International Journal of Advanced Science and Technology
Vol. 14, January, 2010

An Investigation into the Radiation Tolerance Problem: The Analytical Modelling Approach

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Abstract

The exposure of integrated electronic components and systems to ionizing radiation may lead to minor deterioration in performance or catastrophic system failure, depending on the level of radiation (as a function of altitude). Mitigation of the radiation-induced hazards is of a major concern for space applications, since electronic components are expected to function without failure for an extended period of time, under extreme operating conditions. The work presented in this paper examines the effect of radiation on electronic components through analytical modeling of parameters, some of which are design-dependent and others are process-dependent. Examinations of the inter-dependency of these parameters would aid identifying possible solutions to the radiation tolerance problem.

Keywords: *Analytical modelling, radiation, traps, space, performance, estimation, prediction.*

1. Introduction

The dropping cost and increased availability of satellite construction and space launch capabilities have fueled the race between countries to gain a presence in space, with the objective of securing their commercial, research and military interests [1].

The ability of a satellite to perform a given task – e.g. tracking and monitoring, for instance, adversary's systems [2] – is governed by the performance of on-board electronic systems. Any deterioration in the performance of electronic systems - due to radiation [3] - will adversely affect a satellite's operation. Severe deterioration of a satellite's electronic components may, ultimately, lead to system failure. The radiation induced failure may be the result of displacement damage [4], ionization damage, single event effects [5][6] and transient effects [7]. The degree of radiation damage incurred by a satellite's components (EC) will depend on the type of radiation and the degree of radiation-EC interaction as well as the EC operating conditions. The damage mechanisms may yield temporary or permanent behavioural malfunction. Therefore, radiation hardening is an essential requirement for the reliable operation of a system in space. Methods for dealing with space radiation include the shielding of the outer surface of a satellite or a space vehicle [8][9].

This paper considers an analytical approach to the problem of space radiation. The analytical modelling expressions presented herein examine the effect of space radiation – represented by a set of parameters - on the behaviour of an electronic component. Establishing a relationship between many of the critical parameters affecting the response of an EC would also allows for optimization of ECs performance, under the effect of space radiation. In this work, an EC is viewed as a process with a set of events being executed in a particular manner to satisfy certain objectives. The assertion and execution of an event(s) may be governed by a set of parameters, internal and external to the EC. Variation in these parameters may impair the functionality of the process with potentially undesirable consequences.

This paper is structured as follows: Section 2 briefly introduces process-domains and analytical modelling expressions. A sample of simulation results is shown in Section 3. Conclusions are given in Section 4.

2. Model Setting

For a fabricated electronic component, assume a reliable and stable semiconductor material, and defect-free components. To assess the effect of space radiation on the EC, two domains are created, as shown in Figure 1. The aim is to establish a relationship between the two domains, with each domain having its own parameters that influence their respective processes. Assume ρ_s represents a set of parameters for the space domain and ρ_c represents a set of parameters for the EC domain.

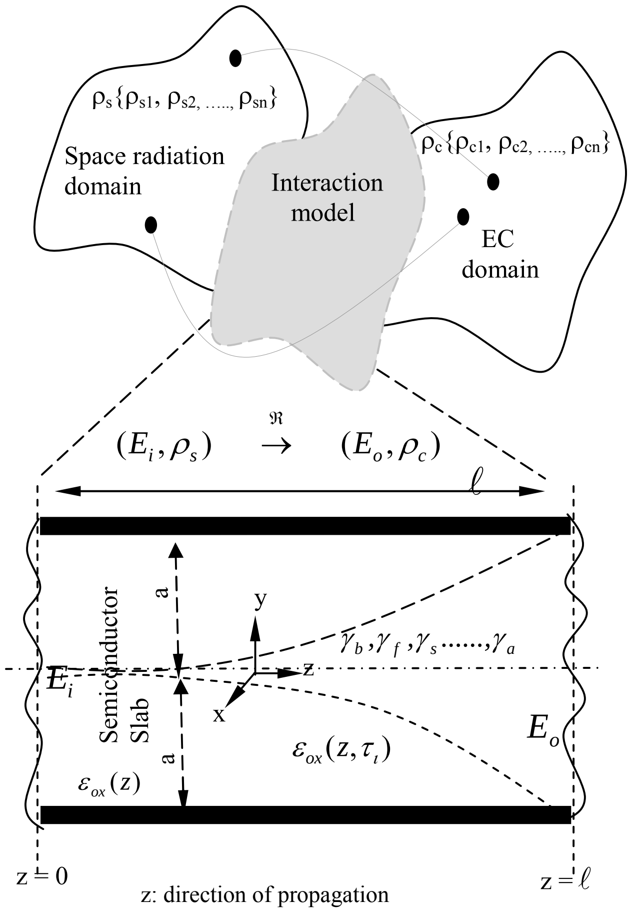

Figure 1. Domain representation

By investigating the induced interaction between the two domains, useful information for reducing the radiation effects could be obtained.

