A Modified MODPEX Model for MOSFET and Parameter Optimization Using Excel-based Genetic Algorithm

Zhiyang Chen
Automotive & Power Group
ON Semiconductor
Phoenix AZ USA
Zhiyang.chen@onsemi.com

Richard Lindeman
Automotive & Power Group
ON Semiconductor
Phoenix AZ USA

***Abstract*—MODPEX is widely used in industry and universities to produce Pspice model for power semiconductor devices, including MOSFETs. However, the model generated by MODPEX for MOSFETs does not include channel charge at strong inversion condition. This paper presents a modified MODPEX model for MOSFETs, which includes channel charge at strong inversion condition. A process based on genetic algorithm (GA) implemented in Microsoft Office Excel is developed to optimize parameters of the modified MODPEX model. Static and dynamic validation proves that the modified MODPEX model improves simulation accuracy in both switching loss and driver loss.**

I. INTRODUCTION

MODPEX has been used in generating spice models for various power semiconductor devices, including MOSFETs[1]. It has been widely used in industry and research by electrical engineers to build simulation models for semiconductor devices. However, the models generated by MODPEX have no flexibility to change structure or components to include various physics, like channel charge at strong inversion condition. To include channel charge at strong inversion condition, traditional MODPEX models for MOSFETs have to be modified.

Whenever a MODPEX MOSFET model is modified, parameters for the MOSFET model must be re-extracted and optimized. There are basically two methods to extract parameter for spice models. One is calculus-based method, in which derives are used, the other is guided random search technique. Comparing with the calculus-based method, guided random search technique is more robust and can search global optimization solution [2].

Genetic Algorithm (GA) is one of the random search techniques. Genetic algorithm directly searches the best solution in all the solution space. It is easy to understand, and has clear calculation flow and is easy to program in mathematical software, like MS Office Excel. Simple genetic algorithm is used in this paper.

II. TRADITIONAL MODPEX MOSFET MODEL

Figure 1 shows the structure of traditional MODPEX MOSFET model [3] [4].

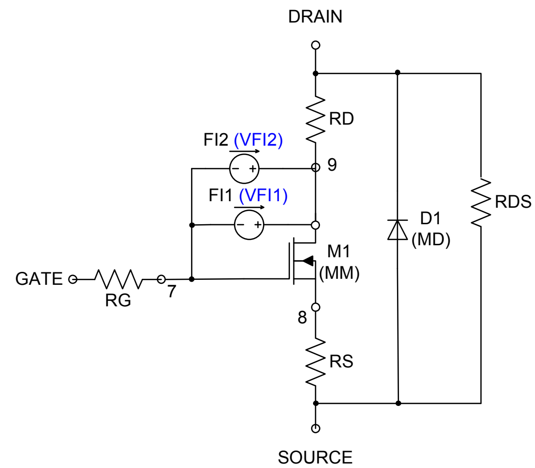

Figure 1: Structure Of traditional MODPEX MOSFET model

In Figure 1, M1 is the main MOSFET. Voltage dependant capacitances are not included in M1. Only parasitic capacitances, such as gate-source overlay capacitance CGSO and gate-drain overlay capacitance CGDO, are included in M1.

In Figure 1, D1 is the MOSFET body diode. Both diode reverse recovery loss and power loss operating in the third quadrant are captured by the diode. The structure of body diode model is shown in [3]. Capacitance of D1 in Figure 1 and D2 in Figure 2 are shown in equation (1)[5].

$$
\begin{aligned}
&V_{AK} \le FC \cdot VJ \\
&\quad C_D = CJ0 \cdot \left(1 - \frac{V_{AK}}{VJ}\right)^{-M} \\
&V_{AK} > FC \cdot VJ \\
&\quad C_D = CJ0 \cdot (1 - FC)^{-(1+M)} \cdot \left[1 - FC \cdot (1+M) + M \cdot \frac{V_{AK}}{VJ}\right]
\end{aligned}
\qquad \textbf{(1)}
$$

here, FC, VJ, CJ0, and M are model parameters.

