Development of Non-Fourier Thermal Attitude for Three-Dimensional and Graphene-Based MOS Devices

Zahra Shomali^{a,*}, Abbas Abbassi^b, Jafar Ghazanfarian^c

^a*Mechanical Engineering Department, Amirkabir University of Technology, 424 Hafez Avenue, P.O. Box 15875-4413, Tehran, Iran.*

^b*Mechanical Engineering Department, Amirkabir University of Technology, 424 Hafez Avenue, P.O. Box 15875-4413, Tehran, Iran.*

^c*Mechanical Engineering Department, Faculty of Engineering, University of Zanjan, Zanjan, Iran.*

Abstract

In this paper, the intact subject of 3-D MOSFETs is studied. Three well-known 3-D MOSFET nano-devices, including a common three dimensional silicon MOSFET, the FinFET, and the Tri-Gate, are dealt. Firstly, by implying the three dimensional non-linear Dual-Phase-Lag method, the obtained results are verified with the existent data. Contemporaneously, the important parameter $B = \tau_t/\tau_q$, which is prerequisite for DPL modeling, is found for the 3-D silicon. The adjusted parameter B , is used to study the 3-D transistors with temperature-dependent thermal characteristics. It is found that taking into account such relevancy, makes the overall trends of distributions unmodified. Finally, the effect of contemplating the graphene sheet heat remover in a 3-D Tri-Gate MOSFET is investigated. Notably, the graphene makes the process of cooling the transistor get accelerated. It is obtained that 40 *ps*

*Corresponding author. Tel.: +98 (24)33054142

Email addresses: shomali.zahra@gmail.com (Zahra Shomali), abbassi@aut.ac.ir (Abbas Abbassi), j.ghazanfarian@znu.ac.ir (Jafar Ghazanfarian)

after switching off the heat generation region, the value of the peak temperature of a 3-D Tri-Gate transistor along the center-line with a graphene heat remover, becomes 20% lower than that of a common 3-D Tri-Gate MOSFET. This finding shows that the Fourier calculations, overestimate the results.

Keywords: , Three Dimensional, Non-Fourier, Nanoscale Heat Transfer, MOSFET, FinFET, Tri-Gate

Nomenclature

B	phase-lag ratio	C	Volumetric heat capacity ($Jm^{-3}K^{-1}$)
k	thermal conductivity ($WK^{-1}m^{-1}$)	v	average velocity of sound (ms^{-1})
Q	Volumetric heat source (Wm^{-2})	q	heat flux (Wm^{-2})
x	direction (m)	y	direction (m)
z	direction (m)	E_{ss}	Steady-State error
k_{BT}	Boltzmann constant ($m^2kgs^{-2}K^{-1}$)	n	density and direction normal to boundary
γ	dummy variable (x,y,z)	Y	dummy variable (q,T)
t	time (s)	T	Temperature (K)
Kn	Knudsen number		

Greek

α	BC coefficient (kgm^{-3})	ω	under-relaxation factor
λ	mean free path of phonons (m)	$\mathbf{r}$	coordinate
τ	relaxation time (s)		

superscript

* non-dimensional condition

subscript

q	heat flux	t	gradient temperature
i	counter		

1. Introduction

The silicon metal-oxide-semiconductor field effect transistor (MOSFET), has been the main block of the semiconductor industry since 1960 [1]. The size of these MOS transistors has been decreased continuously over the past decades to a mean size of few-ten nanometer in the most recently designed MOSFETs. Hence, as the transistor dimensions have reached the nanoscale regime, the classical equations of continuum mechanics are ineffective. Consequently, the traditional continuum heat diffusion equation is not a good choice for nanoscale heat transfer investigation. Also, the usage of the atomistic methods for complex geometries due to their time-consuming, difficulties, and complex characteristic is not faultless [2]. Besides, the thermal issues such as self-heating in MOSFETs, are nowadays an important contention in design and optimization considerations of these SOI nano-devices [3].

Accordingly, the innovative models with less computational cost and more simplicity have been introduced to rectify the outcome of classical equations such as Fourier's law [4–9]. In fact, the Fourier's law encounters serious challenges in heat conduction prediction at ultra-small temporal and spatial scales. Several theoretical and experimental studies have reported that nanoscale heat conduction violates Fourier's law [10–12]. Consequently, the thermal properties deviate significantly from that of the normal sizes [13]. It is important to note that the failure of the Fourier's law in nanomaterials with phonon mean free path much shorter than the characteristic length also occurs [14]. This can be due to the ultrahigh-speed heat flux, resulting from the exceedingly high temperature gradient or the very-low cross-section area. In

such situations, although the characteristic length is within nanoscale range, but the continuum assumption is still valid. This presumption is not fundamentally explainable but according to the potentiality for using in technical and engineering applications is of great interest. Several theories have been developed to describe the heat transport in nanomaterials, including phonon dynamics [15], phonon hydrodynamics [16], thermomass theory [17], and phase lagging models. In the meantime, the dual-phase-lag (DPL) model as a new modified constitutive equation to investigate the non-Fourier heat transport in various cases such as nanoscale MOSFETs [18–20], ultra-fast laser-pulsed processes [21–24], living tissues [25–27], and Carbon nanotube [28–31] has attracted attentions. Due to the simpleness, straightforwardness, flexibility, and accurateness of this method, it can be a good choice for the study of transistors with various geometries.

