Simulating CMOS Circuits Containing Multiple FET types Including the Geometric Dependence of correlation among different FET types

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ABSTRACT

Advanced CMOS technologies offer a variety of active and passive devices to meet the complex and stringent demand of current circuit design market. For MOSTFET, different threshold FETs such as high (HVT), regular (RVT) and low (LVT) threshold voltages are often available for a designer to optimize the performance and power consumption of a circuit by selection of the appropriate device type.

However, this multiple device offering increases the complexity of device fabrication and wafer processing cost. To make the process simpler and more controllable, some processes are shared among different FETs and passives, which led to "interesting" device to device correlation with geometry dependency. For example, FET characteristics such as threshold voltage, current and capacitance can be strongly correlated between device types in spite of uncontrollable variables such as random dopant fluctuation, which are dominant factors for uncorrelated variation to all FETs. Therefore, a unique correlation in a circuit performance within a die can be observed. Faster ring oscillator delay can be found in both RVT and HVT oscillators within a chip and vice versa.

Previous work used principle component analysis to capture this partial correlation mathematically [1] but only addressed minimum length devices. In this paper, the device to device correlations are analyzed in terms of the physical sources for common and independent variation as a function of geometry dependence and the correlations are captured in compact models using BSIM. These models can yield wider circuit design window regardless of the device geometries used compared to previous compact models.

Keywords: correlated coefficient, device correlation, geometrical dependency, compact modeling.

1 INTRODUCTION

A variety of devices are available within a recent CMOS technology. Often different threshold MOSFETs such as high, regular and low threshold, are processed together and available for a designer's choice. Nonetheless, these varieties increase the complexity and the cost of processing. Therefore processing simplification became important to reduce the complexity and the manufacturing cost and time.

However, this shared processing flow introduces unique processing variation couplings among devices, which can be found in electrical characteristics of devices. One good example is gate-poly control, which affects not only MOSFETs but also any device with a poly gate such as MOSVAR in a similar manner. If poly-gate process variation becomes negative or positive, the some electrical characteristics of MOSFETs and MOSVAR will simultaneously response to this variation change. In the end, a circuit with many correlated devices will exhibit a certain statistical trend. In order to correctly reflect the trend, statistically correlated compact models are needed. Model implementation with correlated characteristics while preserving individual self variation can be a challenged, especially if there are many factors or sources of correlation contribution and large number of devices. In addition, geometrical dependency of the correlation can add more burdens for statistical modeling. In this paper, we will discuss about how to simplify this problem using correlate coefficient and how to implement statistically correlated compact models.

2 FET CORRELATIONS

First of all, it is important to identify which physical factors are main causes of the electrical correlations and afterwards, the implementation of these correlations can be simplified and applied for compact modeling.

2.1 Poly gate and gate oxide correlations

Poly gate length and gate oxide thickness are by far most basic and important factors affecting device correlations. Especially as the critical dimension of device becomes smaller, variations from gate length becomes more dominant factors for correlations as well as self device variations. Obviously all NFETs are sharing same gate length variations as long as they are products of same litho-process and this also can be valid between NFET and PFET depending on the line process.

Figure 1 shows normalized poly gate length variations for NFET and PFET within a die and the correlations are strong. Another strong correlation can be found in gate oxide variations for same type of FETs. Figure 2 shows the strong correlation for gate oxide as well. Although figures doesn't consider different geometries but it is well known that the correlations are pretty much similar for different gate lengths. Therefore, these highly correlated factors can be easily correlated by setting CC. at one or close to one.