The parameters influencing the behaviour of semiconductor materials – thus affecting the performance of semiconductor devices - are variables [10]:

$$\gamma_f = f\{\lambda, d_c\} \tag{1}$$

$$\gamma_s = f\{\theta, \tau_v\} \tag{2}$$

$$\gamma_p = f\{f\} \tag{3}$$

where

γ_f : free-carrier absorption, γ_s : absorption due to scattering,

γ_p : photon absorption; λ : wavelength, d_c : doping carrier, θ : incident angle, τ_v : thickness variation, f : frequency.

The traps build-up process depends on a set of parameters:

$$TrP = f(T, z, N, \tau, X)\Big|_{x=\{\gamma_f, \gamma_s, \gamma_p\}} \tag{4}$$

With

$$N = f(T, \rho) \tag{4a}$$

$$\tau = f(T, z) \tag{4b}$$

$$X = f(\ell); \tag{4c}$$

$$T = f(h) \tag{4d}$$

Where :

T: temperature;

z: distance across which a carrier travels before being captured by a trap [9].

N: number of recombination centres, and

τ: the time taken before a carrier recombine.

ρ: doping

From Figure 1:

The net flow of carriers – per unit time – is as follows [11]:

$$C_n = \frac{\left(z/n\right)\left(C_{z_i} - C_{z_j}\right)}{z/\upsilon}\Bigg|_{0<z<\ell;\, v=f(T);\, n=f(T))} \tag{5}$$

with

$$z_j > z_i\Big|_{z_i, z_j \in z} \tag{6}$$

υ: the speed at which a carrier travels.

n: the number of directions taken by carriers.

From (5)

$$C_n = -\sigma \frac{\partial C(z)}{\partial z}\Bigg|_{\sigma = zv/n} \tag{7}$$

Considering the concentration of carriers 'C' at distance ℓ is C_ℓ, and at $z \geq 0$ is C_z, then the changes in concentration – in the +z direction - could be represented as follows:

$$C_\ell = C_z - \kappa_c \ell\Big|_{C=f(T_o)} \tag{8}$$

with

$$\kappa_c = -\frac{\partial C_\ell}{\partial \ell} \tag{9}$$

Similarly, the change in traps – in the +z direction – is as follows:

$$TrP_n = \left.\frac{\partial TrP(z)}{\partial z}\right|_{TrP=f(T_o)} \tag{10}$$

$$TrP_z = TrP_\ell - \kappa_t \ell \tag{11}$$

with

$$\kappa_t = -\frac{\partial TrP_z}{\partial \ell} \tag{12}$$

Since the level of radiation depends on altitude, temperature-caused traps will increase with increasing height. The following analytical expressions will consider height 'h' as an additional dimension. The postscripts 'o' and 'h' refers to variables at sea-level and high altitudes, respectively, as shown in Figure 2.

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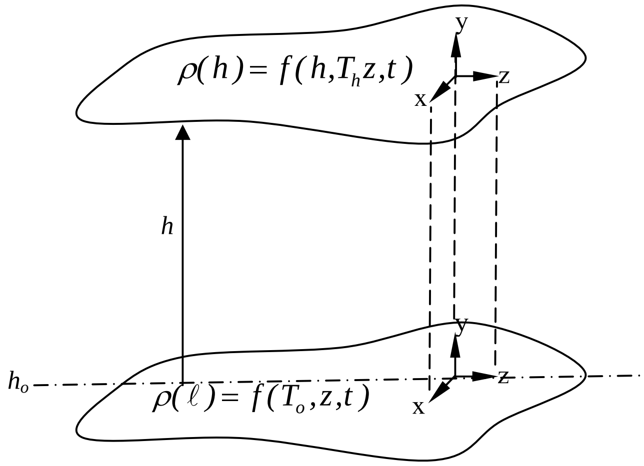