Additionally, due to the complicated conditions existed in the transistors, simulations of these nano-devices considering real conditions seems to be necessary and worthwhile. Although, there have been many works dealing with the transistors as one- or two-dimensional nano-systems [32–34], there are few works, which have claimed to investigate the more realistic three-dimensional transistors.

In the work by Nasri *et al.* [35], a three-dimensional Tri-Gate is investigated using the single-phase-lag model. This work implies many limitations and approximations. Above the fact that the single-phase-lag model (Cattaneo-Vernote model) does not predict the behavior of nano-scale systems precisely, the coefficients used in the temperature-jump boundary condition are the ones used for a two-dimensional system. These two coefficients

are obtained, respectively, by the two-dimensional results of the DPL model [34] and SPL model [36] and, consequently, are applied to the single-phase-lag simulation of three-dimensional cases. In the present work, the three-dimensional non-linear dual-phase-lag model is used to simulate the realistic structure of the several different three-dimensional silicon MOS devices.

As the simulation of 3-D MOSFETs are completed, the effect of inserting the graphene heat spreader between the substrates of the transistor, on the thermal behavior of these nano-structures are investigated. In the last decade, graphene, a 2-D material with odd properties and high electrical and thermal conductivity has attracted lots of attention. First, the graphene sheet was proposed to replace the silicon in the MOSFET industries. Zero bandgap of graphene leads to low on-off current ratios of 2 to 20, which makes the large-area-graphene unsuitable candidate for MOSFET technology. The current ratio can be increased by shrinking the graphene sheet in one-dimension and making the graphene nanoribbons. Although the thermal conductivity of narrow graphene ribbons decreases, there are some proposal for the use of these nano-materials for making new generation of transistors [37, 38].

Despite the unsuitability of large-area-graphene sheet for the substitution of silicon in SOI transistors, its extremely high intrinsic thermal conductivity suggests to use this two-dimensional material as an appropriate candidate in thermal management of the nano-electronics devices. In recent years, there have been several works proposing the graphene sheet as a lateral heat spreader. But, even though the thickness of the graphene sheet is 0.324 nanometers and hence the non-Fourier methods should be applied to study

these nano-systems, to the best of our knowledge, all of researches used the Fourier technics, and ignored the important non-Fourier effects [39–42]. In the present work, by the numerical modeling of the MOSFET including a graphene sheet between the Si and SiO_2 substrates, using the non-linear 3-D-DPL model, the real role of graphene heat spreader is investigated.

In the current study, first, the accuracy of the new 3-D DPL numerical modeling is investigated. By using the fact that enlarging the third dimension, the 3-D results should reach that of the 2-D problem, the findings are verified. Secondly, by comparing the 3-D-DPL simulation of the FinFET and Tri-Gate silicon MOSFETs without a heat spreader with the data obtained from the Lattice-Boltzman simulation of three-dimensional MOSFETs [43], the three-dimensional coefficients of the 3-D DPL model are computed. Then, the realistic modeling of transistors with a graphene sheet heat spreader is performed by using 3-D nonlinear/linear DPL method.

2. Geometry and boundary conditions

The goal of this paper is to present the non-Fourier investigation of more realistic Three-Dimensional transistors. Also, the effects of using a graphene sheet as a heat spreader in the SOI MOSFETs such as typical 3-D Tri-Gates are treated. Hence, four different three-dimensional MOSFET devices are modeled in various circumstances as shown in Figs. 1(a-c). The heat source and boundary conditions are chosen in similarity to a real 3-D MOSFET.

2.1. Case I: A 3-D common silicon MOSFET

In case I, a three dimensional silicon transistor of size 100, 1000, and 50 nm, respectively, in x , y , and z direction with constant initial temperature

of 300 K is investigated. As it is manifested in Fig. 1(a), the heat generation zone of $10\text{ nm} \times 1000\text{ nm} \times 10\text{ nm}$ is created in the middle of the cubic MOSFET due to the operation of the transistor. This functionality results in the creation of the hot spot and the rearrangement of the temperature distribution in the MOSFET. The heat transport is studied while the heat generation zone produces volumetric heat during the whole time of the simulation. All boundaries except the bottom boundary, at which the temperature is kept constant at room temperature, are adiabatic. In the limit of large depth transistor, the results of our 3-D DPL modeling are verified with the data presented in [34]. Hence, this case is proceeded for the 3-D MOSFET with considering constant thermal parameters of the bulk silicon. Further, the size of the heat generation zone, L_H , which shows the characteristic length of the simulation, is the most important geometrical parameter of heat conduction.

