Modeling and Estimation of Total Leakage Current in Nano-scaled CMOS Devices Considering the Effect of Parameter Variation*

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ABSTRACT
In this paper we have developed analytical models to estimate the mean and the standard deviation in the gate, the subthreshold, the reverse biased source/drain junction band-to-band-tunneling (BTBT) and the total leakage in scaled CMOS devices considering variation in process parameters like device geometry, doping profile, flat-band voltage and supply voltage. We have verified the model using Monte Carlo simulation using an NMOS device of 50nm effective length and analyzed the results to enumerate the effect of different process parameters on the individual components and the total leakage.

Categories & Subject Descriptor:
B.6.3 [Logic Design]: Design Aids –*Estimation*
B.7.2 [Integrated Circuits]: Design Aids – *Estimation*
General Terms: Design, Experimentation, Theory.
Keywords: band-to-band tunneling,, gate leakage, subthreshold leakage, threshold voltage, variability, Monte Carlo.

1. INTRODUCTION

CMOS devices have been scaled down aggressively in each technology generations to achieve higher integration density and performance. However, the leakage current has increased drastically with technology scaling [1]-[4] and has become a major contributor to the total IC power. Moreover, the increasing statistical variation in the process parameters has emerged as a serious problem in the nano-scaled circuit design [4] and can cause significant increase in the transistor leakage current [5]-[6]. Designing with the worst case leakage may cause excessive guard-banding, resulting in a lower performance [5]-[6]. Hence, accurate estimation of the total leakage current considering the effect of random variations in the process parameters is extremely important for designing CMOS circuits in the nano-meter regime.

Different leakage mechanisms contribute to the total leakage in a device [1]. Among them, the three major ones can be identified as: Subthreshold leakage, Gate leakage and reverse biased drain-substrate and source-substrate junction Band-To-Band-Tunneling (BTBT) leakage [7]. In scaled devices each of these leakage component increases drastically resulting in a dramatic increase in the total leakage current [7]. Moreover, each component depends differently on the transistor geometry (gate length (L_g), Source-Drain extension length (L_{SDE}), oxide thickness (T_{ox}), junction depth (Y_j), width (W)), the doping profile (channel doping (N_{dep}) and "halo" doping (N_{pocket}) concentration), the flat-band voltage (V_{fb}), and the supply voltage (V_{dd}) [7]-[9]. Hence, statistical variation in each of these parameters results in a large variation in each of the leakage components, thereby, causing significant increase in the nominal leakage. Although, several work has been reported addressing the estimation of the subthreshold leakage current considering parameter variation [5]-[6] none of them have addressed the gate leakage and the BTBT leakage. In this work:

- We have provided analytical models to estimate the mean and the standard deviation (S.D.) of the *gate leakage*, the *BTBT leakage* and the *total leakage* with parameter variation (one parameter at a time and simultaneous variation of all parameters).
- We have analyzed and modeled the *correlation* among the leakage components with respect to different process parameters.

*This work is supported in part by Semiconductor Research Corp., MARCO, Gigascale Silicon Research Center, DARPA PACC program, Intel and IBM.

ISLPED'03, August 25–27, 2003, Seoul, Korea.

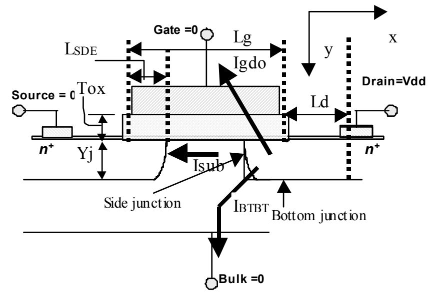

Figure 1: Device geometry and major leakage components in a "off" transistor (Vgs =0, Vds = Vdd, Vbs =0)

2. ESTIMATION OF LEAKAGE COMPONENTS

In the "off" state (V_{gs}=0, V_{ds}=V_{dd}, V_{bs}=0) of a transistor the major leakage components are: the gate-to-drain overlap leakage (I_{gdo}), the subtheshold leakage (I_{sub}) and the drain-substrate junction BTBT leakage (I_{BTBT}) (Fig. 1). In this section we present an analytical approach to estimate the mean and the S.D. of these three leakage components considering variation in the transistor geometry (L_g, L_{SDE}, T_{ox}, Y_j, W), V_{fb}, doping profile (N_{pocket} and N_{dep}) and V_{dd}. Each of the parameters is considered to be independent of each other and the distribution is assumed to be Gaussian [6]. The model is derived considering an NMOS device of 50nm effective length at room temperature (T=300K). The nominal values of the parameters are chosen based on the models available in [10], [11] and considering the guideline given in [4]. For each leakage component the analytical models are verified against Montecarlo simulations, considering 10,000 parameter values (or vectors when simultaneous variations have been considered) using MATLAB.