Figure 2. Domain representation, including height as an additional dimension

Considering a different dimension 'h', i.e. altitude; $T = f(h)$, equations similar to (7)-(12) could be obtained by mapping the variable *z* to that represented by *h*:

$$\rho_{f(T_o)} \xrightarrow{TrP_n, \kappa_t, C_n, \kappa_c} \rho_{f(T_h)} \tag{13}$$

As the interest is in the effect of temperature – as a function of radiation at high altitudes – on traps, and from (13):

$$\left.\frac{\partial C(h)}{C_n} = \delta \frac{\partial z}{z}\right|_{\delta = \nu/n; \nu = f(T_h)} \tag{14}$$

From (14)

$$\ln(C) = \delta \ln(kh) \tag{15}$$

$$\ln(C_o) = \delta \ln(kh_o) \tag{16}$$

Subtracting (16) from (15) and taking the exponential, give

$$\frac{C}{C_o} = \left(\frac{h}{h_o}\right)^{\delta} \tag{17}$$

Similarly

$$\frac{TrP}{TrP_o} = \left(\frac{h}{h_o}\right)^{\delta} \tag{18}$$

From (17) and (18)

$$C(h) >> C(h_o); TrP(h) >> TrP(h_o)\Big|_{v>>>n; T>>>T_o} \tag{19}$$

The performance '*P*' of an EC is inversely proportional to *TrP*:

$$P \quad \alpha \quad \frac{1}{TrP} \tag{20}$$

As an increase in traps yields degradation in performance, and taking the relationship shown in both (17) and (18) into consideration

$$P_o = P_n e^{-\alpha z}\Big|_{\alpha = f(TrP(h_o),,t); 0<z<\ell} \tag{21}$$

with

$$P_h = P_n e^{-\kappa z}\Big|_{\alpha \in \kappa; \kappa = f(TrP(h),t); 0<z<\ell} \tag{22}$$

P_o: performance at sea-level; P_n: nominal performance; P_h: performance at distance h from sea level.

The nominal performance is considered as a reference against which changes in performance at sea-level and at high altitude are determined. Small variations in parameters around the nominal value are considered acceptable. Each of P_h and P_o is a function of greater variations in parameters.
Treating the deterioration in performance as a process, P_h and P_o are modeled as shown in Figure 3,

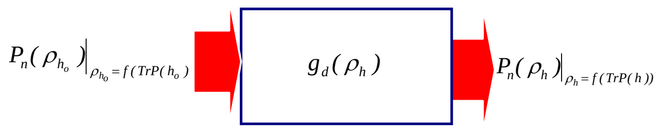

Figure 3. Process representation

$g_d(\rho_h)$ could be thought of as an attenuation process that yields a decline in performance.
As

$$T_h >>> T_o \tag{23}$$

the radiation-caused traps will significantly exceed those generated at sea-level, i.e. significant degradation in the EC performance at high altitudes when compared to that at sea-level. Hence, the relationship between (21 and (22) could be expressed as follows:

$$P_h = P_o e^{-\alpha_h}\Big|_{\alpha_h = e^{\alpha_o}} \tag{24}$$

α_o and α_h represent attenuation coefficients at sea-level and at high altitudes, respectively.
Applying Maclaurin's series:

$$P_h = -P_o + \left.\frac{(-P_n)^{m+1}}{(m+1)!\,P_o^m}\right|_{m\geq 0;} \tag{25}$$

In general, if the performance P is considered as a set of parameters:

$$P\left\{s_i^n\right\}\Big|_{i\geq 0,n\geq 1} \tag{26}$$

then by approximating (25) and using (26)

$$P_h \approx c_1 s_i^{-n} + c_2 s_i^n \Big|_{i\geq 0;n\geq 1;;c_2=P_n} \tag{27}$$

where

s_i^n : EC-dependent parameter, e.g. dielectric parameters, threshold/sub-threshold voltage shifts, leakage current.

and

$$c_1 = Kc_2\big|_{K=0.5} \tag{28}$$

Differentiating (27) with reference to s_i^n :

$$\frac{\partial P(h,z,t)}{\partial s_i^n} = nc_2 s_i^n - 2nc_1 s_i^{-(n+1)} \tag{29}$$

Considering the concept of minimal performance [12], the minimum change in parameter s_i^n

$$s_{i,min}^n = \sqrt{c_1 / c_2}\Bigg|_{\frac{\partial P(h,z,t)}{\partial s_i^n}=0} \tag{30}$$