In Figure 1, RDS is the MOSFET body resistance. RD is the drain resistance, RS is the source resistance, and RG is gate resistance.

Figure 2 is the control circuit of the controlled current sources FI1 and FI2 in Figure 1. The current of controlled current source FI1 is the current flowing through zero-voltage source VFI1; the current of controlled current source FI2 is the current flowing through zero-voltage source VFI2. Capacitance of D2 in Figure 2 is expressed by equation (1).

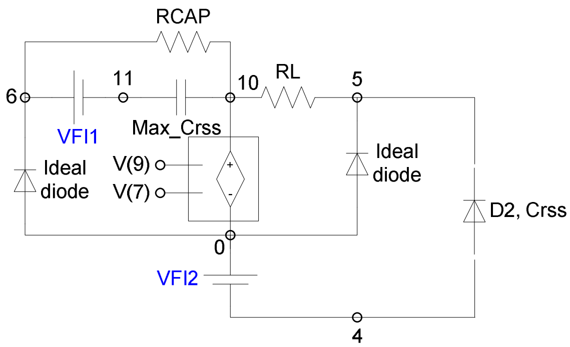

Figure 2: Structure of control circuit for FI1 and FI2

Voltage of node 10 is controlled by voltage difference between node 9 and node 7, which is expressed by equation (2).

$$\boldsymbol{V(10) = V(9) - V(7)} \qquad \textbf{(2)}$$

One can see that max_Crss charges or discharges and the nonlinear capacitor Crss is shorted by an ideal diode when voltage V(9)<V(7). This process happens at the last instant of MOSFET switching-on and the first intant of MOSFET switching-off. The nonlinear capacitor Crss charges or discharges and max_Crss is blocked by another ideal diode when V(7)<V(9). This procedure happens when the drain-source voltage is increasing or decreasing. The capacitances max_Crss and Crss function in a complimentary way. As a result, max_Crss and Crss form the function of Crss in a complete switching cycle.

III. MODIFIED MODPEX MODEL FOR MOSFET

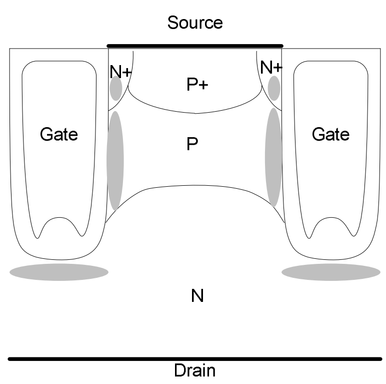

Figure 3: physical structure of MOSFET

All the model components in section 2 are strictly based on physics. However, the capacitance of MOSFET introduced by charges in channel region is not included in the model. Only overlay parasitic capacitance between gate and source, and between gate and drain In Figure 3 are included in M1 in Figure 1. In fact, the charge introduced by gate bias is much more significant than parasitic overlay capacitance when strong inversion layer forms in channel region. Charges introduced by gate bias have strong effect on gate-source capacitance and gate-drain capacitance, which as a result have significant effect on switching characteristics of MOSFET. Therefore, it is necessary to have MOSFET model which takes into account the channel charge introduced capacitances.

Taking intrinsic gate charge $Q_{G\text{-}CH}$ into account, capacitances between gate and drain, and between gate and source are expressed by equation (3) and (4).

$$C_{GS-CH} = \left.\frac{\partial Q_{G-CH}}{\partial V_{GS}}\right|_{V_{GD}} \qquad \textbf{(3)}$$

$$C_{GD-CH} = \left.\frac{\partial Q_{G-CH}}{\partial V_{GD}}\right|_{V_{GS}} \qquad \textbf{(4)}$$

In strong inversion, by integrating gate charge along channel, the total gate charge is obtained and expressed by equation (5) [5].

