Parametric Variations of Transistor Doping Profiles for Ultra Low Power Applications

Xhino M. Domi [1], Emadelden Fouad [2], Muhammad S. Ullah [*3]

[1]Student, Department of Electrical and Computer Engineering, Florida Polytechnic University, Lakeland, Florida, 33805, USA

[2]Instructor, Department. of Natural Science, Florida Polytechnic University, Lakeland, Florida, 33805, USA
[3]Assistant Professor, Dept. of Electrical and Computer Engineering, Florida Polytechnic University, Lakeland, Florida, 33805, USA

Abstract

The VLSI industry is facing the significant parasitic effects that creates a serious problem for further development in the nanoscale domain. However, instead of replacing the traditional MOSFET design, it would be more advantageous to apply different doping profiles for ultra-low power applications. With a comprehensive review of Gaussian doping, Uniform doping, and Delta doping profiles and analysis of the FET technology characteristics that use these doping profiles, a comparison can be made among them for integrated circuit design engineers. These doping profiles are compared based on how well they perform between non-ideal and ideal environments. Also, both digital and analog performance parameters are measured to ensure the uniqueness of each doping profile. After getting a list of benefits from each doping profile that is presented in this paper, it is concluded to determine which doping profile works best against a host of parasitic effects. Finally, this paper also conclude that what type of possible applications do these doping profiles.

Keywords: *Subthreshold Swing, Uniform Doping, Gaussian Doping, Delta doping, and Ultra Low Power.*

I. INTRODUCTION

In today's VLSI industry, there are dozens of doping profiles with different application, different chemical compositions, and different physical characteristics [1, 3, 5, 7, 8, 9, 12, 14, 15]. This is mainly because of smaller transistors sizes which has the more non-ideal characteristics. These characteristics appear the results in terms of performance issues, power consumption problems, and temperature dependencies which hindering the transistor efficiency [1]. With the current technology in place, engineers must use what they can and minimize major changes to ensure that these problems are tackled but won't drastically change the market and keep up with the standards in place for optimization of transistor performance.

In the circuit and logic levels, most of the problems can only be optimized, but not eliminated [2]. Therefore, the issues must be addressed in the transistor level where chemical makeup and transistor design can be modified to fix or at least minimize parasitic effects as much as possible. There is still an issue with working in the transistor level. A complete remodelling of the transistor can be costly as it will affect all levels above the transistor level and there are many physical limitations that are difficult to overcome. The potential possible modifications could be transistor doping profile, doping technique, gate modification, and drain to source channelling effects and so on. Out of all of those, doping profile is one of the more easily modifiable as it changes the chemical makeup of the transistor. In the different chemical makeups, there are significant changes in non-ideal effects. Concentrating on doping profiles is also relatively cheap and does not overhaul the idea of FET technology [3].

Therefore, it's important to help distinguish which type of doping profiles can be used when designing a transistor down to its physical properties; especially because new designs and manufacturing techniques help with non-ideal effects for smaller transistor sizes. Separating doping profiles by which parasitic effect they can minimize the best can help establish what application they can be used for and help with deciding which to include in the design.

The objective is to identify when doping profiles can be applied to best maximize its efficiency at a task or to help minimize non-ideal parasitic effects in a transistor. The chosen doping profiles are Uniform doping, Gaussian doping, and Delta doping. Uniform doping is being the conventional doping profile that can been seen in many bulk transistors today. On the other hand, Gaussian is doing a complex mathematical model of how to dope source and drain on a FET technology. Besides, delta doping is being like uniform in design, but includes a lightly dope delta layer underneath the source and drain of the transistor. A representation of

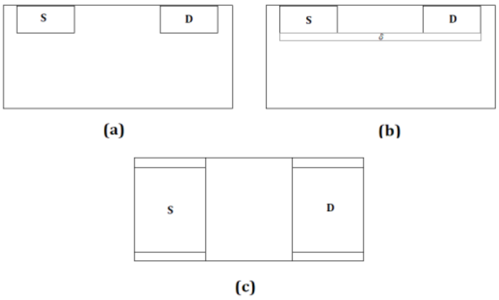

Figure 1. Representation of each individual doping profiles. (a) Uniform doping profile, (b) delta doping profile, and (c) Gaussian doping profile.

