISF	Impulse sensitivity function
ITRS	International technology roadmap of semiconductors
I-V	Current-voltage
JFET	Junction field-effect transistor



Acronym	Meaning
LC	Inductance-capacitance
LNA	Low-noise amplifier
MBE	Molecular beam epitaxy
MOCVD	Metal-organic chemical vapour deposition
MOSFET	Metal-oxide-semiconductor field-effect transistor
nMOSFET	n-channel MOS transistor
PD	Partially depleted
pMOSFET	p-channel MOS transistor
PSD	Power spectral density
PVD	Physical vapour deposition
RF	Radio frequency
RTS	Random-telegraph-signal
S	Source
SCE	Short channel effect
SNR	Signal-to-noise ratio
SOI	Silicon-on-insulator
TCAD	Technology computer aided design
TEM	Transmission electron microscopy
VCO	Voltage controlled oscillator
WKB	Wentzel-Kramers-Brillouin

## Appendix III

### SOLUTIONS TO PROBLEMS

#### Solution problem 1-1.

We calculate the mean square noise voltage for the different alternatives.

A: Only thermal noise

$$\overline{v_n^2} = 4kTR\Delta f = 4 \times 1.38 \times 10^{-23} \times 300 \times 5000 \times 10^6 \text{ V}^2 = 8.28 \times 10^{-11} \text{ V}^2.$$

B:  $T_n = 500 \text{ K}$

$$\overline{v_n^2} = 4kT_n R\Delta f = 1.38 \times 10^{-10} \text{ V}^2.$$

C:  $v_{n,rms} = 15 \text{ } \mu\text{V}$

$$\overline{v_n^2} = v_{n,rms}^2 = 2.25 \times 10^{-10} \text{ V}^2.$$

D: Power spectral density  $S_V = 2 \times 10^{-16} \text{ V}^2/\text{Hz}$

$$\overline{v_n^2} = S_V \times \Delta f = 2 \times 10^{-16} \times 10^6 \text{ V}^2 = 2 \times 10^{-10} \text{ V}^2.$$

E:  $R_n = 10 \text{ k}\Omega$

$$\overline{v_n^2} = 4kTR_n\Delta f = 1.656 \times 10^{-10} \text{ V}^2.$$

Answer: A, B, E, D, C.

### Solution problem 1-2

The thermal noise from the resistor is

$$S_{I,th} = 4kT/R = 4 \times 1.38 \times 10^{-23} \times 300 / 200 \text{ A}^2/\text{Hz} = 8.28 \times 10^{-23} \text{ A}^2/\text{Hz}.$$

The thermal noise and the  $1/f$  noise are uncorrelated. Thus

$$S_{I,tot}(f) = 8.28 \times 10^{-23} + 2.5 \times 10^{-19} / f \text{ A}^2/\text{Hz}.$$

The noise power is given by integrating the PSD over the bandwidth

$$\overline{i_n^2} = \int_1^{10^4} S_{I,tot} df = 8.28 \times 10^{-23} \times (10^4 - 1) + 2.5 \times 10^{-19} \times \ln\left(\frac{10^4}{1}\right) \text{ A}^2 =$$

$$8.3 \times 10^{-19} + 2.3 \times 10^{-18} \text{ A}^2 = 3.1 \times 10^{-18} \text{ A}^2 \Rightarrow i_{n,rms} = \sqrt{\overline{i_n^2}} = 1.8 \text{ nA}.$$

### Solution problem 1-3

The noise equivalent circuit is shown in Fig. A-1.

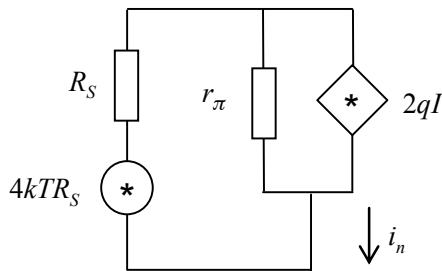


Figure A-1. Noise equivalent circuit in example 1-3.  $r_\pi = kT/qI$ .

The two noise sources are uncorrelated. We use the superposition principle to calculate the noise current from each source.