$$Q_{G-CH} = \frac{2}{3} C_i \frac{(V_{GS} - V_T)^3 - (V_{GD} - V_T)^3}{(V_{GS} - V_T)^2 - (V_{GD} - V_T)^2} \qquad \textbf{(5)}$$

Applying equation (5) into equation (3) and (4) gives equation (6) and (7).

$$C_{GS-CH} = \frac{2}{3} C_i \left[1 - \left(\frac{V_{GT} - V_{DS}}{2V_{GT} - V_{DS}}\right)^2\right] \qquad \textbf{(6)}$$

$$C_{GD-CH} = \frac{2}{3} C_i \left[1 - \left(\frac{V_{GT}}{2V_{GT} - V_{DS}}\right)^2\right] \qquad \textbf{(7)}$$

Here, $V_{GT}=V_{GS}-V_{TH}$. Ci is the capacitance of gate oxide.

The modified MODPEX MOSFET model, in which channel charge induced capacitance is include, is shown in Figure 4.

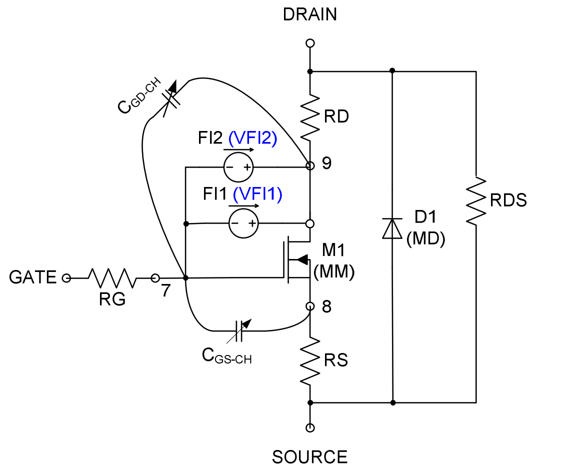

Figure 4: Structure of modified MODPEX model for MOSFET

The difference between traditional MODPEX model and modified MODPEX model is that two time variant capacitance $C_{GS\text{-}CH}$ and $C_{GD\text{-}CH}$ are inserted between gate and source, and between gate and drain. The rest components of modified MODPEX model is the same comparing with traditional MODPEX model, except parameter values must be re-optimized.

IV. Parameter Extraction

Due to the fact that the new model of MOSFET is modified from original MODPEX model, a new optimization procedure has to be developed to extract parameter values for capacitances in the modified MODPEX model. These components and parameters are shown in [6][7].

TABLE I. OPTIMIZATION COMPONENTS AND PARAMETERS

Components	***Parameters***
D1	FC, VJ, CJ0,M
D2	FC, VJ, CJ0,M
M1	CGSO and CGDO
$C_{GS\text{-}CH}$ and $C_{GD\text{-}CH}$	C_i

To find the optimized parameter values for the 11 parameters in table I, genetic algorithm is used. Initialization procedures of simple GA includes: encoding solutions, determining fitness function, determining evolution function, determining reproduce rate and determining mutation rate.

A. Encoding and un-coding solutions

Linear coding method is used in this simple GA. A gene is assigned 10 bits, which form a 10 bits binary number. There are 1024 values of each gene, which is linearly distributed in solution space. Solution space then is discretized into 1023 sections. Therefore, the coding method for a solution is shown in equation (8).

$$\mu_{binary} = \frac{\mu - \mu_{min}}{\mu_{max} - \mu_{min}}(2^{10} - 1) \qquad \textbf{(8)}$$

Here, μ is the value in solution space. μ_{max}, μ_{min} are maximum and minimum limits of solution space. μ_{binary} is the value coded in binary format, which forms a gene.

