Algorithms on the Extraction of BSIM MOSFET Model Parameters via Measurement Data

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Abstract

In this paper, parameter extraction algorithms are designed from the BSIM3v3 MOSFET model equations. The solution codes for the equations are written by MATLAB. The algorithms are designed to give results from only devices characteristics data. BSIM MOSFET model parameters are extracted by these algorithms. The SPICE simulations are performed using extracted parameters also. Simulation results have been compared with real measurement data. Hence, the work is finalized by determining the model performance and its accuracy.

1 Introduction

At the down of its fifth decade, the semiconductor industry continues to grow at a surprising pace. High-speed and low-power integrated circuits are used in an ever expanding plethora of applications, permeating every aspect of our life. One of the most critical parts of this technology is high-quality circuit design [1].

Circuit simulations are one of the essential part in designing integrated circuits. The accuracy of circuit simulation depends on the accuracy of the model of the transistors [1,2]. For this reason, nowadays, it is more important to construct developed accurate models for determining the accurate circuit performance than every time. It is encountered new physical mechanisms while increasing of complexity in the model. This reason directed to the designers toward high level difficult models.

The development of compact MOSFET models for circuit simulation started with appearing of first circuit simulators. Since then to now many transistor models such as MOS1, MOS2, MOS3, BSIM1, BSIM2, have come up. MOS 1 is very simple MOSFET model but it is accurate only long-channel and uniform-doping devices. MOS 2 is more complex than MOS 1 and based on device physics but it is still not accurate in submicron geometries. MOS 3 introduced with many empirical assumptions and it is not physically based. The short channel and narrow-width effects are not modeled accurately in MOS 1, 2, 3. BSIM has been developed to overcome these drawbacks. In BSIM3 the short-channel and narrow-width effects as well as high-field effects are well modeled [1-3].

In this paper it is aimed to obtain BSIM MOSFET model parameters using with real measurement data. Firstly it is mentioned BSIM models which is related extraction parameters. Then extraction steps are determined and extraction algorithms are constructed to get BSIM model parameters. Extraction algorithms are applied TUBITAK 0.7µm test transistors' measurement data. From experimental data BSIM model parameters are extracted. Hence, the work is finalized by determining the model performance and its accuracy.

2 BSIM MOSFET Model

2.1 Complete Threshold Voltage Model in BSIM3v3

With considerations of all physical mechanisms such as non-uniform doping effects, short and narrow channel effects, complete BSIM3v3 threshold voltage model can be expressed as follows [1,5,6]:

$$\begin{aligned}
V_{th} &= V_{TH0} + K_1\left(\sqrt{\Phi_s - V_{bseff}} - \sqrt{\Phi_s}\right) - K_2 V_{bseff} \\
&+ K_1\left(\sqrt{1+\frac{N_{LX}}{L_{eff}}} - 1\right)\sqrt{\Phi_s} + \left(K_3 + K_{3B}V_{bseff}\right)\frac{T_{OX}}{W_{eff}{}' + W_0}\Phi_s \\
&- D_{VT0}\left(e^{\left(-D_{VT1}\frac{L_{eff}}{2l_t}\right)} + 2e^{\left(-D_{VT1}\frac{L_{eff}}{l_t}\right)}\right)\left(V_{bi} - \Phi_s\right) \\
&- \left(e^{\left(-D_{SUB}\frac{L_{eff}}{2l_{to}}\right)} + 2e^{\left(-D_{SUB}\frac{L_{eff}}{l_{to}}\right)}\right)\left(E_{TA0} + E_{TAB}V_{bseff}\right)V_{ds} \\
&- D_{VT0W}\left(e^{\left(-D_{VT1W}\frac{W_{eff}{}' L_{eff}}{2l_{tw}}\right)} + 2e^{\left(-D_{VT1W}\frac{W_{eff}{}' L_{eff}}{l_{tw}}\right)}\right)\left(V_{bi} - \Phi_s\right)
\end{aligned} \tag{1}$$

In Eq. (1), the second and third terms are for vertical non-uniform doping effect, the fourth term is used to model the lateral non-uniform doping effect, the fifth term is for the narrow width effect, the sixth and seventh terms are related to the short channel effect due to DIBL, and the last term is to describe the small size effect in devices with both small channel length and small width [1,5].