each doping profile can be found in [15]. The transistor characteristics of each doping profile will be analysed to determine what aspects the doping profile best performs in terms of I-V Characteristics with respect to V_{GS} and V_{DS}, and temperature dependence. This should reduce decision making from a design perspective as it eliminates the need to evaluate when a doping profile can be used or when it could be effective to use a doping profile in a circuit. Furthermore, there will be analysis on how those doping profiles perform for analog and digital applications to ensure that each doping profile has at least one unique application or performs more efficiently than the rest in one area. Most of the data involving analog applications will derive from the characteristics and known mathematical models. The type of analog data presented will be based on what can be most easily derived from each of the doping profile calculations.

II. PREVIOUS RESEARCH WORK ON DOPING PROFILES

In 1989, a paper "Ideal FET Doping Profile" was published by V. A. K. Temple who describing how each MOSFET voltage and geometric topology which has an ideal drain region that yields the optimum resistance and breakdown voltage [1]. This was a time where doping profiles were still in experimentation stages and there were debates on to measure doping profiles and how to find the most effective in terms of resistance. Shortly after in 1982, short-circuit dissipation of static CMOS circuitry and its impact on the design of buffer circuits were elaborated on a short circuit formula for simple calculations [2]. The summary of mathematical model is shown in Table 1. Following that in 1991, David W. Feldbaumer and Dieter K. Schroder happened upon a discovery in which instead of using C-V measurements for determine doping profile effective, they instead opted for threshold voltage and substrate calculations [3]. During their discovery, they notice that small channel devices had a non-ideal effect that was not yet known at the time and concluded with small channels that had unpredictable and skewed results.

Not to long after that, P. G. Young, R. A. Mena, S. A. Alterovitz, S. E. Schacham and E. J. Haugland in 1992, all had an interesting of how delta doping a quantum well actually makes the well temperature independent [4]. Then in 1996, a paper on different MOSFET doping profiles were compared based of their threshold voltage, delay time, and device parameters called "A Comparative Study of Advanced MOSFET Concepts" was published [5]. Equation 4 and Equation 6 are derived in [5]. This paper admit the value of non-ideal delta doping threshold that would be in between the ideal uniform doping and the ideal delta doping. There was only one constant that needed to be changed and that was averaged into 4.5 for non-ideal representation as seen in Eq. 6. Fast forward to 2011, Wolpert, David, and Paul Ampadu have documented a paper about how temperature affects semiconductors [6]. This paper is mainly as a reference point to ensure that there is a good correlation between the simulation and theory.

Then, in 2013, an Analytical Modeling of a Double Gate MOSFET Considering Source/Drain Lateral Gaussian Doping Profile had defined a Gaussian threshold equation for the process [7]. This paper provides Eq. 6 and is not modified due to its complex nature. Following that on 2013 and 2014, two similar papers, "Optical Effects on the Characteristics of GaAs Nanoscale FinFET with Vertical Gaussian Doping Profile" [8] and "Optical Effects on the Characteristics of a Nanoscale SOI MOSFET with Uniform Doping Profile" [9], were published to display the capabilities of uniform doping and Gaussian doping when it comes to optics. These papers show that uniform doping does perform admirably, but Gaussian proves to be much more effective.

The 2015 marked a time where delta doping was used in Mohanty, S.S.'s paper and four different variations of delta doped transistors [10]. All of them showing promising high frequency cut-offs. On year later, both Conductivity Enhancement in Organic Electronics by Delta Doping [11] and Improved Cut-off Frequency for Cylindrical Gate TFET Using Source Delta Doping [12] further emphasizes on how delta doping is a great conductor and a high cutoff frequency. One focused on how in an organic electronic the doping profile improves performance, while the other emphasizes on how delta doping profiled transistors have high cut off frequencies. Following that, Sood, Himangi created a paper [13] where uniform and Gaussian doping profiles were used to see how viable this new cylindrical MOSFET model. It was observed that Gaussian did outperform uniform in low power consumption application. Soon afterwards, Subthreshold Current and Swing Modeling of Gate Underlap DG MOSFETs with a Source/Drain Lateral Gaussian Doping Profile [14] created a mathematical model to optimize Gaussian profile subthreshold current and swing. Finally, Comprehensive doping scheme for MOSFETs in ultra-Low-Power subthreshold circuits design [15] in 2017 discusses how

