Jia *et al. Nanoscale Res Lett* (2021) 16:29
https://doi.org/10.1186/s11671-021-03490-6

Nanoscale Research Letters

NANO EXPRESS

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Analytical Model for the Channel Maximum Temperature in Ga_2O_3 MOSFETs

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Abstract

In this work, we proposed an accurate analytical model for the estimation of the channel maximum temperature of Ga_2O_3 MOSFETs with native or high-thermal-conductivity substrates. The thermal conductivity of Ga_2O_3 is anisotropic and decreases significantly with increasing temperature, which both are important for the thermal behavior of Ga_2O_3 MOSFETs and thus considered in the model. Numerical simulations are performed via COMSOL Multiphysics to investigate the dependence of channel maximum temperature on power density by varying device geometric parameters and ambient temperature, which shows good agreements with analytical model, providing the validity of this model. The new model is instructive in effective thermal management of Ga_2O_3 MOSFETs.

Keywords: Analytical model, Maximum temperature, Ga_2O_3, Thermal conductivity

Background

Gallium oxide (Ga_2O_3)-based metal–oxide–semiconductor field-effect transistors (MOSFETs) are excellent candidates for next generation power electronics, which are benefited from two major advantages of Ga_2O_3: the significantly high bandgap (~4.8 eV) and high-quality bulk crystals produced at low cost [1]. Tremendous efforts have been devoted to improving its electrical properties in all aspects like current density [2], breakdown voltage [3], and power figure-of-merit [4]. With the experimental confirmation of its unprecedented potential for power electronic devices [5–9], it is now of paramount importance to explore the performance and reliability of Ga_2O_3 MOSFETs, such as the issue of self-heating effects and hence the channel maximum temperature (T_{max}), due to its relatively low thermal conductivity (κ, 0.11–0.27 $Wcm^{-1}\,K^{-1}$ at room temperature) [1].

In recent years, various methods for estimating the T_{max} of Ga_2O_3 MOSFETs have been proposed theoretically and experimentally [10–13]. In general, numerical simulations can quantitatively estimate T_{max} of a certain device. However, this is time consuming [14]. On the other hand, the extraction of T_{max} through experiments is always underestimated [15]. Therefore, an analytical model has to be made in order to adequately model the T_{max} in Ga_2O_3 MOSFETs, which can provide sufficient accuracy with time-efficiency and qualitative assessments [14].

In this paper, we propose an analytical model of T_{max} for Ga_2O_3 MOSFETs by employing Kirchhoff's transformation, considering the dependence of κ on temperature and crystallographic directions for Ga_2O_3. The proposed model can be applied for Ga_2O_3 MOSFETs with native or high-thermal-conductivity substrates. The validity and the accuracy of the analytical model are methodically verified by comparison with the numerical simulations via COMSOL Multiphysics.

Methods and Model Development

The analytical model for T_{max} in Ga_2O_3 MOSFETs is proposed based on the structure shown in Fig. 1. Key parameters of structure are listed in Table 1. In fact, it has been demonstrated that Joule heating is concentrated at the drain edge of the gate in Ga_2O_3 MOSFETs [13]. In order to simply the model, it is assumed that the heating effect from the gate is uniform [12] and can completely penetrate through the gate oxide due to its

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Table 1 Key parameters of structure

Symbol	Quantity	Default value
L_g	Gate length	2 μm
L	Device length	150 μm
t_{ch}	Channel thickness	300 nm
t_{sub}	Substrate thickness	500 μm

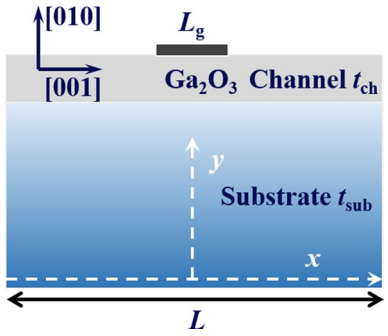

Fig. 1 The schematic diagram of Ga_2O_3 MOSFET

negligible thickness. Different substrate materials underneath Ga_2O_3 channel are considered in this model, such as bulk Ga_2O_3 and high κ materials, aiming at the board feasibility and compatibility. Thus, the device is viewed as a two-layer problem. The substrate contacts with an ideal heat sink so that the bottom surface is isothermal, and its temperature equals to that of ambient temperature (T_{amb}, 300 K by default). Adiabatic boundary conditions were imposed on other surface of the structure. These boundary conditions can be summarized as [14, 16]

$$\kappa_y \frac{\partial T}{\partial y}\bigg|_{y=t_{ch}+t_{sub}} = \begin{cases} \frac{P}{L_g} |x| \le \frac{L_g}{2} \\ 0 |x| > \frac{L_g}{2} \end{cases}, \tag{1}$$

$$T|_{y=0} = T_{amb}, \tag{2}$$

$$\frac{\partial T}{\partial x}\bigg|_{x=-\frac{L}{2}} = \frac{\partial T}{\partial x}\bigg|_{x=\frac{L}{2}} = 0, \tag{3}$$

where P, T and κ_y denote the power dissipation density, temperature and thermal conductivity of [010] direction for Ga_2O_3, respectively. It should be emphasized that the unit of P is W/mm in this paper.