2.2 BSIM3v3 Mobility Model

A good mobility model is critical for the accuracy of a MOSFET model. Mobility depends on many process parameters and device bias conditions [5].

Several mobility model options are provided for choosing in BSIM3v3 to users. A selector parameter called mobMod is used for this purpose. The mobility expression for strong inversion is given in Eq. (2). The mobility expression has been designated as mobMod=1.

$$\mu_{eff} = \frac{\mu_o}{1 + \left(U_A + U_C V_{bseff}\right)\left(\frac{V_{gsteff} + 2V_{th}}{T_{OX}}\right) + U_B\left(\frac{V_{gsteff} + 2V_{th}}{T_{OX}}\right)^2} \quad (2)$$

3 BSIM Parameter Extraction Algorithms

3.1 Parameter Extraction Strategy and Procedure

Parameter extraction is an important part of model development. Two different strategies are available for extracting parameters: the single device extraction strategy and group device extraction strategy [5]. BSIM3v3 uses group device extraction strategy. This requires measured data from devices with different geometries. All device are measured under the same bias conditions.

For their geometries, four type devices are introduced. These are large-sized, short-channel, narrow-channel and small-sized MOSFETs. This determination is shown in **Fig. 1**.

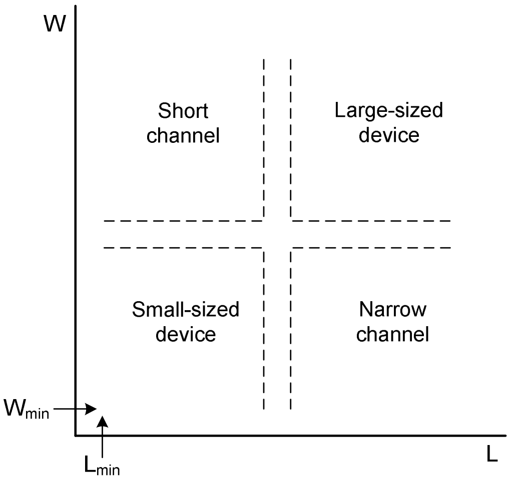

Fig. 1. Device geometries used for parameter extraction [5]

The classification of devices according their geometries is very important to extract model parameters belonging different effects. For instance, in large sized device model parameters are independent of some physical mechanisms, such as short and narrow channel effects, parasitic resistance etc. So in this time, interested parameters are large-sized device threshold voltage (V_{Tideal}) and the body effect coefficients K_1 and K_2 [5].

Before any model parameters can be extracted, some process parameters have been provided. They are listed below in Table 1.

The parameters are extracted in the following procedure (Table 2). These procedures are based on a physical understanding of the model and based on local optimization.

Table 1. Prerequisite input parameters prior to extraction process [5]

Parameter	Physical Meaning
T_{ox}	Gate oxide thickness
N_{ch}	Doping concentration in the channel
T	Temperature at which the data is taken
L_{drawn}	Mask level channel lenght
W_{drawn}	Mask level channel width
X_j	Junction depth

Table 2. Parameter extraction steps

Extracted Parameters	Device geometries	Experimental Characteristics
V_{TH0}, K_1, K_2	Large-sized device (Large W & L)	Ids-Vgs @ Vds=0.05V, Vbs parameter
μ_0, U_A, U_B, U_C	Large-sized device (Large W & L)	Ids-Vgs @ Vds=0.05V, Vbs parameter
N_{LX}, D_{VT0}, D_{VT1}, D_{VT2}	Different and small L, large and fixed W	Ids-Vgs @ Vds=0.05V, Vbs parameter
W_0, K_3, K_{3B}	Different and small W, large and fixed L	Ids-Vgs @ Vds=0.05V, Vbs parameter
D_{VT0W}, D_{VT1W}, D_{VT2W}	Small-sized device (Small and different W&L)	Ids-Vgs @ Vds=0.05V, Vbs parameter

3.2 Extraction of Threshold Voltage

A graphically based method has been considered for determining threshold voltage. Calculation steps are given below: In **Fig. 1** it is shown that the application of the threshold voltage extraction steps and obtaining.