TABLE I
RELATED MODELS FOR DIFFERENT PROCESS AND PARAMETRIC VARIATIONS FOR DIGITAL APPLICATIONS

Model Name	Model	Reference
Drain Current in threshold	$I_{DS} = I_{ds0} e^{\frac{V_{GS}-V_{th}}{nv_T}} (1 - e^{\frac{-V_{DS}}{v_T}}) (1 + \lambda V_{DS})$	[2]
Subthreshold current	$I_{ds0} = \beta v_T^2 e^{1.8}$	[2]
Drain Current in Saturation	$I_D = \frac{K}{2} (V_{GS} - V_{th})^2 (1 + \lambda V_{DS})$	[2]
Threshold voltage for Uniform Doping	$V_{thu} = V_{FB} + 2\Phi_f + 6(2\Phi_f + V_{SB}) \frac{t_{ox}}{x_{bg}}$	[4]
Threshold Voltage for Gaussian Doping	$V_{thg} = V_{FB} + 2\Phi_f - c_{1max} e^{\frac{-x_{min}}{\lambda}} - c_{2max} e^{\frac{x_{min}}{\lambda}} + \frac{\lambda^2 q (N_A^- - N_{SD}^+(x_{min}))}{\varepsilon_{si}}$	[6]
Threshold Voltage for Delta Doping	$V_{thd} = V_{FB} + 2\Phi_f + 4.5(2\Phi_f + V_{SB}) \frac{t_{ox}}{x_{bg}}$	[10]

TABLE II
RELATED MODELS FOR DIFFERENT PROCESS AND PARAMETRIC VARIATIONS FOR ANALOG APPLICATIONS

Model Name	Model	Reference
Transconductance	$g_m = K(V_{GS} - V_{th})$	[11], [16]
Output Resistance	$R_0 = \frac{1}{g_m}$	[11], [16]

different doping profiles handle subthreshold results and was a point of comparison for the paper.

III. METHODOLOGY

MATLAB will serve as a major component to analyze the data from the previous works and obtain data points for drain voltage (VDS), gate voltage (VGS), drain current (ID), and temperature (T). First a set of data will be an I-V characteristics graph with ID and VDS, the second will be an I-V characteristics graph with a logarithmic ID and VGS, third T vs ID graph, fourth a look at threshold voltage (Vth) vs oxide thickness (tox), fifth a Vth vs doping density (NA) graph, and finally a Vth vs intrinsic doping (ni) graph to conclude. All of this can be observed in Figure 2.

After, transconductance and output resistance will be calculated based of the results of each doping profile and the individual reports on the doping profiles seen in the referenced research papers. Then, they will be compared to one another similarly to before. Once all that is done, a table will list out and highlight which doping profile performed the best at dealing with a certain non-ideal effect or what type of application they most fit in. Related models to calculate drain current, threshold voltage with different process and parametric variations for digital applications are shown in Table 1 while transconductance and output resistance for analog application are shown in Table 2.

IV. SIMULATION RESULTS AND ANALYSIS

With the simulation in hand, as seen in Figure 2 (a-f), subthreshold swing and temperature have a similar pattern because of the dependency of the chemical makeup of the doping profiles consisting of only silicon and silicon dioxide. Therefore, the analysis on those categories means very little for doping profiles. Note that Gaussian doping has a mismatch after reaching past threshold, this is not indicative of any oddities, only a mathematical mismatch.

As for how V_{th} is affected by intrinsic concentration, carrier density, and oxide thickness, then we see a clear divide. Gaussian in all three respects follows a trend in which a small change in any of the three does not affect the threshold value, instead large ratio differences will. While, uniform and delta being so similar because of their Vth calculations, but delta doping having a lower threshold voltage every time because of the small sheet layer resulting it to be less effected by all the other variables.

Transconductance and output resistance shows a similar pattern to temperature dependency and subthreshold swing, in which the dependency is based on the chemical makeup of the device and not how the transistor is doped.