The κ value of Ga_2O_3, one of the key parameters for the thermal characteristic of material, plays an important role in the diffusion of heating effect as well as the accuracy of model. That is to say, a carefully description of κ value is required, due to its serious anisotropy and temperature-dependence [17]. In general, the dependence of κ of Ga_2O_3 on temperature (T) along two different crystal orientations ([001] and [010]) is given by

$$\kappa_{[001]}(T) = 0.137 \times \left(\frac{T}{300}\right)^{-1.12}, \tag{4}$$

$$\kappa_{[010]}(T) = 0.234 \times \left(\frac{T}{300}\right)^{-1.27}. \tag{5}$$

The comparison study of T_{max} at different P was carried out by COMSOL Multiphysics, considering constant and realistic κ, respectively. We found that at a P of 1 W/mm, T_{max} values of 533 K and 622 K are obtained, respectively (not shown). Therefore, it is quite necessary to take into account the impacts of T and crystallographic direction on the κ of Ga_2O_3 in the model.

The temperature behavior is governed by the heat conduction equation. The heat conduction equation at steady-state in Ga_2O_3 domain is

$$\frac{\partial}{\partial x}\left(\kappa_x(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\kappa_y(T)\frac{\partial T}{\partial y}\right) = 0, \tag{6}$$

where κ_x denotes the thermal conductivity of [001] direction for Ga_2O_3. The nonlinear heat conduction equation can be solved by employing Kirchhoff's transformation. However, the application of Kirchhoff's transformation may be restricted due to the highly anisotropic κ in Ga_2O_3, which is valid, strictly speaking, only for materials with isotropic κ [14]. Given the above limitation, one should not consider κ_x and κ_y to be two independent variables. Figure 2 shows the relationship between the thermal resistivity, i.e., $1/\kappa$, and T for directions of [001] and [010] over a large T range, respectively. It can be seen that $1/\kappa_y$ can be substituted with $1/(c\kappa_x)$ and c is chosen to be equal to 1.64. Consequently, Eq. (6) can be transformed to the following equation:

$$\frac{\partial}{\partial \mathrm{x}}\left(\kappa_x(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial \mathrm{y}}\left(c\kappa_x(T)\frac{\partial T}{\partial y}\right) = 0. \tag{7}$$

Based on the preceding approximations of κ_x and κ_y, the Kirchhoff's transformation can be employed without any restrictions. Besides, it also can be seen that the reciprocal of κ is expected to be proportional to T. Thus, in order to reduce the computational complexity, the expression of $1/\kappa_x$ can be simplified as $1/\kappa_x = aT + b$, as shown in Fig. 2. The reason for the use of a, b and c is just convenience in writing the equations that follow.

By the application of Kirchhoff's transformation and the method of separation of variables, the expression of T_{max} can be derived as

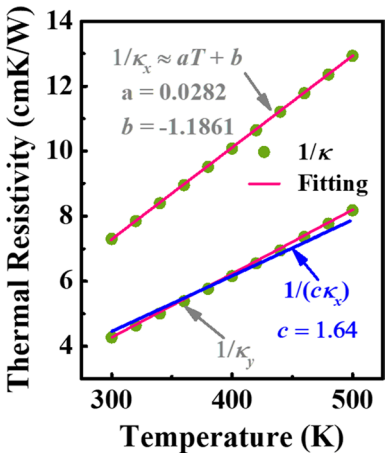

Fig. 2 The relationship between the thermal resistivity and *T* for directions of [001] and [010]. Green symbols and red lines denote actual and fitted values, respectively. Blue line represents the hypothesis of $1/\kappa_y \approx 1/(c\kappa_x)$, where $c = 1.64$

$$T_{max} = \left(T_{amb} + \frac{b}{a}\right) exp\left(\frac{aP(t_{ch} + t_{sub})}{cL} + \frac{aPSL}{\sqrt{c}\pi^2 L_g}\right) - \frac{b}{a}, \tag{8}$$

where

$$S = \sum_{n=1}^{\infty} \frac{\sin n\pi \frac{L_g}{L}}{n^2} \frac{\sinh 2n\pi \frac{t_{ch}+t_{sub}}{\sqrt{cL}}}{\cosh 2n\pi \frac{t_{ch}+t_{sub}}{\sqrt{cL}}}. \tag{9}$$

It should be pointed out that *S* is a convergent infinite series and its approximate value which can be obtained easily is used in calculation instead of its actual value.