From the thermal noise source using Ohm's law:

$$S_{I_n,1} = \frac{4kTR_S}{(R_S + r_\pi)^2}.$$

From the shot noise source using the current-division principle

$$S_{I_n,2} = 2qI \frac{r_\pi^2}{(R_S + r_\pi)^2}.$$

Answer: The total PSD is according to the superposition principle

$$S_{I_n} = S_{I_n,1} + S_{I_n,2}.$$

### Solution problem 1-4

The measured noise consists of superimposed  $1/f$  noise and white noise (thermal noise). From the graph:

$$S_V = 2 \times 10^{-13} / f + 5 \times 10^{-16} \text{ V}^2/\text{Hz}.$$

The resistance can be calculated from the thermal noise level

$$R = \frac{5 \times 10^{-16}}{4kT} \Omega = 30 \text{ k}\Omega.$$

The Hooge noise model (see Eq. 1-37)

$$\frac{S_R}{R^2} = \frac{S_V}{V^2} = \frac{\alpha_H}{fN} \quad (V = RI \Rightarrow S_V = S_R I^2 \Rightarrow S_V / V^2 = S_R / R^2).$$

We need to determine the number of (free) electrons  $N$

$N = \text{electron concentration} \times \text{sample volume} \Rightarrow$

$$N = 10^{17} \text{ cm}^{-3} \times 10^{-3} \text{ cm} \times 10^{-2} \text{ cm} \times 10^{-4} \text{ cm} = 10^8.$$

Answer:  $\alpha_H = \frac{fNS_V}{V^2} = \frac{10^8 \times 2 \times 10^{-13}}{(30 \times 10^3 \times 16.6 \times 10^{-6})^2} = 8 \times 10^{-5}$ .

**Solution problem 2-1**

The noise equivalent circuit is shown in Fig. A-2.

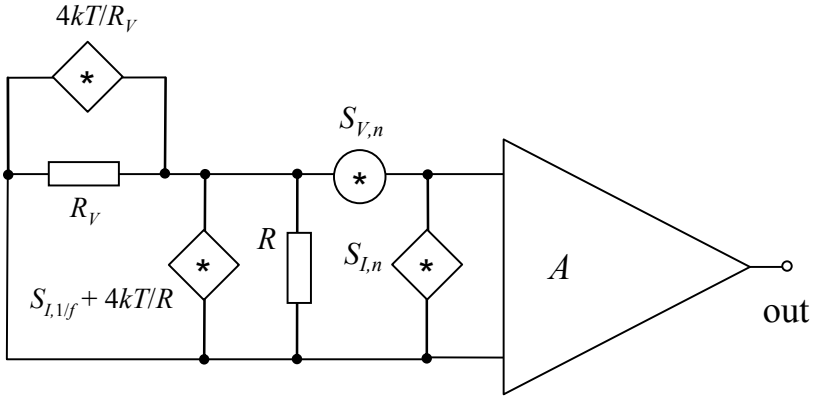


Figure A-2. Noise equivalent circuit in example 2-1.

Answer:

The voltage noise at the output can be written according to the superposition principle:

$$\begin{aligned}
 S_{V,out} &= \left( \frac{4kT/R_V \cdot R_V^2 R^2}{(R + R_V)^2} + \frac{(S_{I,1/f} + 4kT/R) \cdot R_V^2 R^2}{(R + R_V)^2} \right. \\
 &+ \left. S_{V,n} + \frac{S_{I,n} \cdot R_V^2 R^2}{(R + R_V)^2} \right) \cdot A^2 \\
 &= \left( \frac{4kTR_V R}{(R + R_V)} + \frac{S_{I,1/f} R_V^2 R^2}{(R + R_V)^2} + S_{V,n} + \frac{S_{I,n} \cdot R_V^2 R^2}{(R + R_V)^2} \right) \cdot A^2.
 \end{aligned}$$

**Solution problem 2-2**

Using Eqs. (2-8) to (2-10),  $p = 2$  for number fluctuation noise and

$g_{ch}(R_{SD} + R_L) \ll 1$  gives

$$S_{I_{D,tot}} = \frac{A \cdot I_D^2}{fWL(V_{GS} - V_T)^2} + g_{ch}^2 R_{SD}^2 \frac{B \cdot I_D^2}{f}$$

where  $A$  and  $B$  are constants. At a constant  $V_{DS}$  in the linear regime

$$g_{ch} = \left( \frac{dI_D}{dV_{DS}} \right) = \left\{ I_D = \frac{W}{L} \mu C_{ox} (V_{GS} - V_T) V_{DS} \right\} = I_D / V_{DS}.$$

Thus,

$$S_{I_{D,tot}} = \frac{A \cdot I_D^2}{fWL(V_{GS} - V_T)^2} + \frac{R_{SD}^2}{V_{DS}^2} \frac{B \cdot I_D^4}{f}.$$