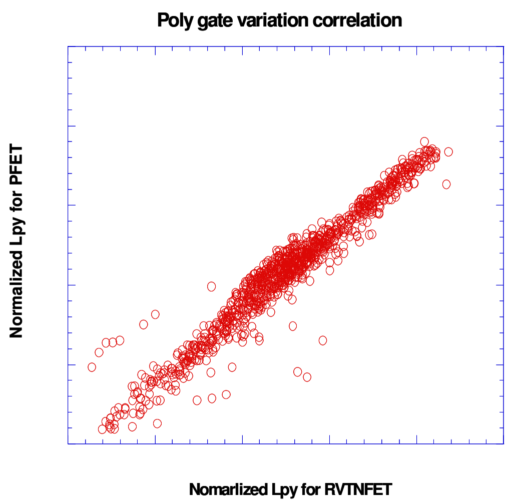


Figure 1. The gate length variations between RVT NFET and RVT PFET

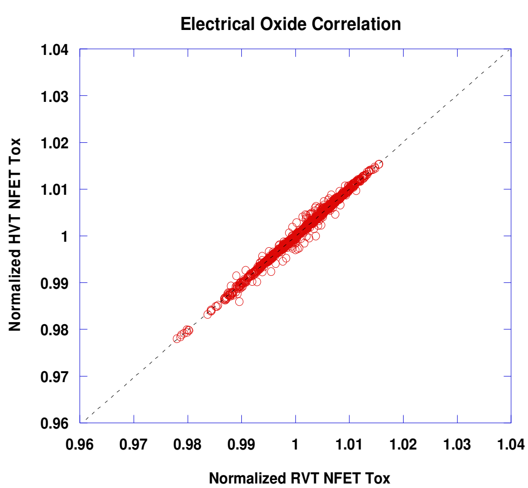


Figure 2. Gate oxide variations between RVT and HVT Nfets.

2.2 Threshold voltage and Current correlations

For recent technologies, halo implant is an essential part of device processing to reduce short channel effect and punch-through as the device scaled down into deep sub-nanometer. In addition to halo implant, threshold channel implant can be used to differentiate threshold of devices. For example, lower implant dose is given to low threshold device in respect to a regular threshold MOSFET. Therefore, at a given device, total effect threshold of device can be simply approximated as

$$V_{th} \approx V_{th\_halo} + V_{th\_chan} \qquad (1)$$

, where V_{th_halo} and V_{th_chan} are for halo implant and threshold tailor implant respectively.

One possible scenario is that channel implants (Vth_chan) are processed independently with different dose and energy for different devices while halo implant is processed in a common process during the multi-FET process. Since Vth_halo is shared by different threshold devices, the halo implant affects the devices in similar manner. This relationship entails the electrical correlation which is stronger as channel length devices get shorter. Figure 3 shows the strong threshold correlations for short channel device and geometrical dependent CC coefficients.

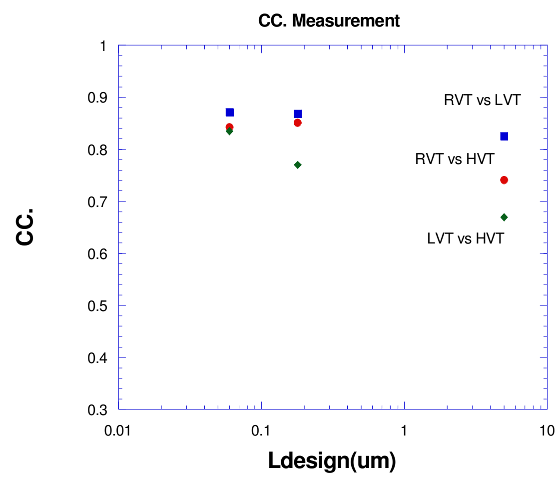


Figure 4 Linear threshold voltage correlated coefficient (CC) vs different channel length for HVT, LVT and RVT.

For current wise, we observed similar behaviors from correlation as well. Interestingly, the current correlations are stronger than threshold voltage correlations.

Total current variations can be described as

$$\partial I_{DS\_total} \approx f(\partial V_{th\_total}, \partial I_{DS\_tox}, \partial I_{DS\_poly}, \partial I_{DS\_rds}, \partial I_{DS\_mob}) \qquad (2)$$

where, ∂V_{th_total} , ∂I_{DS_tox} , $\partial I_{DS\_poly,}$, $\partial I_{DS\_rds,} \partial I_{DS\_mob}$ are for variations from threshold, oxide, gate ploy, source-drain series resistance and mobility variations respectively. Since ∂V_{th_total} , ∂I_{DS_tox} , $\partial I_{DS\_poly,}$, ∂I_{DS_rds} components are strongly correlated due to processing flow as we discussed previously, one can easily deduce that variations from mobility are also highly correlated among devices. Additional mobility correlations can increase current correlated coefficient as show in Fig. 5. This additional correlation can be explained by the relationship between effective mobility and halo implants [3]. Effective mobility (μ_{eff}) is known to be related to coulomb scattering (μ_{coul}), phonon scattering (μ_{ph}) and surface roughness scattering (μ_{surf}).