- Measure I_{DS}-V_{GS} characteristics at low V_{DS} (<0.1V, typically 50mV),
- Determine the maximum slope of the I_{DS}-V_{GS} curve, that is maximum gm point,
- Extrapolate I_{DS}-V_{GS} from the max g_m point to I_{DS}=0,
- Note the corresponding extrapolated VGS value (V_{GS0}) for I_{DS}=0 point.
- Calculate V_{th} according $V_{th} = V_{gs0} - 0.5V_{DS}$

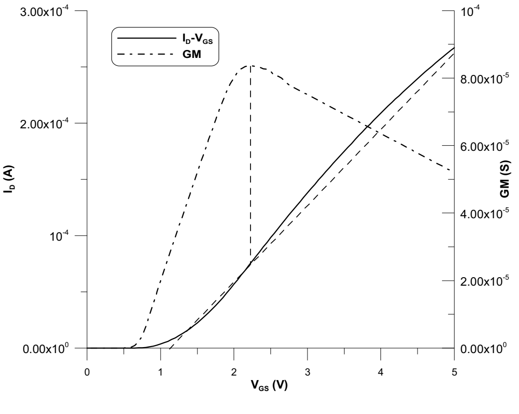

Fig. 2. Extraction of threshold voltage

Table 3. Extraction equations of the model parameters

Extracted Parameter	**Considered Equation**
V_{TH0}, K_1, K_2	$\begin{bmatrix}K_1\\K_2\end{bmatrix}=\begin{bmatrix}\sqrt{\Phi_s-V_{bs\{1\}}}-\sqrt{\Phi_s} & -V_{bs\{1\}}\\ \sqrt{\Phi_s-V_{bs\{2\}}}-\sqrt{\Phi_s} & -V_{bs\{2\}}\end{bmatrix}^{-1}\begin{bmatrix}V_{th\{1\}}-V_{TH0}\\ V_{th\{2\}}-V_{TH0}\end{bmatrix}$
μ_0, U_A, U_B	$\begin{bmatrix}\mu_0\\U_A\\U_B\end{bmatrix}=\begin{bmatrix}1 & -\mu_{eff\{1\}}\frac{V_{gsteff\{1\}}+2V_{th}}{T_{OX}} & -\mu_{eff\{1\}}\left(\frac{V_{gsteff\{1\}}+2V_{th}}{T_{OX}}\right)^2\\ 1 & -\mu_{eff\{2\}}\frac{V_{gsteff\{2\}}+2V_{th}}{T_{OX}} & -\mu_{eff\{2\}}\left(\frac{V_{gsteff\{2\}}+2V_{th}}{T_{OX}}\right)^2\\ 1 & -\mu_{eff\{3\}}\frac{V_{gsteff\{3\}}+2V_{th}}{T_{OX}} & -\mu_{eff\{3\}}\left(\frac{V_{gsteff\{3\}}+2V_{th}}{T_{OX}}\right)^2\end{bmatrix}^{-1}\begin{bmatrix}\mu_{eff\{1\}}\\ \mu_{eff\{2\}}\\ \mu_{eff\{3\}}\end{bmatrix}$
U_C	$U_C=\frac{\mu_0-\mu_{eff}\left[1+U_A\frac{V_{gsteff}+2V_{th}}{T_{OX}}+U_B\left(\frac{V_{gsteff}+2V_{th}}{T_{OX}}\right)^2\right]}{\mu_{eff}V_{bseff}\frac{V_{gsteff}+2V_{th}}{T_{OX}}}$
N_{LX}	$N_{LX}=L_{eff}\left[\left(1+\frac{V_{th}-V_{TH0}-K_1\left(\sqrt{\Phi_s-V_{bseff}}-\sqrt{\Phi_s}\right)+K_2V_{bseff}}{K_1\sqrt{\Phi_s}}\right)^2-1\right]$
D_{VT0}, D_{VT1}	$D_{VT0}\left(\exp\left(-D_{VT1}\frac{L_{eff}}{2l_{t0}}\right)+2\exp\left(-D_{VT1}\frac{L_{eff}}{l_{t0}}\right)\right)=\frac{-V_{th}+V_{TH0}+K_1\left(\sqrt{1+\frac{N_{LX}}{L_{eff}}}-1\right)\sqrt{\Phi_s}}{\left(V_{bi}-\Phi_s\right)}$