From (29) and (30), the minimum change in performance

$$p_{h,min} \approx \delta_c c\Big|_{c=\sqrt{c_1 c_2};\delta_c=f(n)} \tag{31}$$

Dividing (27) and (31), and using (30):

$$\frac{P_h(h,z,t)}{P_{h,min}(h,z,t)} = \frac{1}{\delta_c}\left(\kappa^{\delta_c} + \kappa^{-\delta_c}\right)\Bigg|_{\kappa=\left(s_i^n / s_{i,min}^n\right)} \tag{32}$$

Differentiating (32) with respect to κ

$$\frac{\partial P_h(h,z,t)}{\partial \kappa} = P_{h,in}(h,z,t)\left(\frac{\kappa^{2\delta_c}-1}{\kappa^{2\delta_c-1}}\right) \tag{33}$$

Manipulating (32) and (33), and rearranging

$$\frac{\partial \kappa}{\kappa} = \frac{1}{\delta_c}\left(\frac{\kappa^{\delta_c-1} + \kappa^{-(\delta_c+1)}}{\kappa^{\delta_c} - \kappa^{-(\delta_c+1)}}\right)\cdot\frac{\partial P_h(h,z,t)}{P_h(h,z,t)} \tag{34}$$

3. Simulations

This paper makes use of a MOSFET transistor to investigate and highlight ways of mitigating the effect of space radiation on ECs. A MOSFET transistor is susceptible to ionization-dose damage. Such damage can manifest itself in threshold/sub-threshold voltage shifts, leakage current increase and mobility degradation – hence, deterioration in performance.

<u>Illustration 1</u>:

For a MOS device, the device gain β is dependent on the process parameters (i.e. μ, ε and t_{ox}) and the device geometry (i.e. W and L), as follows [11][13]:

$$\beta = \frac{\mu\varepsilon}{t_{ox}}\left(W/L\right) \tag{35}$$

$$\beta = f\left(\mu, \varepsilon, t_{ox}, L, W\right) \tag{36}$$

μ: the effective mobility of carriers; ε: permittivity of the gate insulator;
t_{ox}: thickness of the gate insulator;
W: the channel width;
L: the gate length.

The effect of oxide traps and interface traps on a MOS transistor could be interpreted as its I-V transfer characteristics is shifted to the left as the radiation-caused temperature increases, with the resulting shift in the input threshold.

An increase in radiation/temperature yields a decrease in the carrier mobility – thus a decrease in β; $\beta \propto T^{-3/2}$. This implies that as temperature increases, the threshold voltage decreases.

As a device is scaled down, the ratio W/L increases – thus counteracting the effect of temperature. Furthermore, increasing the dielectric constant - in the case of deep-sub micron (DSM) designs - is another factor that could balance the effect of increasing temperature.

The effective channel length, as a function of dielectric parameters is given by:

$$L_{eff} = L - \sqrt{2\varepsilon_o\varepsilon_{si}\varsigma}\Big| \tag{37}$$

with

$$\varsigma = \frac{1}{qN}(V_{ds} - (V_{gs} - V_t)) \tag{38}$$

Differentiating (37) with respect to ε

$$\frac{\partial L_{eff}}{\partial\varepsilon} = -\left.\varsigma\middle/\sqrt{2\varepsilon_o\varepsilon_{si}\varsigma}\right|_{\varepsilon=\{\varepsilon_o\varepsilon_{si}\}} \tag{39}$$

$$\frac{\partial L_{eff}}{\partial\varsigma\partial\varepsilon} = -\left.\frac{(\varepsilon+\varsigma)}{\sqrt{2\varepsilon\varsigma}}\right|_{\varepsilon=\{\varepsilon_o\varepsilon_{si}\};\varsigma=f(V_t);V_t=f(TrP);TrP=f(T_h)} \tag{40}$$

From (12) and (40):

$$\frac{\partial TrP}{\partial\varsigma\partial\varepsilon} \approx -\left.\frac{(\varepsilon+\varsigma)}{\sqrt{2\varepsilon\varsigma}}\right|_{\varepsilon=\{\varepsilon_o\varepsilon_{si}\};\varsigma=f(V_t);V_t=f(TrP);TrP=f(T_h)} \tag{41}$$

Similarly, from (9) and (40):

$$\frac{\partial C}{\partial\varsigma\partial\varepsilon} \approx -\left.\frac{(\varepsilon+\varsigma)}{\sqrt{2\varepsilon\varsigma}}\right|_{\varepsilon=\{\varepsilon_o\varepsilon_{si}\};\varsigma=f(V_t);V_t=f(TrP);TrP=f(T_h);} \tag{42}$$

Equations (41) and (42) show that, at the DSM level, the number of traps and excess carriers becomes independent of radiation-caused effects. That is, DSM designs can go some way to counteract harsh environments.