Based on the coding method, the un-coding method for each gene is expressed by equation (9).

$$\mu = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{2^{10} - 1}\mu_{binary} \qquad \textbf{(9)}$$

Equation (9) shows that in order to have sufficiently accurate solution, the solution range $\mu_{max} - \mu_{min}$ must be limited to a range as small as possible.

B. Determining fitness function and evaluation function

The goal of GA is to find and optimize parameter values for the modified MOSFET model, so that the capacitances of modified MOSFET model match the experiment C-V curves as much as possible. The optimization process is to minimize the difference between simulation curves and experiment curves of Ciss, Coss, and Crss. Therefore, it is natural to have variation of simulation curves and experiment curves as fitness function, which is expressed by equation (10).

$$f = \sum_{N} \left(\left|\Delta Ciss \cdot \Delta V\right| + \left|\Delta Crss \cdot \Delta V\right| + \left|\Delta Coss \cdot \Delta V\right| \right) \qquad \textbf{(10)}$$

Here, $\Delta C_{iss} = C_{iss\_sim} - C_{iss\_exp}$, $\Delta C_{rss} = C_{rss\_sim} - C_{rss\_exp}$, $\Delta C_{oss} = C_{oss\_sim} - C_{oss\_exp}$ ΔV is voltage difference of two comparing points. N is experiment data point. $\boldsymbol{f}$ is the area between simulation C-V curves and experiment C-V curves with unit "pF·V".

Due to the fact that optimization is to find the minimum value for fitness function, it is straightforward to choose the reciprocal of fitness function as evaluation function.

In GA reproduce rate, which is between 0.4 and 1, is chosen to be 0.6. Mutation rate, which is between 0.001 and 0.1, is chosen to be 0.01. For simplicity, single point crossover operation is used in the genetic algorithm.

In Excel, each row forms a chromosome and each cell forms a bit in the chromosome. Because there are 10 bits for each parameter, the length of a chromosome is 110 bit, therefore, is 110 cells. Because the population is set to be 80, there are 80 rows of chromosome. As a result, in excel there is a matrix of 80x110, in which each cell is a binary number.

The calculation procedure of simple genetic algorithm in Excel is the following:

- At first, Excel randomly generates 0 or 1 for each cell in the 80x110 matrix.
- Then decode each chromosome to 11 values based on the boundary values of parameters.
- Use the 11 decoded values to simulate the C-V curves for modified MODPEX model.
- Then compare simulation results with experiment data and extract errors. Each chromosome has an error and each generation have 80 error values.
- Then use the reciprocal of error value as evaluation function. Chromosomes with evaluation values that

are higher than average values are copied to next generation.

- A single point crossover operation follows step 5.
- The last step is to randomly change values of some cells from 1 to 0 or from 0 to 1 based on a mutation rate, which is a possibility between 0.001 and 0.1. It is 0.01 for devices parameter optimization for this paper.
- Copy population of first generation to second generation and repeat step 2 to 7 for next generation.

V. EXPERIMENT VALIDATION

A. Static validation

The modified MOSFET model has been applied to MOSFET NTD4815, a product of ON Semiconductor Company. C-V curves are measured with Hewlett Packard 4284A.

Experiment C-V curves and simulation curve of traditional MODPEX model are shown in Figure 5.

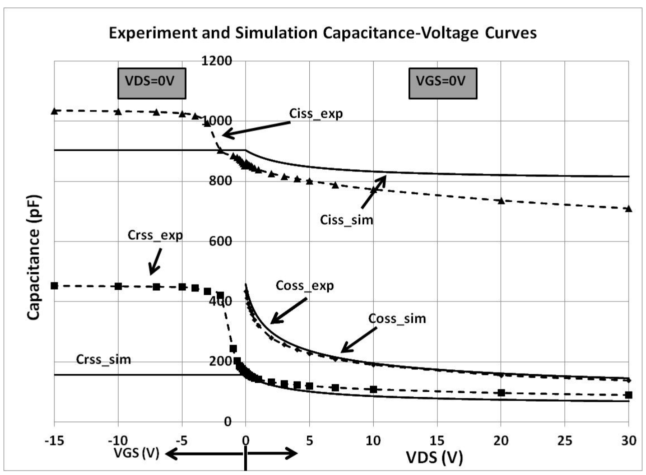

Figure 5: Ciss, Coss and Crss curves Comparison between experiment and simulation of (Dashed lines with marks are experiment curves, solid lines are simulation curves)

Experiment curves and modified MODPEX model are shown in Figure 6.