2.2. Case II: A 3-D FinFET transistor

The schematic of the FinFET, which has been investigated in [43] is shown in Fig. 1(b). The silicon channel is a $22\text{ nm} \times 100\text{ nm} \times 200\text{ nm}$ region. The heat generation zones are two cubic volumes with 10 nm width, 100 nm height, and 200 nm depth. Also, as it is displayed in Fig. 1(b), the substrate is a $100\text{ nm} \times 100\text{ nm} \times 200\text{ nm}$ zone where two cubic regions of SiO_2 substrate are located in its both sides and the remaining compartment is a silicon substrate. The size of the each cubic SiO_2 substrate is $39\text{ nm} \times 32\text{ nm} \times 200\text{ nm}$. Moreover, all boundaries are adiabatic except the bottom plane boundary, which is kept at the ambient temperature.

2.3. Case III: A 3-D Tri-Gate transistor

The typical Tri-Gate MOSFET, is shown in Fig. 1(c). The silicon channel length is 22 nm. Further, the heat generation region of $Q = 10^{19} \text{ W/m}^3$, is an n-shaped volume with 10 nm thickness, and 100 nm depth. The other segments of the transistors such as the substrate shape, are similar to that of FinFETs. In analogy to the previous cases, all the boundaries except the bottom one, which is kept at 300 K, are adiabatic.

2.4. Case IV: A Tri-Gate MOSFET with graphene sheet heat remover

At last, a typical Tri-Gate MOSFET with a graphene heat spreader is investigated. To look more closely, the effects of putting the newly added layers on the mechanism of the heat transfer are studied. In particular, the influence of the graphene sheet insertion, on the maximum value of the hotspot is concerned. The geometry is defined in similarity to the work by Subrina *et al* [39], where the graphene layers are situated between the SiO_2 and Si substrates. The thickness of the each graphene sheet is 0.345 nm. Similar to the foregoing samples, the heat flux of $Q = 10^{19} \text{ W/m}^3$, is applied to the n-shaped region of the silicon channel. All boundaries except the bottom boundary are adiabatic. Hence, the most of the heat generated inside the cubic MOSFET is conducted toward it. In addition, two other sets of circumstances are also explored. First, the case in which the graphene boundaries are also adiabatic, is researched. Then, the transistor is considered to exchange heat from right and left boundaries of the graphene sheet. In other words, two left and right sides of the graphene is kept at the ambient temperature.

3. Mathematical modeling

In this paper, the three-dimensional non-linear DPL modeling is used for the investigation of heat conduction in 3-D MOSFETs with and without graphene sheet heat spreader. The way of using the phase-lagging behavior for heat transfer investigation, firstly, has been opened by the proposition of the single phase-lagging model (CV model), $\vec{q}(t + \tau_q, \vec{r}) = -k \nabla T(t, \vec{r})$, by Cattaneo [44] and Vernotte [45]. In this model, the heat flux vector, $\vec{q}$, is the effect of temperature gradient. Also, τ_q , the relaxation time, is the time delay between these happenings and k is the thermal conductivity. In 1995, Tzou announced a non-Fourier phenomenological equation for heat conduction in which, the heat flux vector somewhere in the material at the time of τ_q , is related to the temperature gradient at the same point at time τ_t via the formula [46, 47],

$$\vec{q}(t + \tau_q, \vec{r}) = -k \vec{\nabla} T(t + \tau_t, \vec{r}), \quad (1)$$

where, τ_q and τ_t are standing for the heat flux and temperature gradient phase lags, respectively. Both parameters are positive and fundamental properties of the material, and may be determined experimentally or numerically. Taylor expanding Eq.1 in three-dimension with respect to time yields:

$$q_\gamma + \tau_q(T) \frac{\partial q_\gamma}{\partial t} = -k(T) \left[\frac{\partial T}{\partial \gamma} + \tau_t(T) \frac{\partial}{\partial t} \frac{\partial T}{\partial \gamma} \right], \quad (2)$$

where, γ is the representative of the x , y and z component of coordinates.

Furthermore, considering $C(t)$ as the volumetric heat capacity of the material, the energy equation is written as,

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = -C(T) \frac{\partial T}{\partial t} + Q. \quad (3)$$

In the present study, three Taylor-expanded DPL equation (Eq. 2), which is coupled with the energy equation, is used simultaneously to investigate the heat transport process [48, 49]. For some cases of transistors, the temperature-dependent thermal properties are considered.