In the case of Ga_2O_3 MOSFETs with high κ substrates, Kirchhoff's transformation cannot be directly applied theoretically. In fact, for the transformation to be valid, the boundary conditions should be either isothermal (constant *T* surface), or have a fixed heat flux density. However, due to the different κ of Ga_2O_3 and substrate material, both of these boundary conditions are not completely met at the Ga_2O_3/substrate interface. Considering that the κ of Ga_2O_3 is much lower than high κ substrate, a hypothesis, the isothermal interface between the Ga_2O_3 and the substrate, is introduced. This hypothesis is instrumental in deriving the expression T_{max} and its validity will be verified later. In this case, the thermal resistance (R_{TH}) of high κ substrate, a ratio of the difference between the T_{int} and T_{amb} and the *PW*, i.e., $R_{TH} = (T_{int} - T_{amb}) / (PW)$, can be calculated as $R_{TH} = LW/(\kappa t_{sub})$, where *W* is the width of substrate [19]. Thus, the expression of the temperature of Ga_2O_3/substrate interface (T_{int}) is

$$T_{int} = \frac{Pt_{sub}}{\kappa_{sub} L} + T_{amb}, \tag{10}$$

where κ_{sub} is the thermal conductivity of heterogeneous substrate, which is assumed to be constant. In addition, it should be pointed out that the thermal boundary resistance between Ga_2O_3 and heterogeneous substrates is not included in the model. Therefore, with the help of Eq. (8), the expression of T_{max} for Ga_2O_3 MOSFETs with heterogeneous substrate can be derived as

$$T_{max} = \left(T_{int} + \frac{b}{a}\right) exp\left(\frac{aPt_{ch}}{cL} + \frac{aPSL}{\sqrt{c}\pi^2 L_g}\right) - \frac{b}{a}, \tag{11}$$

where

$$S = \sum_{n=1}^{\infty} \frac{\sin n\pi \frac{L_g}{L}}{n^2} \frac{\sinh 2n\pi \frac{t_{ch}}{\sqrt{cL}}}{\cosh 2n\pi \frac{t_{ch}}{\sqrt{cL}}}. \tag{12}$$

Results and Discussion

The validity of the analytical model for the T_{max} in Ga_2O_3 MOSFETs was systematically verified in this section, considering both native substrate and the counterpart with higher thermal conductivity. The best way to test the validity of a model is against experimental data. However, some key geometric parameters could not be found in experimental literatures, such as t_{sub} and *L* in Ref. [12]. Therefore, finite-element simulation, one of the most accurate means, is used to verify our model. Figure 3 shows dependence of T_{max} on power density *P* obtained from both COMSOL Multiphysics and analytical model, for Ga_2O_3 MOSFET with native substrate. Varied key parameters are considered, including device length *L*, substrate thickness t_{sub}, and ambient temperature T_{amb}. As shown in Fig. 3a, the T_{max} is naturally increased with the raised power density and the increase rate is boosted with the smaller *L*. This is attributed to that the device with larger *L* allows heat dissipation from the active region and hence its overall temperature is lower than that with smaller *L* at same *P* [11]. That is to say, its R_{TH}, the slope of curves, is smaller than that of latter. Furthermore, since the κ of Ga_2O_3 will decrease with the increase in overall temperature, its R_{TH} will also increase slower than that with smaller *L* consequently, which is obvious in Fig. 3a [19]. Similarly, the investigation of dependence of T_{max} on t_{sub} was performed, as illustrated in Fig. 3b. It is observed that the trend of T_{max} with respect to *P* is same as that in Fig. 3a. The thinner substrate always produces the alleviated rise in T_{max} over the enlarged power density, which is understandable that the thinner substrate, the lower overall temperature, the smaller