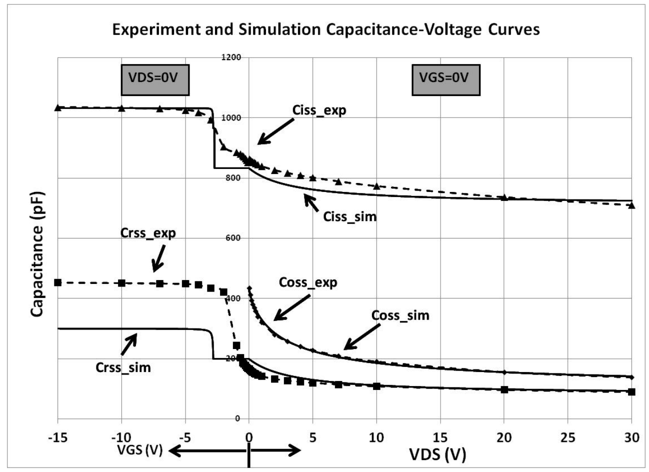

Figure 6: Ciss, Coss and Crss curves Comparison between experiment and simulation (Dashed lines with marks are experiment curves, solid lines are simulation curves)

B. Dynamic validation

Resistive switching experiment has been done to compare the traditional model and new model. Figure 7 shows the experiment setup, in which three boards are included: driver board, test board and mother board. Driver used in test is NCP5911, a 5V driver of ON semiconductor.

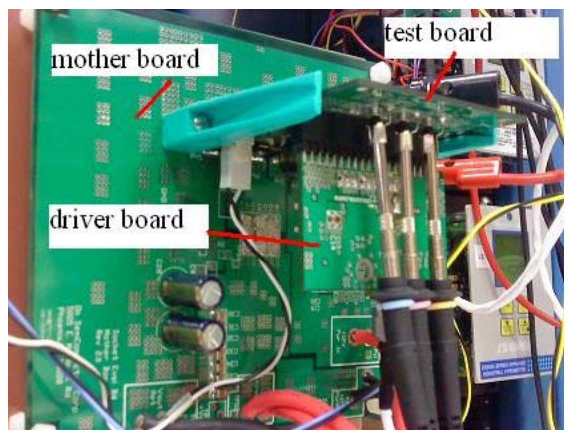

Figure 7: Resistive switching experiment setup

Schematic circuit of experiment setup is shown in Figure 8. To take the full advantage of existing experiment setup, load resistance is connected to source of MOSFET NTD4815.

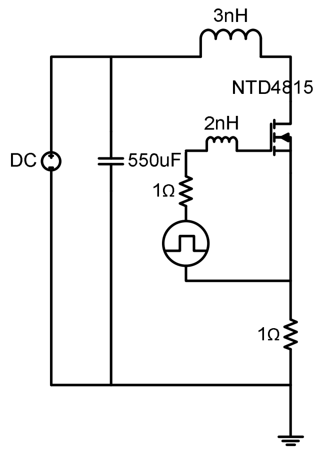

Figure 8: Resistive switching circuit

Figure 9 to Figure 12 are comparison of resistive switching experiment results and simulation results of modified MODPEX model and conventional MODPEX model. Driver waveforms are not shown in these figures. Driver loss comparison of modified MODPEX model, conventional and experiment on driver loss prediction is shown in Figure 13.