It was given that the noise contributions from the S/D resistance and the channel are equally strong at  $I_D = I_{D,1}$ . Thus,

$$\frac{A \cdot I_{D,1}^2}{fWL(V_{GS,1} - V_T)^2} = \frac{R_{SD}^2}{V_{DS}^2} \frac{B \cdot I_{D,1}^4}{f} \Rightarrow$$

$$\frac{R_{SD}^2}{V_{DS}^2} \frac{B}{f} = \frac{A \cdot I_{D,1}^{-2}}{fWL(V_{GS,1} - V_T)^2}.$$

At  $I_D = I_{D,1}/3$ :

$$I_D \propto (V_{GS} - V_T) \Rightarrow (V_{GS} - V_T) = (V_{GS,1} - V_T)/3.$$

The relative contribution from the  $1/f$  noise in the S/D resistance to the output drain current noise equals

$$\frac{\frac{R_{SD}^2}{V_{DS}^2} \frac{B \cdot I_D^4}{f}}{\frac{R_{SD}^2}{V_{DS}^2} \frac{B \cdot I_D^4}{f} + \frac{A \cdot I_D^2}{fWL(V_{GS} - V_T)^2}} = \frac{1}{1 + \frac{A \cdot I_{D,1}^2 / 3^2}{\frac{fWL(V_{GS,1} - V_T)^2 / 3^2}{A \cdot I_{D,1}^{-2} \cdot I_{D,1}^4 / 3^4}}}$$

$$= \frac{1}{1 + 3^4} \approx 1.2\%.$$

Answer: The noise from the S/D resistance is only 1.2% of the total output drain current noise at  $I_D = I_{D,1}/3$ .

### Solution problem 2-3

RTS noise can be observed on top of the  $1/f$  noise when the RTS noise PSD is larger than the  $1/f$  noise PSD.

Using Eq. (1-37) for the  $1/f$  noise

$$S_{I,1/f} = \frac{\alpha_H \cdot I_D^2}{fN}$$

and Eq. (1-31) for the RTS noise with  $N_T = 1$  (one trap)

$$S_{I,RTS} = \frac{I_D^2}{N^2} \frac{\tau}{1 + (2\pi f)^2 \tau^2}.$$

The RTS noise PSD is maximized relative to the  $1/f$  noise when  $\tau = 1/2\pi f$ .

Answer: the condition to observe RTS noise

$$S_{I,RTS} > S_{I,1/f} \Rightarrow$$

$$\frac{I_D^2}{N^2} \frac{\tau}{2} > \frac{\alpha_H I_D^2 2\pi\tau}{N}$$

$$N < \frac{1}{4\pi\alpha_H}.$$

**Solution problem 2-4**

RTS noise can be observed if

- (i) the number of traps is small *and*
- (ii) the RTS noise is higher than the  $1/f$  noise.

We make the assumption that RTS can be observed if there are less than 5 active traps.

Thus, using Eq. (2-12)

$$4kTWN_{t,z} < 5 \Rightarrow WL < \frac{5}{4kTN_{t,z}}.$$

It was given that  $z = 2 \text{ nm}$  and  $N_t = 1 \times 10^{17} \text{ cm}^{-3} \text{ eV}^{-1}$ . Hence,

$$WL < 0.24 \mu\text{m}^2.$$

The number of carriers  $N$  must also satisfy Eq. (2-11). For a MOSFET in inversion

$$N = WLC_{ox}(V_{GS} - V_T) / q$$

Thus,

$$N < \frac{1}{4\pi\alpha_H} \Rightarrow \alpha_H < \frac{q}{4\pi WLC_{ox}(V_{GS} - V_T)}.$$

This relation is valid in strong inversion. The RTS noise is easiest to discover when  $V_{GS} - V_T$  is small. Therefore, we assume  $V_{GS} - V_T = 0.1 \text{ V}$ . Furthermore,  $C_{ox} = \epsilon_{ox}/t_{ox} = 1.73 \cdot 10^{-6} \text{ F/cm}^2$ . Thus, the requirement on  $\alpha_H$  is found to be

$$\alpha_H < 3 \cdot 10^{-5}.$$

Answer: RTS noise is estimated to be observed in a device with a gate area  $W \cdot L$  smaller than  $0.24 \mu\text{m}^2$  and with a Hooge parameter for background  $1/f$  noise lower than  $3 \cdot 10^{-5}$ .