Looking more precisely to the DPL and energy equations by taking the derivative of Eq. 2 with respect to the one of the components like x , it can be seen that the result of taking into account the temperature-dependent properties causes the appearance of the terms such as $\frac{\partial \tau_q}{\partial x}$. This corresponds to the non-monotonous distribution of τ_q . It is conspicuous that the components of the heat flux vector can not be removed between the three DPL equations and the energy equation, and consequently, these equations should be separately solved. In addition, the boundary-phonon scattering is considered by exerting the following mixed-type boundary condition in analogy to the work done by Ghazanfarian and Abbassi [33, 34],

$$T_s - T_w = -\alpha Kn \frac{\partial T}{\partial n}|_{\Omega}. \quad (4)$$

Here, T_s and T_w are respectively, the temperature-jump of the wall and the boundary temperature. α is a non-dimensional modifiable coefficient, Ω includes all boundaries of the solution domain, and n is the direction of the outward normal vector of the boundary. Also the Knudsen number, Kn , is the ratio of the mean free path to the size of the system. Hence, the above equation is the boundary condition applied to the all open bottom boundaries. Further all the other adiabatic boundaries fulfill the following condition:

$$\vec{q} \cdot \vec{n} = 0. \quad (5)$$

More importantly, the non-dimensional parameter B , which is the ratio of the temperature relaxation time, τ_t , to the heat flux relaxation time, τ_q , is defined. Then, $B\tau_q$ is substituted for τ_t in Eq. 2.

The values of two unknown parameters α and B , for each instant of time, have been computed and presented for 1-D and 2-D silicon devices [33, 34]. In this work, for some three-dimensional silicon structures, the values of the two unknown parameters α and B , for each instants of time, is determined in a such way that the results of the 3-D DPL model is in agreement with the solutions of the lattice Boltzmann equation. It is obtained that the value of the parameter B , changes with time and is given by the following relations

$$B = 0.25\Theta(20 - t^*) + 1.9\Theta(t^* - 20) \quad (6)$$

where, t^* is the dimensionless time, which is scaled to 1 *ps*. As it is shown, a simple Heaviside step function is found for parameter B . Also the unified $B = 0.25$, for all times is also checked. It is attained that this unique B roughly predicts the overall behavior of the temperature and heat flux distributions. This non-zero B , manifests that the thermal behavior deviates from the Fourier's law. Inevitably, replacing the Fourier's law by the non-Fourier methods such as the present 3-D DPL model is an essential development. Just as the time passes, B increases to prevent the reduction of the effect of the phase-lagging term. On the other hand, as the system reaches the steady state, the effect of the phase-lagging term diminishes. As a result, the value of the parameter B has a limitation.

4. Numerical considerations

In the following subsections, the numerical issues in modeling the different four cases of MOSFETs are discussed thoroughly.

4.1. *Applied method*

In the present work, the 3-D DPL and energy equations are discretized simultaneously by using the fully implicit finite difference scheme with the central discretization of all derivatives associated with the Dirichlet, Neumann, and Robin Boundary conditions. Solving three components of DPL model along with the energy equation makes sense since four first-order coupled partial differential equations (PDE)s are solved instead of one single third-order PDE. This simplification results in some numerical difficulties, which are thoroughly explained in Shomali and Abbassi [48].

4.2. *Convergence contemplation*

Owing to the utilization of the mentioned method for modeling the desired structures, and also the appearance of the non-linearity due to the consideration of the temperature-dependent thermal properties, the under-relaxation factors are introduced as ω_T and ω_q . These factors are used in the beginning of a new iteration for $Y = T, q$ via the following relations, $Y_i = \omega_Y Y_i + (1 - \omega_Y) Y_{i-1}$. It is obtained that the value of these factors strongly relies on the value of B . As B becomes larger, the relaxation factors, which make the convergence of the solution easier get smaller. Strictly speaking, it is found that, when B is smaller than 0.1, the relaxation factors $\omega_{q,T} \leq 0.8$ are sufficient to satisfy the heat flux and temperature convergence. Furthermore, taking $\omega_{q,T} \leq 0.1$ is adequate for fulfilling the convergence condition

of the problem with $0.1 < B < 0.45$. For greater B , the under relaxation factors are needed to decrease to 0.05 or even smaller. Obviously, the optimum computational time is reached by the consideration of maximum values of the indicated $\omega_{T,q}$. It is important to note that by taking into account the temperature-dependent thermal properties, smaller under-relaxation factors should be used.

4.3. Grid independency check

Moreover, the tolerance of residuals of temperature and heat flux on convergence relative to the infinity norm is set to 10^{-10} . Further, the mesh-independence test is checked for all cases. As it is seen in table. 1, the mesh for a common 3-D MOSFET is a uniform three-dimensional $101 \times 101 \times 201$ numerical mesh, which is sufficient for generating the mesh-size-independent results for all times. For the FinFET and Tri-Gate structures, the x , y , and z dimensions of the channel are discretized into 22, 201, and 101 nodes. Also, the substrate is meshed by the grid of $101 \times 201 \times 101$ nodes. Besides, the time-step is taken to be 10^{-2} ps. It is attained that these discretizations are the appropriate ones for meshing the structures such that they make the results, mesh- and time-step size independent.