As halo implant is the important factor for threshold correlation, it contributes the mobility correlation by affecting coulomb scattering and phonon scattering. Therefore higher current correlations are contributed by the fact that any variations in halo implant affect the mobility variations.

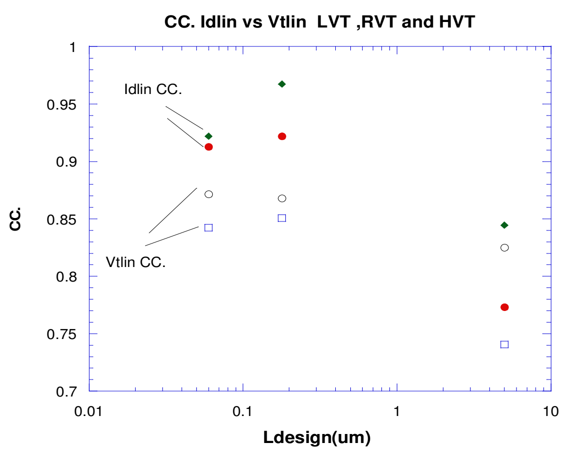


Figure 5, Current and voltage correlation coefficient.

2.3 Correlated Coefficient

We can quantitatively define any relationship between two variables X and Y using correlated coefficient in Eq. 1.

$$CorrCoeff(X,Y) = C.C = \frac{Cov(X,Y)}{\sqrt{\sigma(X)^2\sigma(Y)^2}} \qquad (3)$$

$$C.C \;\; can\ be\ -1 \le C.C \le 1$$

where Cov is covariance between X and Y. $\sigma(X)$ and $\sigma(Y)$ are an individual variances of X and Y respectively.

Based upon Eq. 1, we can also derive the new equation which can reflect the correction between two different devices in Eq. 2. It shows that the self variations of two variables from two devices and correlation are well preserved using correlated coefficient (CC).

$$\begin{aligned} &Vth0_{rvt} = gaussian_{rvt} \\ &Vth0_{hvt} = (gaussian_{rvt} + \sqrt{\left(\frac{1}{CC}\right)^2 - 1} \times gaussian_{hvt}) \times \delta Vth0_{hvt} \times fnorm \\ &fnorm = CC \end{aligned} \qquad (3)$$

Eq. 2 is formulated for BSIM parameter vth0, which we will discuss it in later part of the paper. However this equation can be applied to other parameters in the same manner. Although this equation is for two devices, it can also be used for multiple devices as long as the correlations among devices are strong. For example, 3x3 matrix requires to capture the threshold and current correlation correctly for three HVT, RVT and LVT devices in Eq. 3.

$$\begin{bmatrix} \partial Vth_{rvt\_total} \\ \partial Vth_{hvt\_total} \\ \partial Vth_{lvt\_total} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \cdot \begin{bmatrix} \partial Vth_{rvt} \\ \partial Vth_{hvt} \\ \partial Vth_{lvt} \end{bmatrix} \qquad (4)$$

However, using a multi-dimensional matrix will significantly increase the complexity of compact models and makes it cumbersome to take geometrical dependency into account. The implementation can be mathematically simplified by using a correlated coefficient with an assumption. The assumption is that since the correlation coefficient is a relative concept for two variables and the correlation is strong, the matrix can be simplified and rewritten in the respect to one device point of view such as RVT for an example in Eq. 4.

$$\begin{aligned} &\begin{bmatrix} \partial Vth_{rvt\_total} \\ \partial Vth_{hvt\_total} \\ \partial Vth_{lvt\_total} \end{bmatrix} = \begin{bmatrix} C_{11} & 0 & 0 \\ C_{21} & C_{22} & 0 \\ C_{31} & 0 & C_{33} \end{bmatrix} \cdot \begin{bmatrix} \partial Vth_{rvt} \\ \partial Vth_{hvt} \\ \partial Vth_{lvt} \end{bmatrix} \\ &\partial Vth_{rvt\_total} \approx C_{11} \times \partial Vth_{rvt} \\ &\partial Vth_{hvt\_total} \approx C_{21} \times \partial Vth_{rvt} + C_{22} \times \partial Vth_{hvt} \\ &\partial Vth_{lvt\_total} \approx C_{31} \times \partial Vth_{rvt} + C_{33} \times \partial Vth_{lvt} \end{aligned} \qquad (5)$$

2.4 Correlated Compact Model

After identifying key process components, which can affect the device correlation, the correlated coefficient based can be placed within sub-circuit of each model. Since CC can be easily expressed in terms of geometry, the model can exhibit channel length dependency as shown in Figure 6. One can observe that the model prediction starts to deviate from measurement as CC gets smaller, which is due to our basic assumption used to simplify the matrix form. However, it shows an excellent match over shorter channel length.