The Matlab simulations in Figure 4 – Figure 7 show the effect of changes in the channel dimensions, oxide thickness, and the dielectric constant on a MOSFET transistor.

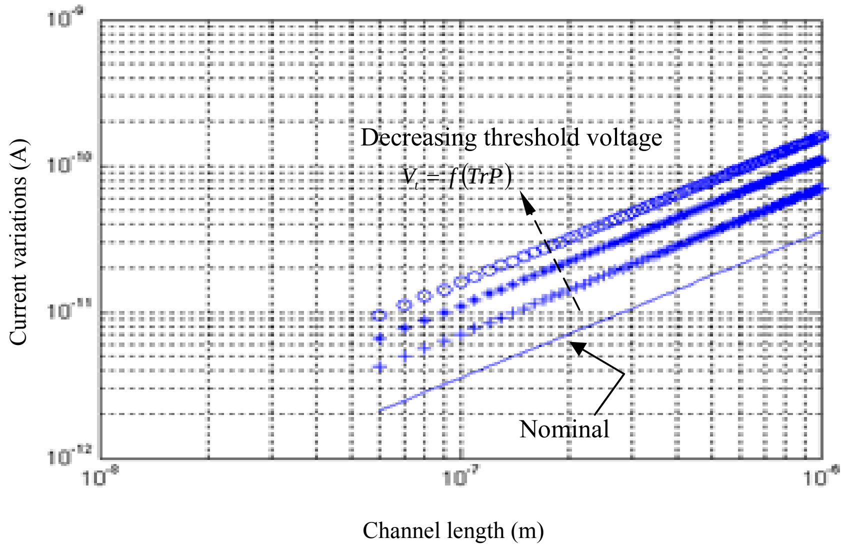

Figure 4 Current variations under varying threshold voltage and W/L [14].

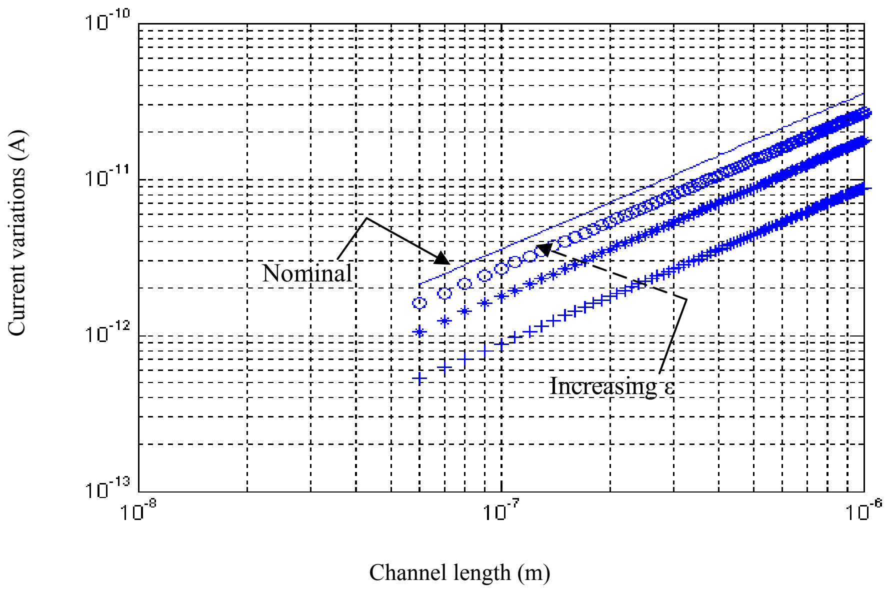

Figure 5. Current variations under varying ε and W/L [14]

Figure 4 shows a plot of the current variation as a function of the channel length, under varying threshold voltages. The responses are linear with a constant gradient of ≈ 0.02 nA (↑) per micro-metre. Figure 5 shows a plot of the current variation as a function of the channel length, under varying dielectric coefficients. The obtained responses are linear with a constant gradient of ≈ 0.02 nA (↓) per micro-metre.