5. Results and discussions

The present 3-D DPL model is employed to study the temperature and heat flux distributions for all four types of 3-D MOSFETs. Also, each of these 3-D transistors are dealt for various conditions. In the forthcoming sections, the obtained results are discussed.

5.1. Case I

The case I explores the modeling of a common 3-D MOSFET by imposing three-dimensional DPL method. The proposed transistor is the same as that of considered in [34], which is a cube with the cross section of $100\text{ nm} \times 50\text{ nm}$, and the depth of $1\mu\text{m}$. The thermal parameters of the bulk silicon at 300 K are given in table 2. As it is shown in Figs. 2(a,b), the results obtained from the new modeling of the 3-D DPL method fit well with the results displayed in [34]. This shows the proficiency and accuracy of the present 3-D numerical simulation. To be more precise it is found that for $t = 10\text{ ps}$, when the out-of-plane dimension is larger than 22 nm , the heat flux and temperature distribution plots along the y coordinate are similar to that of the 2-D MOSFET. In other words, the third dimension will not affect much on results when it is greater than 22 nm . For the y values less than 22 nm , the effects related to the three-dimensionality appear such that the behavior of the heat and temperature profiles are different for all values of the y coordinate.

5.2. Case II

In this section, the FinFET transistor discussed in [43], is studied. By the verification of results obtained from the 3-D DPL non-linear method, with the atomistic results presented in [43], the appropriate value of key parameter B , which is the ratio of τ_t to τ_q can be tuned. In the mentioned work, the results are acquired by implying the finite-volume-lattice-Boltzmann method. In equivalence to the nano-system remarked in [43], the heat generation zone of the FinFET transistor is on for the first 10 ps switching time, then the transistor starts to get cool. As Fig. 3 suggests, in similar conditions, by

searching for the correct value of B for Silicon and Silicon-dioxide, the temperature and heat flux plots match almost well with those of Samian *et al.*

In agreement with the previous studies, the DPL model predicts the heat transfer almost better for lower instants of time [48, 49]. It is important to note that the non-Fourier effects appear for the ultra-fast and micro/nano sized processes. Hence, as the time passes and gets larger relative to the characteristic time, the behavior of the system starts to deviate from the non-Fourier etiquette and it becomes nearer to the Fourier behavior. For this reason, parameter B , which is the principal factor to fit the results of the DPL to the lattice-Boltzmann, enhances as time increase.

Also, as time evolves, a discrepancy between our results and those of Samian *et al.* appears. As it is manifested in Fig. 4, a breaking which is presented in the heat flux plots of $t \geq 15$ ps, come into sight for greater time in our results. The Fig. 5 displays the heat flux profile at $t = 20$ ps. It is obtained that for times greater than 15 ps, the heat flux value drops more quickly due to the enhancement of phase-lags ratio. Moreover, the heat flux is plotted for the unified parameter $B = 0.25$. As it is seen, this unified B does not predict the results accurately. Hence, the time-dependent parameter B is more preferable in the numerical investigation of 3-D Silicon MOSFETs.

In the next step, the effect of considering the more realistic temperature-dependent thermal properties is investigated. The temperature-dependent thermal characteristics of the bulk silicon are presented in [49]. Two different cases of a 3-D FinFET are studied. The first one is the three-dimensional FinFET device with an all-time heat generation zone, while the second con-

figuration is the one in which the heat is generated for the first 10 ps , and then the cooling process takes place. For the first case, as it is shown in Figs. 6(a,b), taking into account such relevance, only changes the value of the obtained temperature and heat flux while it does not drastically modify the trends. This finding is in consistence to the results obtained for the large-sized 1-D transistors, and is in contrast to the results obtained for low-sized 1-D transistor [49]. This deduction is somehow guessable due to the fact that while dealing with systems, as the size of the 1-D transistors increases, the influence of such dependency decreases. Further, Figs. 6(c,d) show that the response of the second case to the temperature-relevance thermal parameters is similar to that of the first one. This is also assigned to the attitude of the large-sized nano-structures.

In addition, by enlarging the time, the difference between the temperature profiles obtained by taking into account the temperature-dependent thermal properties, and the one calculated by considering the constant thermal parameters becomes more accentuated. This is because of the way that the thermal conductivity and the specific heat vary with time. Going through time, the temperature gets higher, which results in much larger specific heat and lower thermal conductivity. Hence, as the time increases the temperature, which inversely depends on C_p , and directly on k decreases much more relative to the case with constant parameters.