**Solution problem 3-1**

Insert  $V_{DS,sat} = (V_{GS} - V_T)/m$  in Eq. (3-50):

$$\frac{S_{I_D}}{I_D^2} = \frac{q\alpha_H\mu_{eff}V_{DS}}{fL^2I_D} = \frac{q\alpha_H\mu_{eff}(V_{GS} - V_T)}{mfL^2I_D}. \quad (A3-1)$$

Then insert Eq. (3-8) for  $I_D$  in the equation above

$$I_D = \frac{W}{L}\mu_{eff}C_{ox}\frac{(V_{GS} - V_T)^2}{2m} \Rightarrow \quad (A3-2)$$

$$S_{I_D} = \frac{2q\alpha_H I_D^2}{fWLC_{ox}(V_{GS} - V_T)}.$$

Comparing with Eq. (3-80) for mobility fluctuation noise in the linear region, we see that the drain current noise is a factor of two higher in the saturation region. Why? The number of carriers in the channel is reduced to 2/3 of its value in the linear region at a certain gate voltage overdrive since the channel at the drain end is pinched off. By using

$$Q_i = C_{ox}(V_{GS} - V_T)\sqrt{1 - x/L}. \quad (A3-3)$$

in Eq. (3-50), the same expression as in Eq. (A3-2) is found.

**Solution problem 3-2**

First, calculate the expression for  $g_m$  in the saturation region from Eq. (3-8)

$$g_{m,sat} = \left( \frac{dI_{D,sat}}{dV_{GS}} \right) = \frac{2I_D}{(V_{GS} - V_T)} = \sqrt{2I_D \frac{W}{L} \frac{\mu_{eff}C_{ox}}{m}}. \quad (A3-4)$$

Inserted in Eq. (3-79), this yields

$$\begin{aligned}
S_{I_D} &= \frac{q^2 k T \lambda N_t}{f^\gamma W L C_{ox}^2} \left( 1 + \frac{\alpha \mu_{eff} C_{ox} I_D}{g_m} \right)^2 g_m^2 = \\
&\frac{q^2 k T \lambda N_t}{f^\gamma W L C_{ox}^2} \left( 1 + \frac{\alpha \mu_{eff} C_{ox} (V_{GS} - V_T)}{2} \right)^2 \frac{2 I_D W}{L} \frac{\mu_{eff} C_{ox}}{m} = \\
&\frac{2 q^2 k T \mu_{eff} I_D \lambda N_t}{f^\gamma L^2 C_{ox} m} \left( 1 + \frac{\alpha \mu_{eff} C_{ox} (V_{GS} - V_T)}{2} \right)^2.
\end{aligned} \tag{A3-5}$$

This expression has the same functional dependence as Eqs. (3-68). The BSIM3 noise model is based on the number fluctuation noise theory. The SPICE2 model in Eq. (3-67) resembles the pure number fluctuation noise model (without correlated mobility fluctuations) in the saturation region.

### Solution problem 3-3

- (a) Mobility fluctuations in the linear or subthreshold region (see Eq. 3-80), or number fluctuations in the saturation region (see Eq. A3-5).  
(b) Mobility fluctuations in the saturation region. See Eq. (3-51).  
(c) Number fluctuations in the linear region. See Eq. (3-39) and note that  $V_{GS} - V_T \propto I_D$ .  
(d) The output noise stems from noise in the drain series resistance. See Eq. (3-12) with

$$S_{I_{R_D}} \gg S_{I_{D,ch}} \text{ and } r_{ch} > R_D.$$

Fig. 2-10 shows a simulation of the situation described above.

- (e) Two alternatives: the noise stems (i) from number fluctuation noise in the channel when biased in the subthreshold region (see Eq. 3-40) or (ii) from noise in the drain series resistance when

$$S_{I_{R_D}} > S_{I_{D,ch}} \text{ and } R_D > r_{ch}.$$

### Solution problem 4-1

First calculate the oxide capacitance  $C_{ox}$  and the transconductance  $g_m$ .

$$C_{ox} = 3.9 \cdot 8.854 \cdot 10^{-14} / (2.2 \cdot 10^{-7}) \text{ F/cm}^2 = 1.57 \cdot 10^{-6} \text{ F/cm}^2.$$

Use Eq. (3-8) to find  $g_m$

$$g_m = \frac{I_D}{[(V_{GS} - V_T) - mV_{DS} / 2]} = 1.30 \text{ mS if we assume } m = 1.$$

(a) Answer: Eq. (3-80)  $\Rightarrow \alpha_H = 7.9 \times 10^{-5}$ .