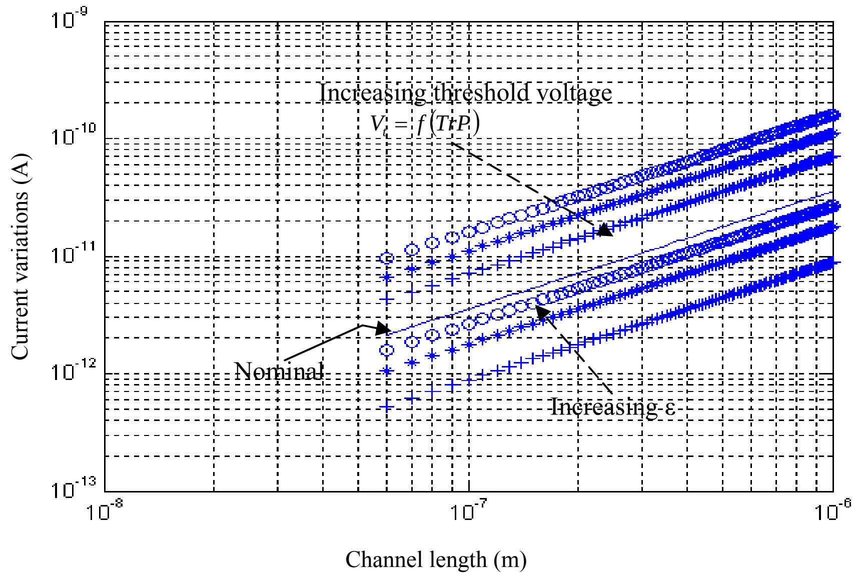

Figure 6. Current variations under varying threshold voltage, ε, and W/L.

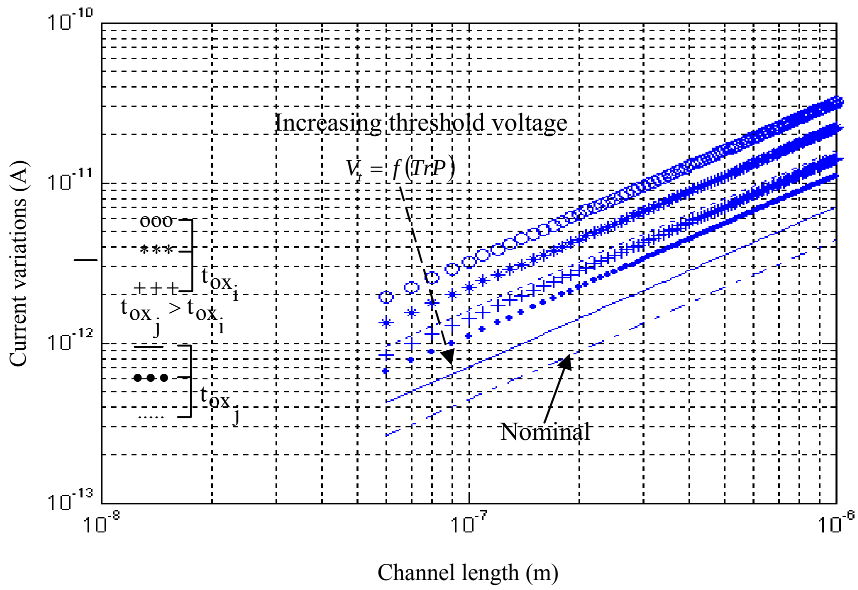

Figure 7. Current variations under varying t_{ox}, threshold voltage and W/L.

Figure 5 shows a plot of the current variation as a function of the channel length, under varying dielectric coefficients. The obtained responses are linear with a constant gradient of ≈ 0.02 nA (↓) per micro-metre.

A similar examination of Figure 6 would reveal the following: (i) the deviation from the nominal response (caused by radiation) would be brought to a minimum by increasing the threshold voltage, and also by increasing the dielectric constant; (ii) combining the above two increases would yield a further reduction in the deviation from the nominal response.

A decrease in the thickness of the oxide layer (i.e. gate insulator) would also yield a reduction in the deviation from the nominal response, as shown in Figure 7. The small variations in current responses – as a result of variations in the above factors - may be considered of little consequence. However, as devices are scaled down, these variations cannot be ignored.