5.3. Case III

At the next step, the 3-D DPL heat conduction model is used for the investigation of heat transfer in 3-D Tri-Gate transistors. In similarity to the mentioned FinFET, the n-shape region of the present 3-D MOSFET

is heated for the first 10 *ps*. One of the most important findings is the appearance of a small peak in addition to the main large peak manifested in the heat flux plots of the FinFET MOSFETs. In Figs. 7(b,d), the first small and second large peaks are appeared. These peaks occur at the places where the heat generation zone meets the non-heating region. Since the heating zone is n-shaped, when the heat flux is plotted versus z , it is expected that two peaks in the heat flux plots take place at the boundaries between the heat generation region and non-heated zone. Hence, when whole top silicon cube act as heat generation region, the small peak disappears. Also, the temperature distribution manifests a non-monotonous behavior. As it is exhibited in Figs. 7(a,c), the temperature presents an unusual enhancement at the region in which the heat generating existed relative to the other places over the center-line of the transistor. In analogy to the appearance of the small peak in heat flux plots, this growth is also due to the act of the n-shaped heat generation zone.

Just as the time passes, the system starts to move to the condition similar to the FinFET structures. This is due to the switching off the heating zone, which results in equivalence of the Tri-Gate and FinFET transistors in larger times. Consequently, as it is obvious from Figs. 8(b) and 9, after $t = 15$ *ps* the second peak in heat flux commences to fade, such that it evanesces completely at 20 *ps*. Accordingly, this disappearance also takes place for the peak appearing in the beginning of the temperature plot, such that as it is presented in Fig. 8(a), at $t = 15$ *ps*, this augmentation is completely resolved.

These results confirm that the presence of the third gate in Tri-Gate

MOSFETs does not make the transistor thermally inefficient. In other words the third gate, which is existed at top of the channel, only mildly changes the heat flux and temperature distributions near the top gate for the first 15 *ps*. In consequence, one more gate of the Tri-Gate coupled to the two gates of the FinFET transistor, makes the Tri-Gate MOSFET electrically more effective while it leaves the thermal affects such as the value of the hotspot nearly untouched. As a result, it is obtained that the use of Tri-Gate MOSFETs instead of the FinFETs has been more beneficial to the nano-electronic industry.

Besides, the more realistic case of a Tri-Gate with temperature-dependent thermal parameters are investigated. In similarity to the Tri-Gate with constant thermal properties, the heat generation zone is considered to be switched on for the first 10 *ps*. As it is conspicuous in Figs. 10(a-d), taking into account such relevancy increases the flux of heat flowing toward the bottom boundary of the Tri-Gate, which accordingly decreases the value of the temperature along the center-line. Hence, all the studies considering the MOSFETs with constant thermal characteristics, have over-estimated the value of the temperature in the whole transistor, and in hotspots. Also, it is found by contemplating temperature-dependent thermal properties that the effect of the presence of the third gate on thermal responses of the Tri-Gate, reduces more quickly. To be more precise, as Figs. 10(b,d) illustrate the second peak of the heat flux profile of the transistor with temperature-dependent thermal properties diminishes more promptly such that it completely disappears at $t = 15$ *ps*. At last, it is obtained that the Tri-Gate transistor with real circumstances is the admirable one for using in the new generation of

electronic chips.

5.4. Case IV

In this part, the other main goal of this paper is implemented. A graphene sheet is added between the silicon and silicon dioxide substrate layers. It is evident that the usage of graphene heat remover effectively decreases the temperature enhancement caused by the generated heat inside the transistor. In the following, the procedure is explained in details. The switching time of the transistor is taken to be 10 ps . During this time the $1 \times 10^{19}\text{W}/\text{m}^3$ heat is produced inside the n-shaped region. After $t = 10\text{ ps}$, this generated heat starts to spread over the transistor. The case IV deals with the 3-D Tri-Gate MOSFET in the presence of the graphene heat removal. To be more precise, the effect of using few-layer graphene (FLG), say, one to twenty layers of the graphene is investigated. In analogy to the previous case, it has been shown that the thickness of the graphene heat spreader directly affects the heat flux removal from the hotspot zone.

It is obtained that for the first 20 ps of the transient regime, this insertion, nearly does not change the behavior of the temperature and heat flux plots. After $t = 20\text{ ps}$, the graphene heat remover slowly exerts influences on the heat flux and temperature distribution of the regions around and at the place of the spreader. As the time passes, the zone which is under the effect of the presence of the graphene gradually enlarges, while the strength of the effect also steadily increases. This finding is easy to understand, since it takes time for the heat generated at the top of the channel to reach to the underlying heat spreader and get perturbed.