Yet, there is a clear application difference between them all. The first, being uniform performing the worst in every category, but has the advantage of being the cheapest method available and the most simplistic. Then follows delta doping, which does what uniform aims to accomplish but better in many regards thanks to extra doping layer underneath. Delta doping also plays a big role for RF integration because of its of how it allows for higher cut-off frequencies. Finally,

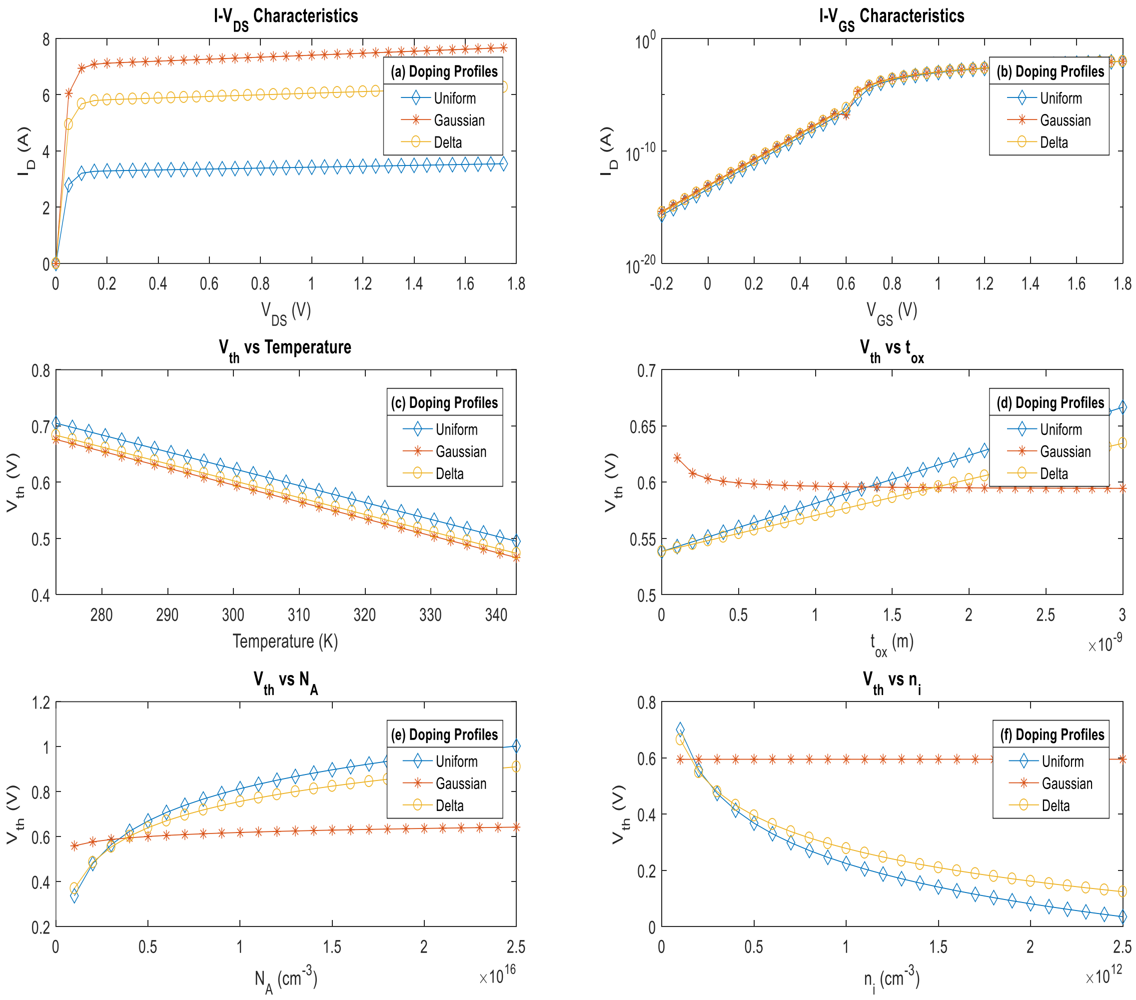

Figure 2. Effect of process and parametric variations on uniform, Gaussian and delta doping profiles. Characteristics of (a) I-V with linear scale; (b) I-V with logarithmic scale; (c) Threshold voltage (V_{th}) with temperature (K); (d) Threshold voltage (V_{th}) with oxide thickness (t_{ox}); (e) Threshold voltage (V_{th}) with doping density (N_A); and (f) threshold voltage (V_{th}) with intrinsic carriers (n_i).