The trap density is found from Eq. (3-79). The correlated mobility fluctuations can be neglected since the gate voltage overdrive is small (0.1 V). Thus,

$$N_t = \frac{10 \cdot 10 \cdot 10^{-4} \cdot 0.075 \cdot 10^{-4} \cdot (1.57 \cdot 10^{-6})^2}{1.602 \cdot 10^{-19} \cdot 1.38 \cdot 10^{-23} \cdot 300 \cdot 10^{-8} \cdot (0.0013)^2} \cdot 1.4 \cdot 10^{-17} \text{ cm}^{-3} \text{eV}^{-1}.$$

Here,  $\lambda = 10^{-8}$  cm was used (see Table 4-4).

Answer:  $N_t = 2.3 \times 10^{17} \text{ cm}^{-3} \text{eV}^{-1}$ .

(note that in order to get the unit eV, multiplication with  $1.602 \times 10^{-19}$  is performed).

(b) Calculate the input gate voltage noise and normalize with gate area

$$WLS_{V_G} = WLS_{I_D} / g_m^2 = 6.2 \mu\text{V}^2 \mu\text{m}^2 / \text{Hz} \text{ (at } f = 10 \text{ Hz)}.$$

According to Table 4-1, the ITRS requires a noise level below  $19 \mu\text{V}^2 \mu\text{m}^2 / \text{Hz}$  at  $f = 10$  Hz for a device with  $L = 75$  nm and  $t_{EOT} = 2.2$  nm (note that the value is given at 1 Hz in the table).

Answer: The ITRS requirements are fulfilled.

### Solution to problem 4-2

The input gate voltage noise is calculated in comparison with the reference device for all four technologies.

Answer:

$$\text{i) } S_{V_G} = S_{V_{G,ref}} \frac{N_t / N_{t,ref} \cdot (t_{EOT} / t_{EOT,ref})^2}{L / L_{ref}} = S_{V_{G,ref}} \cdot \frac{6 \cdot (1/2)^2}{(1/2)} = 3S_{V_{G,ref}} .$$

$$\text{ii) Mobility fluctuation noise: } S_{V_G} = S_{V_{G,ref}} \cdot \frac{2 \cdot (3/4)}{(3/4)} = 2S_{V_{G,ref}} .$$

iii) A front-back gate coupling factor  $(1+N_{t,b}/N_{t,f})$  must be considered in the FD SOI device (see Eq. 4-16).

$$S_{V_G} = S_{V_{G,ref}} \cdot \frac{1}{(2/3)} (1+3) = 6S_{V_{G,ref}} .$$

$$\text{iv) } S_{V_G} = S_{V_{G,ref}} \cdot 2^2 = 4S_{V_{G,ref}} .$$

### Solution to problem 5-1

Identifying Fourier coefficients: (see Eq. 5-1)

$$c_0 = 0.2, c_1 = 1.$$

The  $1/f^3$ -corner frequency is the frequency  $\Delta f$  where the first term and the second term in Eq. (5-2) are equal. Thus

$$0.2^2 \cdot 1 \cdot 10^{-18} / \Delta f = 1 \cdot 10^{-23} (0.2^2 + 1^2) \Rightarrow \Delta f = 3.8 \text{ kHz} .$$

Answer: The  $1/f^3$ -corner frequency is equal to 3.8 kHz.

### Solution to problem 5-2

Denote the noise power (in dBm) due to phase noise with  $P_N$ , the power of the interfering signal  $P_I$  and the power of the signal in the desired channel  $P_C$ . Thus, in order to achieve a SNR of 15 dB

$$\text{SNR} = P_C - P_N = P_I - 40 \text{ dB} - P_N = 15 \text{ dB} . \quad (\text{A5-1})$$

The phase noise with respect to the power of the interfering signal is denoted by  $L$  (dBc/Hz). The noise power is integrated over the channel bandwidth of 200 kHz

$$P_N = L + 10\log(200 \cdot 10^3) + P_f . \quad (\text{A5-2})$$

Inserted in Eq. (A5-1), this yields

$$15 = -40 - L - 10\log(200 \cdot 10^3) \Rightarrow L = -40 - 53 - 15 = -108 \text{ dBc/Hz}.$$

Answer: The phase noise at 2 MHz offset must be lower than  $-108 \text{ dBc/Hz}$ .

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