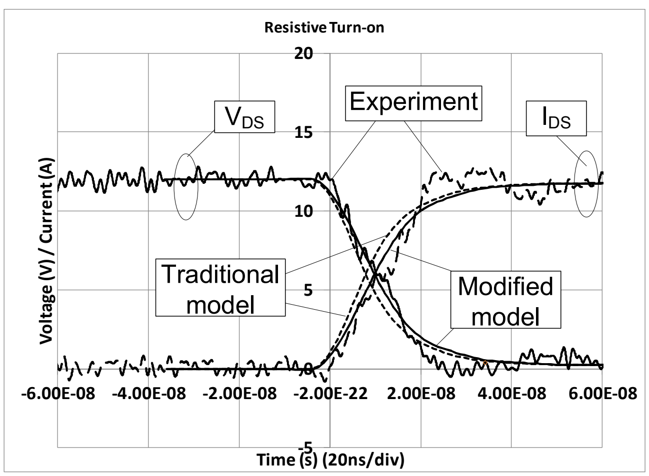

Figure 9: 12V12A resistive switching on validation

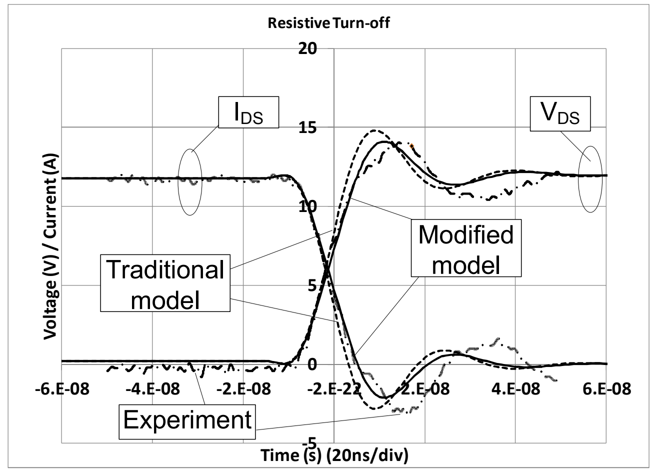

Figure 10: 12V12A resistive switching off validation

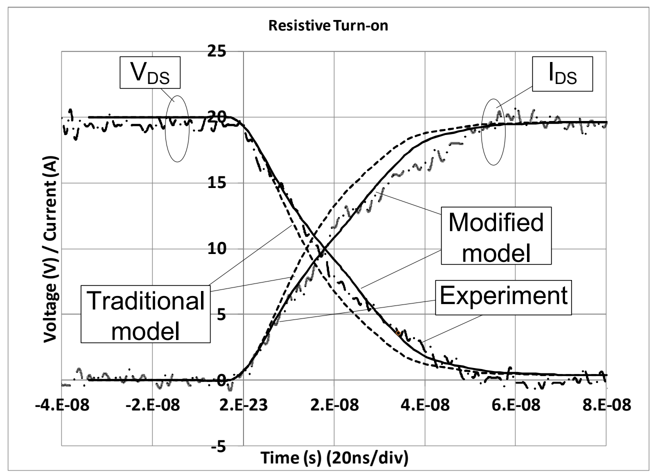

Figure 11: 20V20A resistive switching on validation

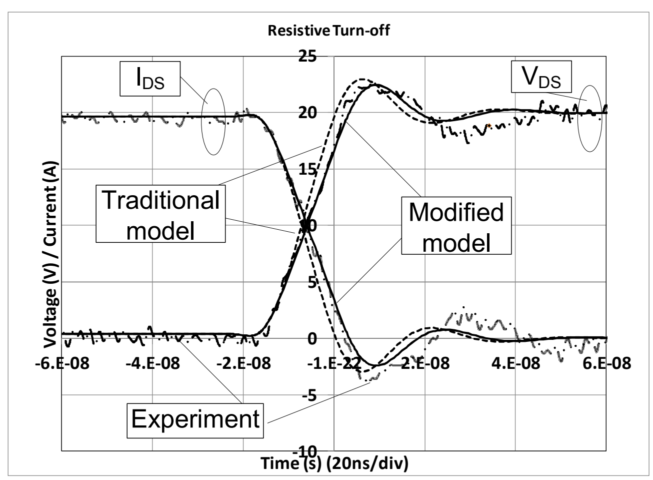

Figure 12: 20V20A resistive switching off validation

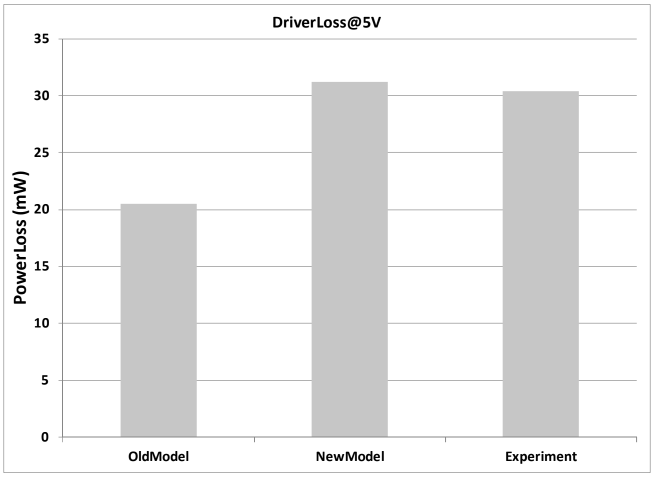

Figure 13: Driver loss at 5V

The overall variation between experiment curves and simulation curves of each generation as a function of generations is in Figure 14. The mutation rate is 0.001, 0.01, and 0.1, respectively.