D_{VT2}	$\exp\left(-D_{VT1}\frac{L_{eff}}{2l_t}\right)+2\exp\left(-D_{VT1}\frac{L_{eff}}{l_t}\right)=\frac{-V_{th}+V_{TH0}+K_1\left(\sqrt{\Phi_s-V_{bseff}}-\sqrt{\Phi_s}\right)-K_2V_{bs}+K_1\left(\sqrt{1+\frac{N_{LX}}{L_{eff}}}-1\right)\sqrt{\Phi_s}}{D_{VT0}\left(V_{bi}-\Phi_s\right)}$
W_0	$\left(K_3+K_{3B}V_{bseff}\right)\frac{T_{OX}}{W_{eff}'+W_0}\Phi_s=V_{th}-V_{TH0}-K_1\left(\sqrt{\Phi_s-V_{bseff}}-\sqrt{\Phi_s}\right)+K_2V_{bseff}$
K_3, K_{3B}	$K_3+K_{3B}V_{bseff}=\frac{V_{th}-V_{TH0}-K_1\left(\sqrt{\Phi_s-V_{bseff}}-\sqrt{\Phi_s}\right)+K_2V_{bseff}}{\frac{T_{OX}}{W_{eff}'+W_0}\Phi_s}$
D_{VT0W}, D_{VT1W}	$\begin{aligned}&D_{VT0W}\left(\exp\left(-D_{VT1W}\frac{W_{eff}'L_{eff}}{2l_{t0}}\right)+2\exp\left(-D_{VT1W}\frac{W_{eff}'L_{eff}}{l_{t0}}\right)\right)=+\frac{-V_{th}+V_{TH0}+K_1\left(\sqrt{1+\frac{N_{LX}}{L_{eff}}}-1\right)\sqrt{\Phi_s}+K_3\frac{T_{OX}}{W_{eff}'+W_0}\Phi_s}{\left(V_{bi}-\Phi_s\right)}\\&-D_{VT0}\left(\exp\left(-D_{VT1}\frac{L_{eff}}{2l_{t0}}\right)+2\exp\left(-D_{VT1}\frac{L_{eff}}{l_{t0}}\right)\right)\end{aligned}$
D_{VT2W}	$\exp\left(-D_{VT1W}\frac{W_{eff}'L_{eff}}{2l_{tw}}\right)+2\exp\left(-D_{VT1W}\frac{W_{eff}'L_{eff}}{l_{tw}}\right)=\frac{\left(\begin{array}{l}-V_{th}+V_{TH0}+K_1\left(\sqrt{\Phi_s-V_{bseff}}-\sqrt{\Phi_s}\right)-K_2V_{bseff}\\ +K_1\left(\sqrt{1+\frac{N_{LX}}{L_{eff}}}-1\right)\sqrt{\Phi_s}+\left(K_3+K_{3B}V_{bseff}\right)\frac{T_{OX}}{W_{eff}'+W_0}\Phi_s\\ -D_{VT0}\left(\exp\left(-D_{VT1}\frac{L_{eff}}{2l_t}\right)+2\exp\left(-D_{VT1}\frac{L_{eff}}{l_t}\right)\right)\left(V_{bi}-\Phi_s\right)\end{array}\right)}{D_{VT0W}\left(V_{bi}-\Phi_s\right)}$

4 Determining Of Model Parameters Using Experimental Data

In order to get measurement data, TUBITAK 0.7µ test transistors are used. There are too many test transistors on a chip which have different W/L combinations and sorted matrix form. **Fig. 3** shows a N-type MOSFET which have 1µm channel lenght and 4.1µm channel width.

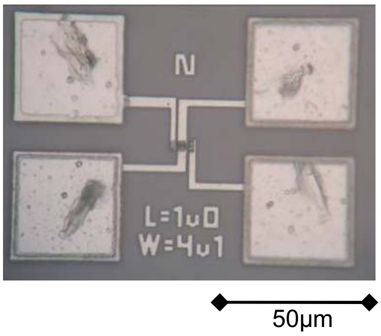

Fig. 3. A test transistor which used during measurements (500X Zoom)

4.1 Extraction of the Simulation Parameters

Using constructed algorithms BSIM parameters for N-type MOS transistors are obtained and given in table **Table 4**.