2.1. Estimation of the Gate Leakage

In the "off" state of a transistor, the gate leakage is dominated by I_{gdo} and can be given by [2]

$$I_{gate} = I_{gdo} = WL_{SDE}A_g\left(V_{dd}/T_{ox}\right)^2 exp\left(\frac{-B_g\left(1-\left(1-V_{dd}/\phi_{ox}\right)^{3/2}\right)}{V_{dd}}T_{ox}\right) \quad (1)$$

where, ϕ_{ox} is the barrier height of tunneling electron (or hole) and T_{ox} is the oxide thickness. A_g and B_g are physical parameters [2]. From Eq. (1) we observe that the gate leakage is sensitive to variations in T_{ox}, V_{dd}, W and L_{SDE}.

2.1.1 Variation in a single parameter

The expected value (mean) of I_{gdo} ($=g(T_{ox})$) with respect to T_{ox} can be obtained by re-writing I_{gdo} as a function of T_{ox} and is given by [12]:

$$E\left[I_{gdo}\right] = E\left[g(T_{ox})\right] = \int_{-\infty}^{\infty} g(T_{ox}) f_T(T_{ox}) dT_{ox} \tag{2}$$

where, $f_T(T_{ox})$ is the probability distribution function of T_{ox}. Since the variation in the process parameters are in the range of 10-20% we can assume the parameters to be concentrated near their mean values [6]. Expanding $g(T_{ox})$ in a Taylor series around the mean of T_{ox} we get [12]:

$$E\left[g(T_{ox})\right] = \int_{-\infty}^{\infty} \left[\sum_{k=0}^{n} \frac{g^{(k)}(\eta_{Tox})}{k!}(T_{ox}-\eta_{Tox})^k\right] f_T(T_{ox})dT_{ox} = \sum_{k=0}^{n} \frac{g^{(k)}(\eta_{Tox})}{k!}\mu_k$$

$$\text{where,}\, g^{(k)}(\eta_{Tox}) = \left.\frac{\partial^k g(T_{ox})}{\partial T_{Tox}^k}\right|_{T_{ox}=\eta_{Tox}} ;\mu_k = \int_{-\infty}^{\infty}(T_{ox}-\eta_{Tox})^k f_T(T_{ox})dT_{ox} \tag{3}$$

where, η_{Tox} is the mean and μ_k is the k-th central moment of T_{ox} distribution. Since the T_{ox} distribution is assumed to be Gaussian, odd moments are zero (i.e. $\mu_k=0$ for odd values of k) [12]. Hence, considering up to 5[th] order derivatives of $g(T_{ox})$ we get:

$$E\left[g(T_{ox})\right] = g(\eta_{Tox}) + \frac{g^{(2)}(\eta_{Tox})}{2}\sigma_{Tox}^2 + \frac{g^{(4)}(\eta_{Tox})}{4!}3\sigma_{Tox}^4 \tag{4}$$

where, σ_{Tox} is the variance of T_{ox}. Following a similar argument, the expected value of $g^2(Tox)$ is given by:

$$E\left[g^2(T_{ox})\right] \approx g^2(\eta_{Tox}) + \frac{(g^2)^{(2)}(\eta_{Tox})}{2}\sigma_{Tox}^2 + \frac{(g^2)^{(4)}(\eta_{Tox})}{4!}3\sigma_{Tox}^4 \tag{5}$$

The S.D. of $g(T_{ox})$ ($\sigma[g(Tox)]$) is given by [12]:

$$\sigma\left[g(T_{ox})\right] = \sqrt{E\left[g^2(T_{ox})\right] - \left[E\left[g(T_{ox})\right]\right]^2} \tag{6}$$

The above derivation is applicable to any function $g(x)$ where, x is a Gaussian random variable and its values are centered around its mean. Moreover, a reasonably good estimation can be obtained by considering up to 2[nd] order derivatives, which reduces the computational complexity. Hence, we can generalize the above procedure to estimate the mean and the S.D. of a leakage component considering variation in a single parameter (say x) as follows:

1. Express the current as function of the variable x (say g(x))
2. Estimate $E\left[g(x)\right]$ as : $E\left[g(x)\right] = g(\eta_x) + \dfrac{g^{(2)}(\eta_x)}{2}\sigma_x^2$
3. Estimate $E\left[g^2(x)\right]$ as : $E\left[g^2(x)\right] = g^2(\eta_x) + \dfrac{(g^2)^{(2)}(\eta_x)}{2}\sigma_x^2$ (7)
4. Estimate $\sigma\left[g(x)\right]$ as : $\sigma\left[g(x)\right] = \sqrt{E\left[g^2(x)\right] - \left[E\left[g(x)\right]\right]^2}$

Hence, using (7) we can find the effect of variation of a parameter (V_{dd}, W, L_{SDE}) on I_{gdo},.

2.1.2. Simultaneous variation of all parameters

The gate current, as a function of the random variables T_{ox}, V_{dd}, L_{SDE} and W, is given by:

$$I_{gate} = I_{gdo} = WL_{SDE}A_g\left(V_{dd}/T_{ox}\right)^2 exp\left(-g(V_{dd},T_{ox})\right)$$
$$\text{where, } g_{TD}(V_{dd},T_{ox}) = B_gT_{ox}\left(1-\left(1-V_{dd}/\phi_{ox}\right)^{3/2}\right)\Big/V_{dd} \tag{8}$$

$E[I_{gdo}]$ can be calculated by expanding $g_{TD}(V_{dd},T_{ox})$ in a Taylor Series around η_{Tox} and η_{Vdd} and considering upto first order term only [6]. This approximation is valid since T_{ox} and V_{dd} values are assumed to be concentrated near their mean and is known as the "linearity approximation". Using this, $E[I_{gdo}]$ can be obtained as:

$$g_{TD}(V_{dd},T_{ox}) = g_{TD}\left(\eta_{V_{dd}},\eta_{T_{ox}}\right) + \frac{\partial g_{TD}}{\partial V_{dd}}\Delta V_{dd} + \frac{\partial g_{TD}}{\partial T_{ox}}\Delta T_{ox} = g_\eta + \alpha_d\Delta V_{dd} + \alpha_{Tox}\Delta T_{ox}$$
$$E\left[I_{gdo}\right] = A_g exp\left(-g_{TD\eta}\right)\times\left[\eta_W\eta_{LSDE}\right]\times E\left[V_{dd}^2 exp\left(-\alpha_d\Delta V_{dd}\right)\right]\times E\left[\frac{1}{T_{ox}^2}exp\left(-\alpha_{Tox}\Delta T_{ox}\right)\right] \tag{9}$$

Using a similar procedure we can calculate $E[I^2_{gdo}]$ and hence we can estimate the S.D. of the gate leakage considering the simultaneous variation of all of the parameters.

2.2. Estimation of Band-to-Band-Tunneling Leakage

In the "off" state of transistors the BTBT current is due to the tunneling in the drain-substrate junction and can be modeled as [2], [7]:

$$I_{BTBT} = \sum_{k=side,bottom} WL_k A\frac{\xi_k}{E_g^{1/2}}V_{dd}\,exp\left(-BE_g^{3/2}\Big/\xi_k\right) \tag{10}$$

where, L_{side} ($=Y_j$) and L_{bottom} ($=L_{SDE} + L_d$) are lengths of side and bottom junctions (Fig. 1), ξ_{side}, ξ_{bottom} are electric fields at side and bottom junctions, A and B are physical parameters [2] and E_g is the band-gap. The electric field at a junction strongly depends on the junction doping [2]. The BTBT current in the MOSFET is controlled by the peak "Halo" doping region, which is present near the side junction [7]. Hence, the total BTBT current is given by:

$$I_{BTBT} = \left[WY_jA\Big/E_g^{1/2}\right]\xi V_{dd}\,exp\left(-BE_g^{3/2}\Big/\xi\right)$$
$$\xi(N_{pocket},V_{dd}) = \sqrt{\frac{2qN_{pocket}N_{sd}}{\varepsilon_{si}(N_{pocket}+N_{sd})}\left[V_{dd}+\frac{KT}{q}\ln\left(\frac{N_{pocket}N_{sd}}{n_i^2}\right)\right]} \tag{11}$$

From (11) we can observe that the BTBT current is sensitive to the variations in W, Y_j, N_{pocket} and V_{dd}.