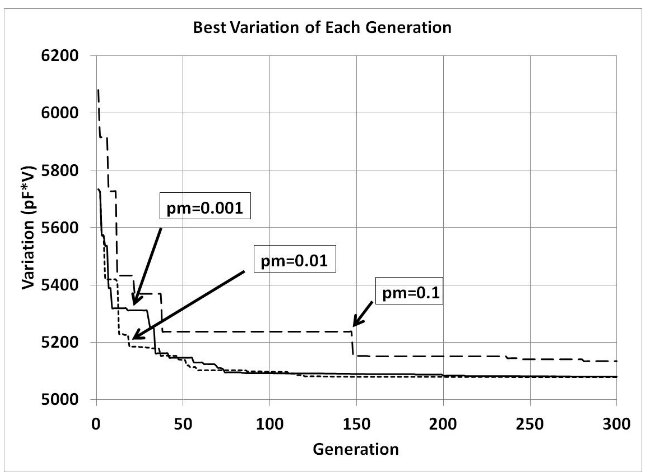

Figure 14: Simple GA calculation results at mutation rate 0.001, 0.01 and 0.1

The overall variation between experiment curves and simulation curves of each generation as a function of generations at various crossover rates is in Figure 15. The crossover operation rate is 0.2, 0.4, 0.6, and 0.8, respectively.

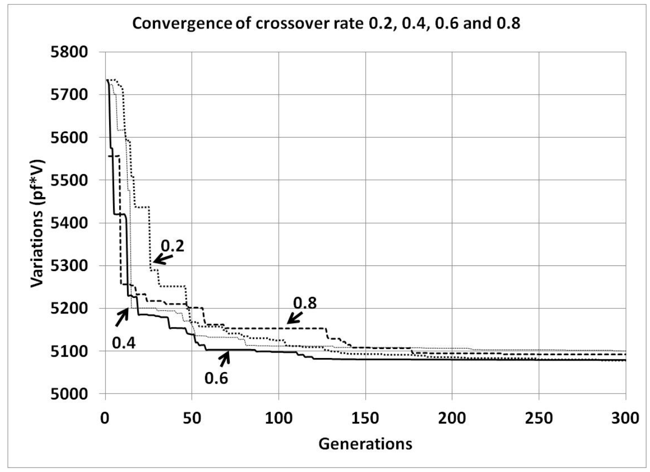

Figure 15: Simple GA calculation results at crossover frequency 0.2, 0.4, 0.6 and 0.8