Table 4. Extracted values of BSIM parameters

Parameter	**Extracted Value**
$\mathbf{V_{TH0}}$	$6.512 \cdot 10^{-1}$
$\mathbf{K_1}$	$7.917 \cdot 10^{-1}$
$\mathbf{K_2}$	$-7.37 \cdot 10^{-2}$
$\boldsymbol{\mu_0}$	$4.496207 \cdot 10^{2}$
$\mathbf{U_A}$	$-3.652 \cdot 10^{-10}$
$\mathbf{U_B}$	$2.565 \cdot 10^{-18}$
$\mathbf{U_C}$	$2.3669 \cdot 10^{-11}$
$\mathbf{N_{LX}}$	$4.2310 \cdot 10^{-7}$
$\mathbf{D_{VT0}}$	3.0546
$\mathbf{D_{VT1}}$	$3.596 \cdot 10^{-1}$
$\mathbf{D_{VT2}}$	$-7.39 \cdot 10^{-2}$

Due to the some drawbacks of proses conditions it is unable to achive certainly accurate values of model parameters for short-channel and small-sized devices.

4.2 Simulation Results

SPICE simulations are performed using with the values of extracted parameters for devices which have different geometries. After the simulations, transfer and output characteristics are obtained for devices at different bias conditions. I_{DS}-V_{GS} and I_{DS}-V_{DS} characteristics for small and large channel devices are achived and given in **Fig. 4**, **Fig. 5**,

Fig. 6 and **Fig. 7** respectively.

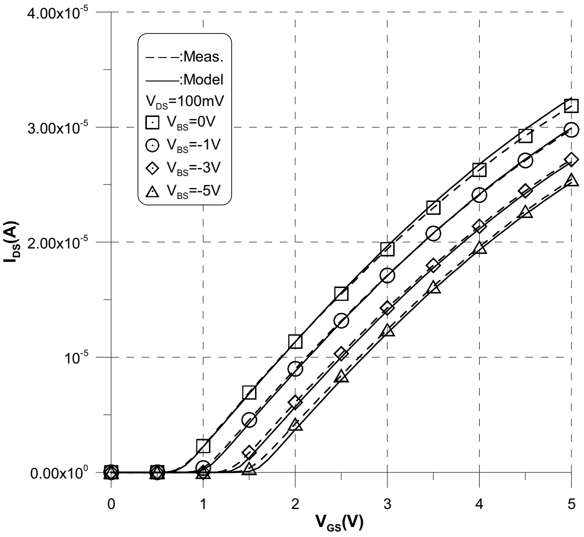

Fig. 4. Long channel MOSFET (L=27µm, W=27µm) I_{DS}-V_{GS} characteristics, V_{BS} parameter, V_{DS}=0.1V

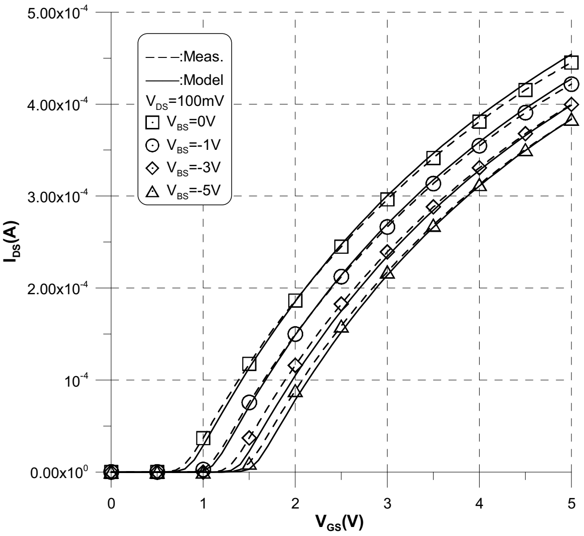

Fig. 5. Short channel MOSFET (L=1.5µm, W=27µm) I_{DS}-V_{GS} characteristics, V_{BS} parameter, V_{DS}=0.1V