TABLE III
DOPING PROFILE CHARACTERISTICS OF MOSFET

Doping Profile	**Threshold Voltage** $V_{th}(V)$	**Subthreshold Swing** $SS\left(\frac{mV}{dec}\right)$	**Transconductance** G_m (℧)	**Output Resistance** $R_0(\Omega)$	**Comments**
Uniform Doping	0.56	~60	0.00389	257	Cheaper, easy to manufacture, and simplistic.
Gaussian Doping	0.59	60	0.00366	273	Great SS, better than most I_{ON}/I_{OFF} ratios, and lower power consumption.
Delta Doping	0.55	~60	0.00392	255	Higher cutoff frequencies, higher transconductance, and allows quantum wells to become independent of temperature

Gaussian has been shown to be much more effective at dealing with subthreshold swing, I_{ON} /I_{OFF}, and power consumption compared to delta and uniform because of its complex mathematics that maximizes the efficiency of the source and drain wells. Table III has shown the results with calculations.

V. CONCLUSION

The investigation of this paper acts as a beginner's guide to help identify ideal and non-ideal effects of uniform, delta, and Gaussian doping profiles. Then a discussion on what applications these doping profiles are used for in the industry to further differentiate between them. Results have showcased that although doping profiles can influence non-ideal characteristics, the chemical makeup of the device plays a much more important role in that regard. Therefore, a further study on the physical characteristics of each doping method needs to be made to further understand the differences between them all.

REFERENCES

[1] V. A. K. Temple, "Ideal FET doping profile," in IEEE Transactions on Electron Devices, vol. 30, no. 6, pp. 619-626, June 1983. doi: 10.1109/T-ED.1983.21180.

[2] H. J. M. Veendrick, "Short-circuit dissipation of static CMOS circuitry and its impact on the design of buffer circuits," in IEEE Journal of Solid-State Circuits, vol. 19, no. 4, pp. 468-473, Aug 1984. doi: 10.1109/JSSC.1984.1052168.

[3] D. W. Feldbaumer and D. K. Schroder, "MOSFET doping profiling," in IEEE Transactions on Electron Devices, vol. 38, no. 1, pp. 135-140, Jan 1991. doi: 10.1109/16.65747.

[4] P. G. Young, R. A. Mena, S. A. Alterovitz, S. E. Schacham and E. J. Haugland, "Temperature independent quantum well FET with delta channel doping," in Electronics Letters, vol. 28, no. 14, pp. 1352-1354, 2 July 1992. doi: 10.1049/el:19920858.

[5] C. H. Wann, K. Noda, T. Tanaka, M. Yoshida and Chenming Hu, "A comparative study of advanced MOSFET concepts," in IEEE Transactions on Electron Devices, vol. 43, no. 10, pp. 1742-1753, Oct 1996. doi: 10.1109/16.536820

[6] Wolpert, David, and Paul Ampadu. "Temperature Effects in Semiconductors." Managing Temperature Effects in Nanoscale Adaptive Systems, 2011, pp. 15–33., doi:10.1007/978-1-4614-0748-5_2.

[7] A. Nandi, A. K. Saxena and S. Dasgupta, "Analytical Modeling of a Double Gate MOSFET Considering Source/Drain Lateral Gaussian Doping Profile," in IEEE Transactions on Electron Devices, vol. 60, no. 11, pp. 3705-3709, Nov. 2013. doi: 10.1109/TED.2013.2282632.

[8] Ramesh, R., et al. "Optical Effects on the Characteristics of GaAs Nanoscale FinFET with Vertical Gaussian Doping Profile." Optik - International Journal for Light and Electron Optics, vol. 124, no. 19, 2013, pp. 4019–4025., doi: 10.1016/j.ijleo.2013.02.007.