Illustration 2: For a MOSFET transistor, consider the parameter $\left(V_{GS} - V_t\right)^2$. From (32):

$$\frac{P_h(h,z,t)}{P_{h,min}} = \frac{1}{\delta_c}\left(\kappa^2 + \kappa^{-2}\right)\Bigg|_{\kappa=\left((V_{GS}-V_t)/(V_{GS}-V_t)_{min}\right)} \tag{43}$$

Differentiating (43) with respect to κ

$$\frac{\partial P_h(h,z,t)}{\partial\left((V_{GS}-V_t)/(V_{GS}-V_t)_{min}\right)} = P_{h,min}\left(\frac{\left(\dfrac{V_{GS}-V_t}{(V_{GS}-V)_{min}}\right)^4 - 1}{\left(\dfrac{V_{GS}-V_t}{(V_{GS}-V)_{min}}\right)^3}\right) \tag{44}$$

Manipulating (43) and (44), and rearranging

$$\frac{\partial P_h(h,z,t)}{P_h(h,z,t)} = \gamma_j \frac{\partial((V_{GS}-V_t))}{(V_{GS}-V_t)}\Bigg|_{\gamma_j=\delta_c\left(\frac{\left(\frac{V_{GS}-V_t}{(V_{GS}-V)_{min}}\right)^4-1}{\left(\frac{V_{GS}-V_t}{(V_{GS}-V)_{min}}\right)^4+1}\right)} \tag{45}$$

Equation (45) shows that the rate of change of a given parameter and that of the performance – thus the rate of change in the radiation – are equal to within a multiplicative constant.

Depending on the nature and the degree of effect of parameters, a system may or may not exhibit a noticeable change in performance. Therefore, it is desirable to consider a reference threshold – such as $s^n_{i,min}$ that yields satisfactorily operation under uncertainty. Determining the variable $s^n_{i,min}$ assists in synthesising the degree of effect of parameter fluctuations on the performance of a system. Example: Consider a transistorized closed-loop control system as show in Figure 8.

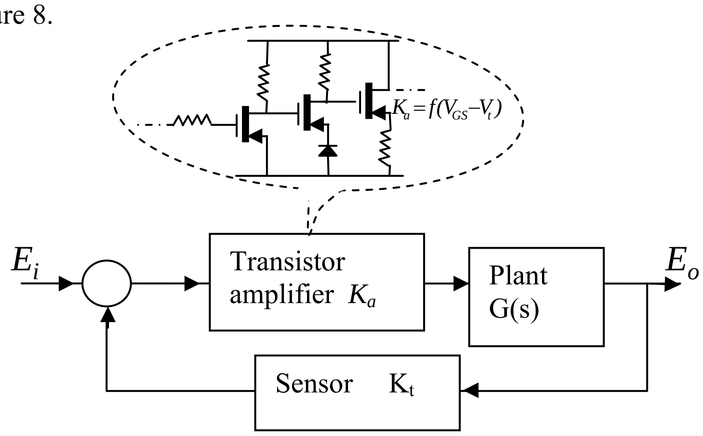

Figure 8. Transistorised closed-loop system

For the system in Figure 8

$$\frac{\partial P(h,z,t)}{\partial K_a} = P^{\sim} = \frac{s}{s^2 + \left[K_a^{-2} + 2K_a^{-2}\right]s + K_a^2}\Bigg|_{K_a=f(V_{GS}-V_t);G(s)=1/s+1;K_t=I;(V_{GS}-V_t)=f(TrP)} \tag{46}$$

The simulation results for (46) are shown in Figure 9.