This slow influence penetration of the graphene heat spreader is shown

in Fig. 11(a). It should be emphasized that when the number of graphene layers is less than ten, the use of the heat spreader is not worthwhile. This is due to the fact that adding the graphene sheets to the transistor makes the designing process more complex and expensive while receiving a very little impact on the reduction of the peak temperature rise. On the other hand, the thermal characteristics of the FLG, in the limit of large number of layers tends to that of graphite. As a consequence, due to the increment of the thickness of the transistor, which is in contrast to the spirit of nano-electronic industry, and also the loss of superior thermal conductivity of the graphene, which is the reason of using this material as a good candidate for heat spreading, the number of graphene layer between the SiO_2 and Si substrate cannot be enlarged non-systematically.

In this paper, it is shown that 10 to 30 graphene sheets are the optimum amount of layers needed as a heat remover. It is attained that this number of layers is not too few such that it could not affect the heat management of the transistors, but also not too many that the problems related to the large number of layers to be appeared.

As it is manifested in Figs. 11(a) and (b), when $t = 10\ ps$, the temperature and heat flux profiles of the Tri-Gate MOSFET with and without a heat spreader are almost the same. But as the time passes, the difference between the temperature and heat flux distributions of these two different 3-D MOSFET becomes more apparent. For instance after $100\ ps$, the insertion of the graphene heat remover decreases the peak temperature rise up to nearly 20%. Further, interestingly, at $t = 150\ ps$, the graphene-based Tri-Gate presents 50% reduction in the maximum temperature value relative

to that of the typical Tri-Gate. Additionally, as it is obvious in Fig. 11(b), the heat flux distribution also varies in the benefit of the reduction of the overall temperature value.

At last, the peak temperature reduction of the other mentioned case of a Tri-Gate MOSFET with a heat spreader is investigated. In similarity to the work by Subrina *et al.* [39], this 3-D Tri-Gate transistor is considered to exchange heat from right and left boundaries of the graphene sheets. It is acquired that the effect of such graphene sheet open boundary does not show up any distinction. That is to say the temperature profiles of the two various 3-D Tri-Gate transistors including a heat removal segment, are the same.

6. Conclusions

The heat transfer issue in three dimensional silicon MOSFET was considered. Three cases of the common 3-D silicon MOSFET, the FinFET transistor, and the Tri-Gate silicon transistor are investigated. The modeling is done by employing the 3-D non-linear DPL method. First, the common 3-D MOSFET and the FinFET transistors are used to verify the results with the existent data. During this verification the parameter $B = \tau_t/\tau_q$ is adjusted for a 3-D silicon material.

Then the typical Tri-Gate transistor is studied and the results are compared to those of FinFET transistors. The appearance of the relative peak of heat flux in addition to the absolute peak existed in the FinFET, is the main contribution in thermal behavior occurring in the Tri-Gate MOSFET. Also, the effect of considering the temperature dependence of the thermal param-

eters on the temperature and heat flux distributions of the 3-D transistors are investigated. It is seen that taking into account such relevancy, does not vary the overall behavior of the profiles and it only changes the values of the temperature and heat flux.

At last, the graphene sheet heat remover is added to the 3-D silicon Tri-Gate MOSFET and the non-Fourier effect of placing the graphene sheet is investigated. It is seen that putting the graphene heat spreader between the silicon and silicon dioxide substrates decreases the overall and in particular the maximum peak temperature rise in the hotspot zone up to 50%. Also, the use of graphene makes the process of device cooling faster. For instance, 100 *ps* after the heat generation zone gets off, the maximum temperature of a 3-D Tri-Gate transistor with a graphene sheet heat spreader becomes 20% lower than that of a common 3-D Tri-Gate MOSFET. It should be also mentioned that the results of the Fourier-based studies over-estimates the effect of setting a graphene heat remover, hence, the non-Fourier investigation of such system is necessary.

In conclusion, due to the absence of the study which precisely concerns the 3-D MOSFETs, the corresponding 3-D dual-phase-lag model for the investigation of non-linear nanoscale heat transfer phenomenon in various 3-D MOS devices, such as FinFET and Tri-Gate transistors is evaluated in this paper. Furthermore, as there is no work considering the non-Fourier effects of the setting graphene as a heat spreader in MOSFETs, these non-Fourier consequences are also studied.

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List of Tables

1	Mesh-time step independency check	33
2	The thermal properties of silicon [32] and silicon-dioxide [50] at $T = 300\text{ K}$	33

List of Figures

1	Schematic of geometry (a) The common 3-D silicon MOSFET, (b) The Fin-field effect transistor, (c) The typical Tri-Gate transistor.	34
2	(a) The comparison of temperature profiles obtained from the present study with the result presented in Ghazanfarian and Shomali [34] at $t = 10 \text{ ps}$, (b) The heat flux versus z over center-line for $t = 10 \text{ ps}$	35
3	(a) The temperature distribution of the FinFET with constant thermal properties over center-line when $t = 5 \text{ ps}$, (b) The heat flux profile for the same FinFET at $t = 5 \text{ ps}$, (c,d) the same as (a) and (b) but for $t = 10 \text{ ps}$	36
4	(a) The center-line temperature profile of the Fin-field effect transistor at $t = 15 \text{ ps}$, (b) The Heat flux distribution along z direction at the center-line of the FinFET when $t = 15 \text{ ps}$. . .	37
5	The heat flux plot of the FinFET at $t = 20 \text{ ps}$	38
6	(a) The temperature and (b) the heat flux distributions for the FinFET with constant (CST) and temperature-dependent (TD) thermal parameters on heat generating region, (c,d) The same as (a,b) but for the FinFET in which the heat generation zone is switched on for the first 10 ps at $t = 15 \text{ ps}$	39