2.2.1. Variation in a single parameter

To estimate the mean and the S.D. considering variation in a single parameter, we have expressed I_{BTBT} as a function of that parameter and followed the procedure given in (7).

2.2.2. Simultaneous variation of all parameters

Using "linearity approximation", we can express ξ and 1/ξ as a Taylor series around $\eta_{Npocket}$ and η_{Vdd} and consider up to first order terms only. Hence, $E[I_{BTBT}]$ can be expressed as:

$$E\left[I_{BTBT}\right] = \left(A\big/E_g^{1/2}\right)E\left[W\right]E\left[Y_j\right]E\left[\xi V_{dd}exp\left(-BE_g^{3/2}/\xi\right)\right] = \left(A\big/E_g^{1/2}\right)\eta_W\eta_{Y_j}\times$$
$$E\left[\left[\xi_\eta+\beta_d\Delta V_{dd}+\beta_d\Delta N_{pocket}\right]exp\left(-BE_g^{3/2}\left(\frac{1}{\xi_\eta}-\frac{1}{\xi_\eta^2}\left(\beta_d\Delta V_{dd}+\beta_d\Delta N_{pocket}\right)\right)\right)\right]$$
$$=\left(\frac{A}{E_g^{1/2}}\right)\eta_W\eta_{Y_j}\xi_\eta exp\left(-\frac{BE_g^{3/2}}{\xi_\eta}\right)E\left[exp\left(\frac{BE_g^{3/2}}{\xi_\eta^2}\beta_d\Delta V_{dd}\right)\right]E\left[exp\left(\frac{BE_g^{3/2}}{\xi_\eta^2}\beta_N\Delta N_{pocket}\right)\right] \tag{12}$$
$$\Delta V_{dd} = V_{dd}-\eta_{Vdd};\Delta N_{pocket} = N_{pocket}-\eta_{Npocket};\beta_d = \left.\frac{\partial\xi}{\partial V_{dd}}\right|_{\eta_{Vdd}};\beta_N = \left.\frac{\partial\xi}{\partial N_{pocket}}\right|_{\eta_{Npocket}}$$

The simplification in the last step follows from the assumption that $\xi_\eta+\beta_N\Delta N_{pocket}+\beta_N\Delta V_{dd}\approx\xi_\eta$.. This assumption is acceptable since parameters are concentrated near their mean. The final two expectations can be solved based on (7). Following a similar procedure $E[I^2_{BTBT}]$ can be obtained. From the expressions of $E[I^2_{BTBT}]$ and $E[I_{BTBT}]$ the mean and the S.D. can be estimated.

2.3 Estimation of the Subthreshold Leakage

The subthreshold current in a "off" transistor is given by [8]:

$$I_{sub} = \mu_0\frac{\varepsilon_{ox}}{T_{ox}}\frac{W}{L}v_T^2e^{1.8}exp\left(\frac{V_{gs}-V_{th}}{S\,v_T}\right)\left(1-exp\left(-\frac{V_{ds}}{v_T}\right)\right) \tag{13}$$

L is the effective channel length ($L=L_g-2L_{SDE}$). Considering the short channel effects, narrow width effect and the effect of non-uniform doping, the threshold voltage of a short channel transistor is given by [2], [8]-[9], [13]:

From (13), and (14) it is observed that the subthreshold current is sensitive to the variation in L (i.e. L_g and L_{SDE}), N_{eff} (i.e. N_{dep}, N_{pocket}), T_{ox}, V_{fb} , V_{dd} and W.