VI. Discussion

Comparing with traditional MODPEX model, the modified MODPEX model has better simulation accuracy, especially for gate source capacitance C_{GS} when V_{GS} is greater than zero. Figure 6 clearly shows that the accuracy of Ciss, Coss, and Crss are improved in both region of VGS>0, VDS=0 and VGS=0, VDS>0. Area between simulation and experiment of C-V curves are reduced from around 9000 pF·V of traditional MODPEX model to around 5100 pF·V of modified MODPEX model.

Dynamic validation shows that modified MODPEX model has better match with experiment voltage and current than conventional MODPEX model, as is shown in from Figure 9 to Figure 12. Due to the better modeling of channel charge in strong inversion, modified MODPEX model has better simulation accuracy in switching time, and therefore switching loss.

Driver loss is also improved in modified MODPEX model. Experiment shows that driver loss for NTD4915 at 5V driver is 30.4mW. Conventional MODPEX model predicts drive loss to be 20.5mW, only 67% of total driver loss. Modified MODPEX model predicts 31.2mW, which give simulation accuracy of 97.4%.

Figure 14 shows the solution evolution of genetic algorithm as a function of generation. Solutions are quickly converged to optimized minimum value in the first 100 generations. After 100 generations, no significant improvement is observed. To save simulation resources, genetic algorithm could be limited to 100 generations.

Mutation rate has significant effect on final solutions of genetic algorithm. Higher mutation rate has faster convergence speed. However, mutation rate higher than 0.01 results in slower convergence speed. Three optimization results vs generation curves at mutation rate 0.001, 0.01 and 0.1 are shown in Figure 14. It is clearly shown that convergence speed with mutation rate 0.01 is highest among three situations.

Crossover rate is another factor that affects the convergence speed. Crossover frequency that is greater or smaller than 0.6 will reduce the convergence speed of genetic algorithm, which is shown in Figure 15. In Figure 15, it takes about 60 generations to converge for the case with crossover frequency 0.6 to optimized vale, while it takes about 130 and 140 generations for cases with crossover frequency 0.2 and 0.8, respectively.

VII. CONCLUSIONS

A modified MODPEX model for MOSFETs is proposed. This model includes channel charge induced capacitances, which is the key capacitance during turn-on and turn-off intervals. Genetic algorithm is designed to optimize capacitances in the model. Improvements are validated by simulation and experiment.

REFERENCES

[1] "MODPEX Modeling Tool", http://www.symmetry.com/

[2] D. Goldberg (1989), Genetic Algorithms in Search, Optimization,and Machine Learning, Addison-Wesley.

[3] Description of ONSemiconductor MOSFET Model www.onsemi.com/pub/Collateral/AND9033-D.PDF

[4] Pspice manual, http://www.electronicslab.com/downloads/schematic-/013/tutorial/PSPCREF.pdf

[5] Tor A. Fjeldly, Trond Ytterdal, Michael S. Shur, "Introduction to Device Modeling and Circuit Simulation", Wiley-Interscience, ISBN 0-471-15778-3

[6] X. Cai, H. Wang, X. Gu, G. Gildenblat and P. Bendix, "Application of the Genetic Algorithm to Compact MOSFET Model Development and Parameter Extraction ," Nanotech 2003, Vol2, pp. 314-317

[7] Q. Zhou, W. Yao, W. Wu, X. Li, Z. Zhu and G. Gildenblat, "Parameter extraction for the PSP MOSFET model by the combination of genetic and Levenberg-Marquardt algorithms", Proc. IEEE ICMTS, March 2009, pp. 137-142