7	(a) The temperature profiles for a Tri-Gate MOSFET with constant thermal characteristic at the center-line when $t = 5 \text{ ps}$, (b) Heat flux versus z for a Tri-Gate transistor at $t = 5 \text{ ps}$, (c) The temperature distribution at 10 ps , (d) The same as (b) but for $t = 10 \text{ ps}$ when $B = 0.25$	40
8	(a) The temperature and (b) the heat flux distributions along the center-line at $t = 15 \text{ ps}$	41
9	The heat flux profiles at the center-line when $t = 20 \text{ ps}$ and $B = 1.9$	42
10	(a) The temperature profiles of the Tri-Gate with constant (CST) and temperature-dependent (TD) thermal parameters along the center-line at $t = 5 \text{ ps}$, (b) The heat flux distribution for the Tri-Gate with CST and TD thermal specifications when $t = 5 \text{ ps}$, (c,d) the same as (a) and (b) but for $t = 15 \text{ ps}$	43
11	(a) The temperature distributions of the Tri-Gate MOSFET with and without the presence of the graphene heat spreader along the center-line at different times, (b) The heat flux distribution for the same transistors mentioned in (a).	44

Table 1: Mesh-time step independency check

<i>number of grids in :</i>	x-	y-	z-direction	<i>time step size (ps)</i>
Case I	101	201	101	0.01
Cases II-IV: channel	22	201	101	0.01
Cases II-IV: substrate	101	201	101	0.01

Table 2: The thermal properties of silicon [32] and silicon-dioxide [50] at $T = 300$ K.

	$ \mathbf{v} $ (ms^{-1})	k ($Wm^{-1}K^{-1}$)	C ($Jm^{-3}K^{-1}$)	λ (nm)
<i>Si</i>	3000	150	1.5×10^6	100
<i>SiO₂</i>	5900	1.4	1.75×10^6	0.4

Figure 1: Schematic of geometry (a) The common 3-D silicon MOSFET, (b) The Fin-field effect transistor, (c) The typical Tri-Gate transistor.

Figure 2: (a) The comparison of temperature profiles obtained from the present study with the result presented in Ghazanfarian and Shomali [34] at $t = 10$ ps, (b) The heat flux versus z over center-line for $t = 10$ ps.

Figure 3: (a) The temperature distribution of the FinFET with constant thermal properties over center-line when $t = 5$ ps, (b) The heat flux profile for the same FinFET at $t = 5$ ps, (c,d) the same as (a) and (b) but for $t = 10$ ps.

Figure 4: (a) The center-line temperature profile of the Fin-field effect transistor at $t = 15$ ps, (b) The Heat flux distribution along z direction at the center-line of the FinFET when $t = 15$ ps.

Figure 5: The heat flux plot of the FinFET at $t = 20 \text{ ps}$.

Figure 6: (a) The temperature and (b) the heat flux distributions for the FinFET with constant (CST) and temperature-dependent (TD) thermal parameters on heat generating region, (c,d) The same as (a,b) but for the FinFET in which the heat generation zone is switched on for the first 10 ps at $t = 15$ ps.

Figure 7: (a) The temperature profiles for a Tri-Gate MOSFET with constant thermal characteristic at the center-line when $t = 5$ ps, (b) Heat flux versus z for a Tri-Gate transistor at $t = 5$ ps, (c) The temperature distribution at 10 ps, (d) The same as (b) but for $t = 10$ ps when $B = 0.25$.

Figure 8: (a) The temperature and (b) the heat flux distributions along the center-line at $t = 15$ ps .

Figure 9: The heat flux profiles at the center-line when $t = 20 \text{ ps}$ and $B = 1.9$.

Figure 10: (a) The temperature profiles of the Tri-Gate with constant (CST) and temperature-dependent (TD) thermal parameters along the center-line at $t = 5$ ps, (b) The heat flux distribution for the Tri-Gate with CST and TD thermal specifications when $t = 5$ ps, (c,d) the same as (a) and (b) but for $t = 15$ ps.

Figure 11: (a) The temperature distributions of the Tri-Gate MOSFET with and without the presence of the graphene heat spreader along the center-line at different times, (b) The heat flux distribution for the same transistors mentioned in (a).