$$V_{th} = V_{fb}+\phi_{S0}-\left[2(V_{bi}-\phi_{S0})+V_{ds}\right]\left[e^{-L/2l_c}+2e^{-L/l_c}\right]+\gamma\sqrt{\phi_{S0}-V_{bs}}\left(1-\frac{\lambda}{L}X_d\right)+V_{nce}$$
$$\phi_{S0} = 2v_T\ln\left(N_{eff}/n_i\right),\ X_d = \sqrt{\frac{2\varepsilon_{si}}{qN_{eff}}(\phi_{S0}-V_{bs})},\ l_C = \sqrt{\frac{\varepsilon_{si}}{\varepsilon_{ox}\varsigma}X_d},\gamma = \frac{\sqrt{2q\varepsilon_{si}N_{eff}}}{\varepsilon_{ox}/T_{ox}}, \tag{14}$$
$$V_{bi} = v_T\ln\left(N_{sd}N_{eff}/n_i^2\right),\ V_{nce} = 3\pi\frac{T_{ox}}{W}\left[\phi_{S0}-\left[2(V_{bi}-\phi_{S0})+V_{ds}\right]\left[e^{-L/2l_c}+2e^{-L/l_c}\right]\right]$$
$$N_{eff} = (1-2L_x/L)N_{dep}+(2L_x/L)N_{pocket};S=1+\left(\varepsilon_{si}/\varepsilon_{ox}\right)\left(T_{ox}/X_d\right)$$

2.3.1. Variation in a single parameter

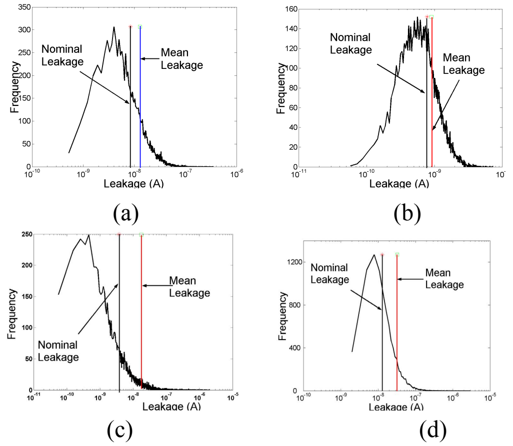

Figure 2: Distribution of leakage components with the simultaneous variation of 20% on all parameters. (a) Gate, (b) BTBT, (c) Suthreshold, and (d) Total Leakage.

Representing I_{sub} as a function of one of the above mentioned parameters and using (7), we can estimate the mean and the S.D. of I_{sub} considering variation in that parameter.

2.3.2. Simultaneous variation of all parameters

Using "linearity approximation" we can represent (V_{th}/Sv_T) as:

$$\frac{V_{th}}{Sv_T} = \frac{V_{th\eta}}{S_\eta v_T} + \lambda_d \Delta V_{dd} + \lambda_N \Delta N_{eff} + \lambda_L \Delta L + \lambda_{fb} \Delta V_{fb} + \lambda_{Tox} \Delta T_{ox} + \lambda_W \Delta V_W$$

$$V_{th\eta} = V_{th}(\eta_{Vdd}, \eta_{Neff}, \eta_L, \eta_{Vfb}, \eta_{Tox}, \eta_W); \quad S_\eta = S(\eta_{Neff}, \eta_{Tox})$$

$$\lambda_d = \left(\frac{1}{Sv_T}\right)\frac{\partial V_{th}}{\partial V_{dd}}; \lambda_N = \left(\frac{1}{S^2 v_T}\right)\left(S\frac{\partial V_{th}}{\partial N_{eff}} - V_{th}\frac{\partial S}{\partial N_{eff}}\right); \lambda_L = \left(\frac{1}{Sv_T}\right)\frac{\partial V_{th}}{\partial L}; \quad (15)$$

$$\lambda_{Tox} = \left(\frac{1}{S^2 v_T}\right)\left(S\frac{\partial V_{th}}{\partial T_{ox}} - V_{th}\frac{\partial S}{\partial T_{ox}}\right); \lambda_W = \left(\frac{1}{Sv_T}\right)\frac{\partial V_{th}}{\partial W}$$

Using the above expressions we can estimate $E[I_{sub}]$ as given by:

$$E[I_{sub}] = \mu_0 \varepsilon_{ox} v_T^2 e^{1.8} exp\left(-\frac{V_{th\eta}}{S_\eta v_T}\right) E\left[W exp(-\lambda_W \Delta W)\right] E\left[exp(-\lambda_N \Delta N_{eff})\right] E\left[exp(-\lambda_{fb} \Delta V_{fb})\right]$$

$$E\left[\frac{1}{L} exp(-\lambda_L \Delta L)\right] E\left[\frac{1}{T_{ox}} exp(-\lambda_{Tox} \Delta T_{ox})\right] E\left[exp(-\lambda_d \Delta V_{dd})\left(1 - exp\left(-\frac{V_{dd}}{v_T}\right)\right)\right] \quad (16)$$

$E[I^2_{sub}]$ can also be estimated using a similar procedure. $E[I^2_{sub}]$ and $E[I_{sub}]$ are used to calculate the mean and the S.D. of the subthreshold current considering simultaneous variations of all parameters.