[9] Gowri, K., and V. Rajamani. "Optical Effects on the Characteristics of a Nanoscale SOI MOSFET with Uniform Doping Profile." Optik - International Journal for Light and Electron Optics, vol. 125, no. 13, 2014, pp. 3195–3200., doi: 10.1016/j.ijleo.2014.01.025.

[10] Mohanty, S.s., et al. "Effect of Delta Doping on the RF Performance of Nano-Scale Dual Material MOSFET." Procedia Computer Science, vol. 57, 2015, pp. 282–287., doi: 10.1016/j.procs.2015.07.485

[11] X. A. Cao, X. M. Li, S. Li and L. Y. Liu, "Conductivity Enhancement in Organic Electronics by Delta Doping," in IEEE Electron Device Letters, vol. 37, no. 12, pp. 1628-1631, Dec. 2016. doi: 10.1109/LED.2016.2620184

[12] Dash, Sidhartha, et al. "Improved Cut-off Frequency for Cylindrical Gate TFET Using Source Delta Doping." Procedia Technology, vol. 25, 2016, pp. 450–455., doi: 10.1016/j.protcy.2016.08.131.

[13] Sood, Himangi, et al. "Performance Analysis of Undoped and Gaussian Doped Cylindrical Surrounding-Gate MOSFET with Its Small Signal Modeling." Microelectronics Journal, vol. 57, 2016, pp. 66–75., doi: 10.1016/j.mejo.2016.10.001

[14] Singh, Kunal, et al. "Subthreshold Current and Swing Modeling of Gate Underlap DG MOSFETs with a Source/Drain Lateral Gaussian Doping Profile." Journal of Electronic Materials, vol. 46, no. 1, 2016, pp. 579–584., doi: 10.1007/s11664-016-4914-6

[15] Hossain, Munem, and Masud H. Chowdhury. "Comprehensive doping scheme for MOSFETs in ultra-Low-Power subthreshold circuits design." Microelectronics Journal, vol. 52, 2016, pp. 73–79., doi: 10.1016/j.mejo.2016.03.007

Xhino M. Domi received B.S. degree in in Computer Engineering from Florida Polytechnic University, Lakeland, FL, USA in 2018.He became a Student Member of IEEE in 2017. He was born in North Miami Beach, FL, USA, in 1996.From 2017-2018, he helped develop an educational tool for Florida Polytechnic University known as Experimental Education: design and Implementation of Nikola Tesla's Egg of Columbus as an Instruction Aid; the paper was later submitted to IEEE SoutheastCon 2018. Mr. Domi was a co-lead for the IEEE SoutheastCon 2018 mobile app and helped establish a precedence of volunteers working to create a mobile application for future IEEE Southeast section conferences. Currently, he is working as an associate engineer at Intel. His research interest include power aware design, VLSI design and digital signal processing.

Emadelden Fouad received his B. Sc and M. Sc degree with Theoretical Physics from Cairo University, Egypt in 1996 and 2001 respectively. Emadelden also finished his PhD with theoretical Nano device from Cairo University, Egypt in 2005. Previously he worked as a teaching assistant, and instructor with the department of Physics at Cairo University. Currently he is working as an assistant professor of physics with the department of natural science at Florida Polytechnic University. His research interest include but not limited to quantum transport characteristics of energy efficient devices, Electromagnetic properties of type II superconductors and emerging nanomaterials like graphene.

Muhammad S. Ullah received his M.S. and Ph.D. degrees in Electrical and Computer Engineering from Purdue University Northwest, IN, USA and University of Missouri-Kansas City, Kansas City, MO, USA in 2013 and 2016 respectively. Before that he received his B. S. degree in Electrical and Electronics Engineering from Chittagong University of Engineering and Technology, Bangladesh in 20018 and worked as Lecturer for 3 years. Currently, he is working as an assistant professor of electrical and computer engineering at Florida Polytechnic University. His research includes on modeling of energy efficient electronic devices particularly tunneling field effect transistor based on emerging 2D nano-materials for digital logic and ultra-low-power applications, high speed VLSI interconnect and modeling and higher order statistics and spectra in signal processing.