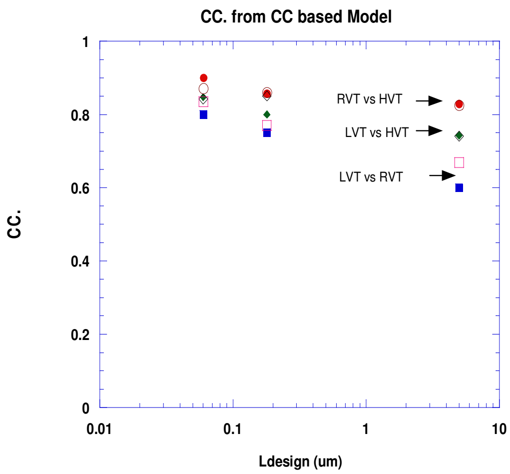


Figure 6 Threshold Voltage correlations among different type of FETs. Filled and empty marks are for models and measurement respectively.

For current variations and correlation wise, Figure 7 shows that model matched the self variance and correlation of current data very well.

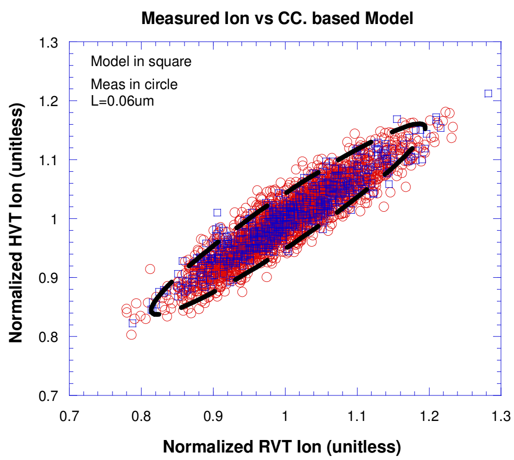
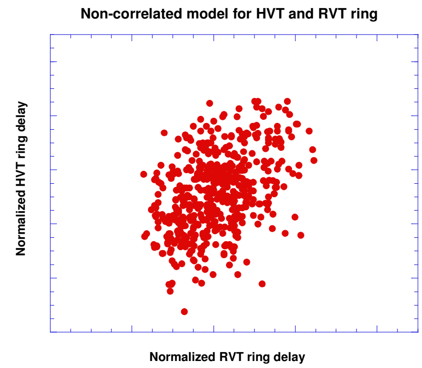
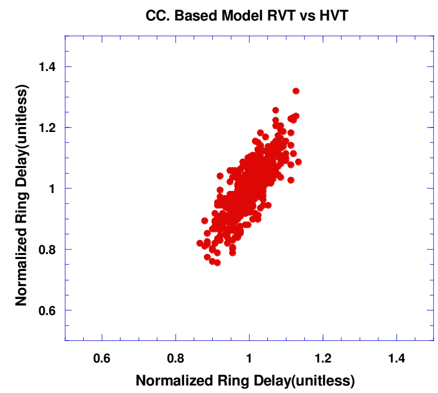


Figure 7 Current variations between HVT and RVT NFETs.

Not only the geometry dependent information is preserved but also it shows the correlated circuit simulation behavior as well. As it is expected, in figure 8, the geometrical dependent correlated model can deliver different correlation amount in circuit behaviors depends on the channel length which cannot be found in other uncorrelated models nor in non-geometrical dependent models.



(a)



(b)

Figure 8 (a) Ring delays with wide channel length device. (b) Ring delays with short (critical) channel length device.

3 SUMMARY

In this paper, we discussed how to capture any geometrical dependent correlations among different type of devices in a simplified manner using correlation coefficient into the compact model and demonstrated that the good results can easily be achieved on current and voltage correlations over different geometries and also circuit performance.

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