2.4. Model verification and Sensitivity Analysis

Table-I, II and III show the effect of parameter variation on the gate-to-drain, the BTBT and the subthreshold leakage. A close match is observed between the analytical (Anlyt.) and the simulated results (Expt.). However, the estimated value of the S.D. deviates from the simulated one, when 20% parameter variation is considered. From Table-I we observe that the gate leakage (I_{gdo}) is most sensitive to a variation in T_{ox} (due to exponential dependence of I_{gdo} on T_{ox}). The BTBT leakage is most sensitive to the variation in N_{pocket} and V_{dd} (Table-III). This is due the fact that the BTBT depends exponentially on the junction electric field, which in turn is proportional to the square root of N_{pocket} and V_{dd} (see (12)). The subtheshold current is extremely sensitive to the variation in L, T_{ox} and V_{fb} (Table-IV). It is also observed that, although I_{sub} is not very sensitive to the channel doping (N_{dep}), however, the variations in the halo doping (N_{pocket}) have a much stronger effect. Variations in L, T_{ox} and N_{pocket} results in an increase in SCE, thereby, cause a large increase in I_{sub}. Moreover, I_{sub} is more sensitive to parameter variation than I_{gdo} and I_{BTBT}. A 20% variation in all parameters results in a 50%, 16%, and 370%, increase in nominal values of I_{gdo}, I_{BTBT} and I_{sub}, respectively (Fig. 2 (a), (b), (c)). We can summarize the above observations as:

The gate leakage is most sensitive to the variation in T_{ox}.
The BTBT is most sensitive to the variation in N_{pocket} and V_{dd}.
The subthreshold current is extremely sensitive to the variation in V_{fb}, T_{ox}, L and N_{pocket}.
Among the three leakage components the subthreshold leakage is most sensitive to the parameter variation.

Table-I
Effect of Parameter Variation on I_{gdo} (Nominal Value=8.43 nA)

Parameter	% variation (3σ)	Mean (nA)		S.D. (nA)		S.D./Mean	
		Anlyt.	Exp	Anlyt.	Expt.	Anlyt.	Expt.
Vdd	20%	8.56	8.54	1.68	1.710	0.196	0.200
Tox	10%	9.32	9.30	4.29	4.430	0.460	0.470
Tox	20%	12.55	12.5	11.00	14.20	0.877	1.140
L_{SDE}	20%	8.43	8.44	0.56	0.560	0.067	0.067
W	10%	8.43	8.43	0.28	0.280	0.033	0.033
All	10%	9.36	9.40	4.46	4.550	0.476	0.484
All	20%	12.74	12.89	11.8	14.82	0.920	1.152

Table-II
Effect of Parameter Variation on I_{BTBT} (Nominal Value=0.78 nA)

Parameter	% variation (3σ)	Mean (nA)		S.D. (nA)		S.D./Mean	
		Anlyt.	Exp	Anlyt.	Expt.	Anlyt.	Expt.
Vdd	20%	0.814	0.816	0.246	0.259	0.303	0.318
Npocket	20%	0.840	0.860	0.404	0.443	0.481	0.515
Yj	20%	0.780	0.780	0.051	0.051	0.066	0.067
W	10%	0.780	0.780	0.026	0.027	0.033	0.034
All	10%	0.813	0.807	0.243	0.252	0.299	0.312
All	20%	0.920	0.905	0.574	0.580	0.624	0.641

Table-III
Effect of Parameter variation on Isub (Nominal Value=3.72 nA)

Parameter	% variation (3σ)	Mean (nA)		S.D. (nA)		S.D./Mean	
		Anlyt.	Expt.	Anlyt.	Expt.	Anlyt.	Expt.
Vfb	10%	6.08	7.09	7.54	11.7	1.240	1.670
Vdd	20%	3.74	3.74	0.43	0.46	0.114	0.124
Npocket	20%	4.45	4.44	2.62	2.91	0.583	0.655
Ndep	20%	3.79	3.78	0.72	0.72	0.191	0.191
L(Lsde,Lg)	20%	6.27	6.97	9.45	13.62	1.50	1.960
Tox	20%	4.54	4.51	2.88	3.17	0.634	0.704
W	10%	3.73	3.73	0.38	0.38	0.100	0.101
All	10%	8.38	9.11	11.66	19.18	1.400	2.106
All	20% (Vfb=10%)	15.00	17.55	38.00	61.43	2.500	3.500