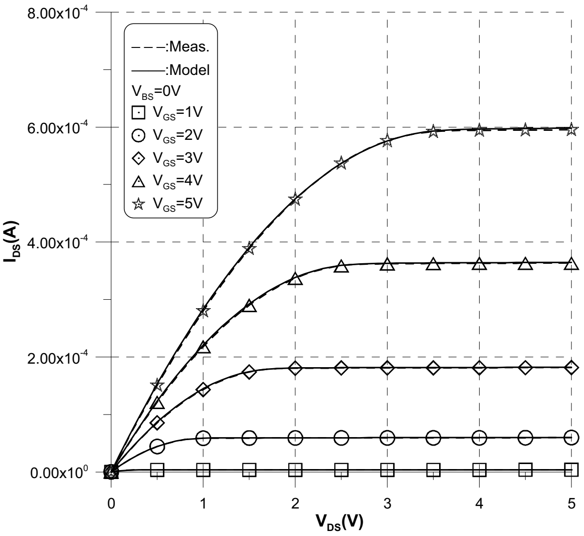

Fig. 6. Long channel MOSFET (L=27µm, W=27µm) I_{DS}-V_{DS} characteristics, V_{GS} parameter, V_{BS}=0V

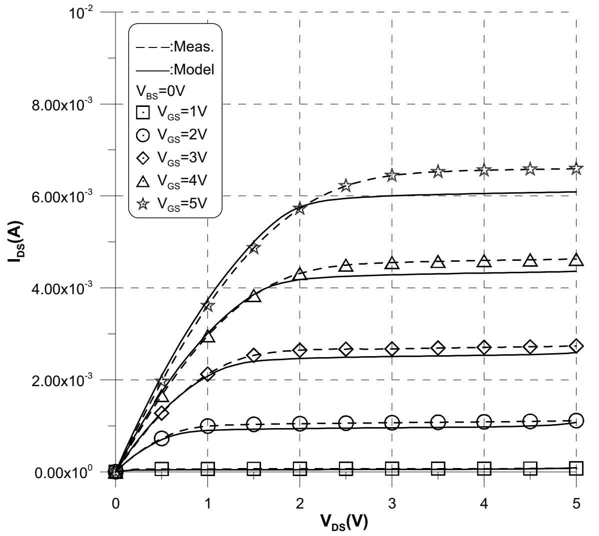

Fig. 7. Short channel MOSFET (L=1.5μm, W=27μm) I_{DS}-V_{DS} characteristics, V_{GS} parameter, V_{BS}=0V

4.3 Determing of the Method's Performance

Determination of error analysises for different operation region is so important to make a decision on model performance. Error analysises are realized for all W/L combinations and results are listed in **Table 5**.

Table 5. Performance analysis of the method

		RMS Error (%)				
	Region of the curve	V_{GS}=1V	V_{GS}=2V	V_{GS}=3V	V_{GS}=4V	V_{GS}=5V
Long Channel MOSFET (L=27μm, W=27μm)	Linear Region	0.87	1.12	1.25	1.43	1.78
	Saturation Region	0.58	0.77	0.98	1.10	1.22
	Complete Region	**0.82**	**1.08**	**1.13**	**1.27**	**1.55**
Short Channel MOSFET (L=1.5μm, W=27μm)	Linear Region	1.25	1.68	2.01	2.48	2.91
	Saturation Region	2.67	3.44	4.97	6.04	9.65
	Complete Region	**2.59**	**3.22**	**3.65**	**4.03**	**6.34**

5 Conclusion

In this study it is constructed algorithms which aimed at determining BSIM MOSFET model parameters using with experimental data. In MATLAB it is determined parameters and constructed method's application using with SPICE via model algorithms.

Evaluating of study results can be realized in view of two main stage which contains construction at related mathematical background and its application. The construction of theoretical background it is aimed to achieve the most appropriate results without using calculate methods and process. When observing model's physical and analytical form it can be said that the algorithm style is obtained which is high rate preferred without empirical expression.

The characteristics obtained from method's application showed that the simulation results are suitable with experimental results. Besides this, it is determined error levels under different bias conditions concerning separate operation region. When observing the results, generally it is seemed that in the all operation region good level performance is provided. Especially, it is very acceptable around at 1% level error rate which obtained large-sized MOSFET model. In short-channel transistor, generally error rate is at around max 10% level which increase depends on gate-source voltage. However, in linear region and small V_{GS} values, performance is in good levels. Furthermore, for obtaining appropriate results especially in the large geometry values which contain short channel circumstances, it can be made concessions from long linear channel and in this way it can be gained optimum performances for all geometries.

Finally, in the light of the detailed results related with graphics and error analysis given with the tables, it is seemed that, high level performance is obtained thanks to the developed method.

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