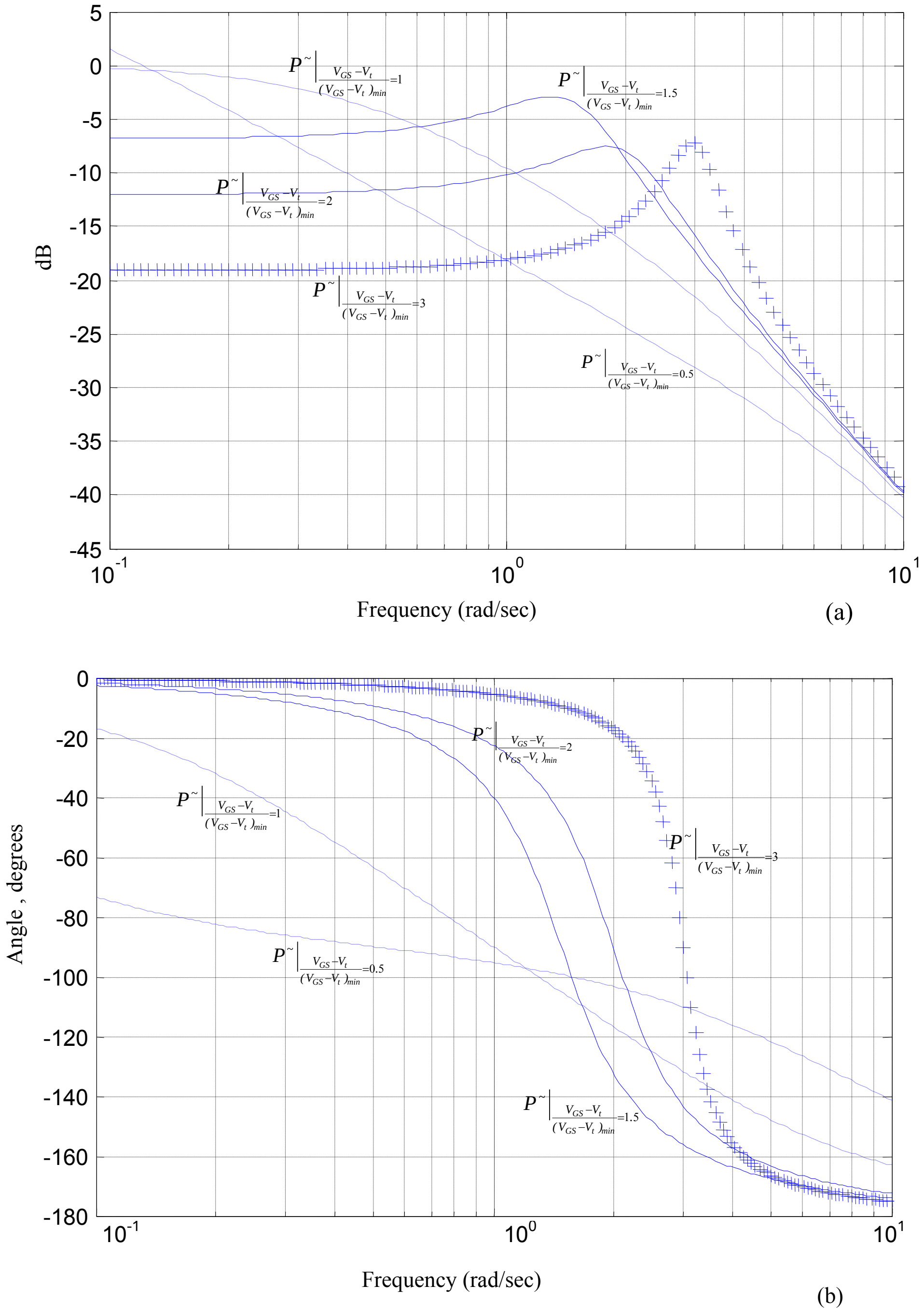

Figure 9. (a) The phase-response under parameter fluctuations;
(b) The gain-response under parameter fluctuations.

From Figure 9, the effect of changes in parameters (as a function of changes in radiation) yields different responses – in the frequency domain. This information is useful for verification and also for real-time testing of EC performance. For given parameter-fluctuations, if an EC exhibits a noticeable deviation from the nominal performance, then the design rules have to be re-visited and updated for better EC performance.

4. Conclusion

The success of planned operations – *e.g.* for characterization and tracking objects in space - will depend on the performance of the electronic systems employed. However, space-born electronic systems are vulnerable to space radiation that may inflict damages ranging from minor performance deterioration to catastrophic system failure. The presented analytical expressions showed that scaling technologies can go some way to minimizing the radiation-induced effects.

The analytical expressions encompass a number of parameters, which are of spatial and temporal nature. In addition to their ability to estimate the expected responses of an EC to radiation-induced changes, these expressions also provide a means of testing electronic components as well as assessing their performance - *e.g.* the extent to which changes in traps (as a function of radiation) affect behaviour. The analytical expressions could be realized as an electrical circuit for investigating the effect of radiation on space born electronic systems. This is desirable for many reasons, but mainly because assessing the performance and testing real systems may be costly or impractical – thus leading to cost effective approach to reduce risk both in the design and operation of integrated electronic components.

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