3. ESTIMATION OF THE TOTAL LEAKAGE

The total leakage current of a transistor is given by:

$$I_{TOTAL} = I_{gdo} + I_{sub} + I_{BTBT} \quad (17)$$

The mean and the S.D. of the total leakage are given by [12]:

$$E[I_{TOTAL}] = E[I_{gdo}] + E[I_{sub}] + E[I_{BTBT}] = \eta_{Igdo} + \eta_{Isub} + \eta_{IBTBT}$$

$$E[I^2_{TOTAL}] = E[I^2_{gdo}] + E[I^2_{sub}] + E[I^2_{BTBT}] + 2E[I_{gdo} I_{sub}] + 2E[I_{sub} I_{BTBT}] + E[I_{gdo} I_{BTBT}] \quad (18)$$

$$\sigma^2_{TOTAL} = E[I^2_{TOTAL}] - [E[I_{TOTAL}]]^2 \quad \text{and} \quad Cov(X,Y) = E[XY] - E[X]E[Y]$$

$$\text{Correlation Coefficient} = R = Cov(X,Y)/\sigma_x \sigma_y$$

The mean and the S.D. of the total leakage component considering the variation in a single parameter and simultaneous variation of all parameters can be calculated based on (18) and using the models developed in sections 2.1, 2.2 and 2.3. We can estimate the covariance of leakage components with respect to one parameter using the following general method.

$$E[g(x)h(x)] = g(\eta)h(\eta) + \frac{\sigma^2}{2}\left[g^{(2)}(\eta)h(\eta) + 2g^{(1)}(\eta)h^{(1)}(\eta) + g(\eta)h^{(2)}(\eta)\right] \quad (19)$$

$$Cov(g(x)h(x)) = E[g(x)h(x)] - E[g(x)]E[h(x)]$$

To estimate the covariance considering simultaneous variation of all parameters, we first represent I_{gate}, I_{BTBT}, and I_{sub} as products of the functions of a single parameter (using (9), (12), and (16)). That allows us to evaluate the covariance of the leakage components.

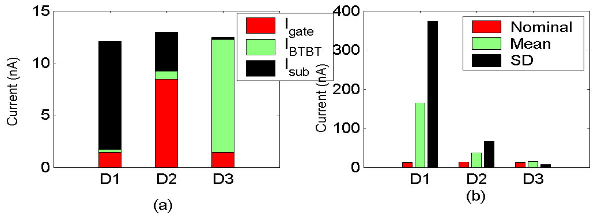

Figure 3: Effect of Relative Magnitude of Leakage Components on Sensitivity to Parameter Variation (a) Nominal Values, (b) simultaneous variation of all parameters (20%)

3.1. Model verification and sensitivity analysis

Table-IV shows the total leakage is very sensitive to the variations in V_{fb}, L and T_{ox}. It is observed from Table-V that the leakage currents are strongly correlated to each other with respect to the variation in T_{ox}, L_{SDE} and V_{dd}. The negative correlation among the BTBT and the subthreshold leakage with respect to N_{pocket} variation (due to the fact that an increase in N_{pocket} lowers I_{sub} but increases I_{BTBT}) reduces the sensitivity of the total leakage to the N_{pocket} variation. Moreover, the effect of variations in the total leakage is less severe than the effect of variation in the subthreshold leakage (Fig. 2). This is because of the fact that under nominal condition the gate leakage is the dominant leakage component, and is less sensitive to parameter variation than the subthreshold component. We can summarize the above discussions as:

The total leakage is extremely sensitive to the variation in *L*, T_{ox} and V_{fb}.
The correlation among leakage components has a non-negligible effect on the overall variation.
The effect of variations on the total leakage depends on the relative magnitude of the individual leakage components.

Table-IV
Effect of Parameter Variation on I_{TOTAL} (Nominal =12.93nA)

Parameter	% variation (3σ)	Mean (nA)		S.D. (nA)		S.D./Mean	
		Anlyt.	Exp	Anlyt.	Expt.	Anlyt.	Expt.
Vfb	10%	15.30	16.13	7.54	11.30	0.493	0.703
Vdd	20%	13.12	13.13	2.38	2.44	0.187	0.186
Npocket	20%	13.65	13.75	1.62	2.57	0.118	0.187
Ndep	20%	13.00	13.00	0.696	0.72	0.053	0.060
L(Lg,Lsde)	10%	13.43	13.40	2.08	2.71	0.15	0.167
L(Lg,Lsde)	20%	15.49	15.67	5.40	9.64	0.35	0.61
Tox	10%	14.00	14.03	5.39	5.70	0.384	0.407
Tox	20%	17.80	18.01	13.13	17.52	0.740	0.978
W	10%	12.94	12.95	0.682	0.677	0.053	0.052
All	10%	20.58	18.72	19.72	19.75	0.958	1.05
All	20% (Vfb=10%)	36.88	32.47	66.19	78.5	1.80	2.40

Table-V
Correlation of Leakage Components

Parameter	% variation (3σ)	I_{BTBT} & I_{sub}		I_{sub} & I_{gate}		I_{BTBT} & I_{gate}	
		Anlyt.	Exp	Anlyt.	Expt.	Anlyt.	Expt.
Vdd	20%	0.988	0.994	0.991	0.999	0.99	0.996
Npocket	10%	-0.983	-0.933	0	0	0	0
Tox	10%	0	0	0.985	0.995	0	0
L(Lsde,Lg)	10%	0	0	0.98	0.953	0	0
W	10%	0.999	0.999	0.999	0.999	0.999	0.999
All	10%	0.011	0.014	0.073	0.095	0.091	0.110
All	20% (Vfb=10%)	0.023	0.033	0.107	0.124	0.094	0.091

To illustrate the last conclusion we have designed three NMOS devices (D1, D2 and D3) with 50nm effective length such that, the subthreshold leakage is the dominant component in D1, the gate leakage is dominant in D2 while the BTBT is dominant in D3 (Fig. 3 (a)). This is achieved by changing the oxide thickness and the doping profile parameters. It is observed that the total leakage in device D1 is most susceptible to the parameter variation (Fig. 3 (b)). This establishes the fact that the susceptibility of the total leakage to the parameter variation depends on the relative magnitude of the leakage components. The mean and the S.D. of the subthreshold and the BTBT leakage increases with an increase in the temperature as these two components depends strongly on temperature [7] (Fig. 4). However, the gate leakage is almost insensitive to the temperature variation [7]. Both the mean and the S.D. of the total leakage increase with an increase in the temperature (Fig. 4). Hence, the effect of the parameter variation is more severe at a higher temperature. It is also observed that the nominal and mean leakage and in the S.D. is observed in the scaled technologies (Fig. 5).

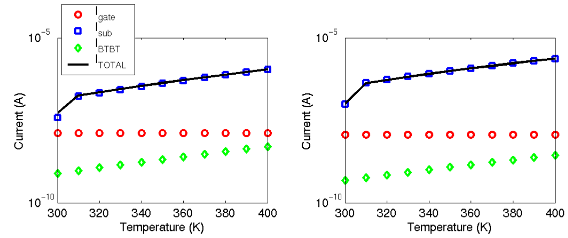

Figure 4: Effect of parameter variation at different temperature: (a) the mean, and (b) the S.D. of the leakage

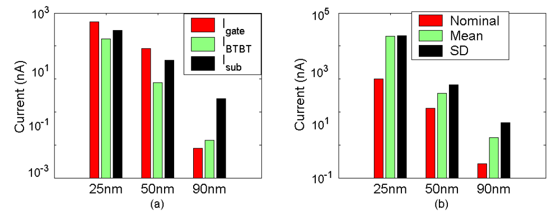

Figure 5: Effect of Parameter Variation at Different Technology (a) Nominal Values, (b) simultaneous variation of all parameters (20%)

4. CONCLUSION

In this research we have developed analytical models to estimate the effect of the parameter variation on the gate, the subthreshold, the BTBT and the total leakage. The models have been verified with Monte Carlo simulations. It has been shown that the parameter variation has significant impact on each leakage component and can cause large variation in the total leakage. Hence, in conclusion we believe that, the derived model will be extremely useful in the estimation of the total leakage in logic circuits considering the effect of parameter variations.

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