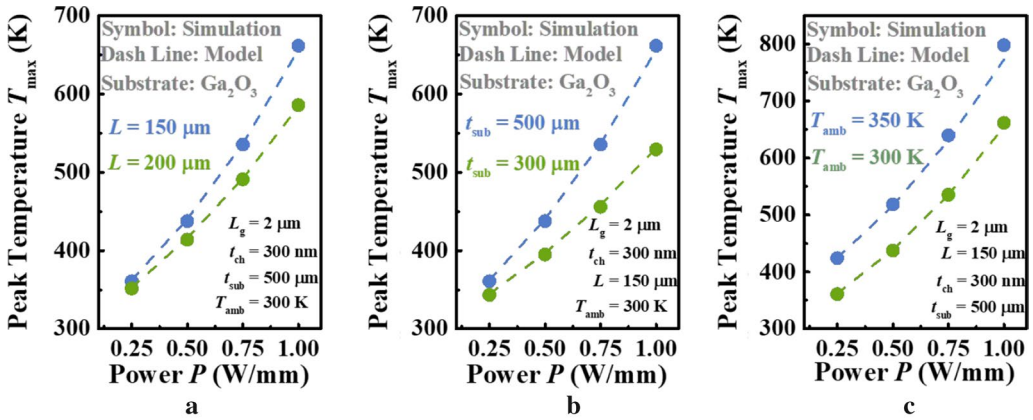

Fig. 3 Dependence of T_{max} on **a** the length of device L, **b** the thickness of substrate layer t_{sub}, and **c** ambient temperature T_{amb} at different power P. Symbols and lines denote the results of proposed model and simulation, respectively

R_{TH} and its increase rate, just like the analysis in Fig. 3a. Figure 3c compares the influence of T_{amb} on T_{max} as P increases. It is evident that the difference between two curves increases slowly, which is different from those in Fig. 3a, b. Ordinarily, R_{TH} is dominated by the geometric parameters of device and the κ value of material. However, considering that the structure is fixed in this case, the increase in R_{TH} is only induced by the decrease in κ of Ga_2O_3. On the other hand, a high level of agreement is observed for the proposed model, which considers the T- and direction-dependent relationship for the κ of Ga_2O_3, confirming the scalable nature of the model. On average, the difference of proposed model and simulation is < 1 K. The overall excellent agreement observed suggests that the proposed model is highly effective and accurate.

Likewise, as shown in Fig. 4, the similar comparisons are repeated for Ga_2O_3 MOSFETs on high κ substrate, SiC. Here, the steps for L and T_{amb} that we choose are larger than those in Fig. 3, and the varied channel thickness t_{ch} is considered instead of t_{sub} in this case. Otherwise, the difference between two curves of T_{max} with respect to P in each figure will be undistinguishable, owing to the efficient heat dissipation capacity of SiC substrate. The κ of SiC (3.7 Wcm^{-1} K^{-1}) applied is a default parameter in COMSOL Multiphysics software. Thanks to high κ of SiC, it can be seen clearly from all figures that the increase in T_{max} is approximately linear as P increases, which means that the influence of temperature on the R_{TH} of device is negligible. It should be pointed out that our model can describe this linear relationship successfully. However, it is obvious that the T_{max} calculated by current model is lower than that predicted by simulation, and this difference is more evident with the increase in power consumption. To show this mechanism, simulated T_{int} are extracted with the power increasing and compared with calculated T_{int} by Eq. (10)

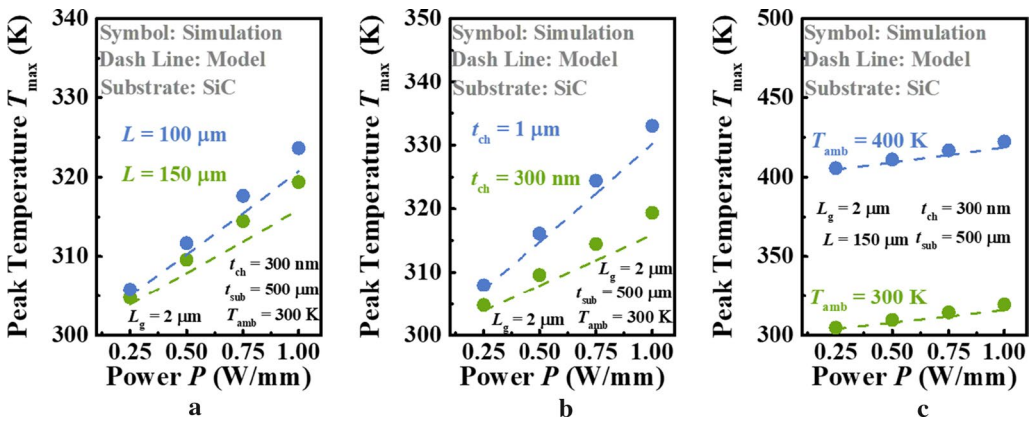

Fig. 4 Dependence of T_{max} of Ga_2O_3 MOSFETs with SiC substrate on **a** the length of device L, **b** the thickness of Ga_2O_3 layer t_{ch}, and **c** ambient temperature T_{amb} at different power P. Symbols and lines denote the results of proposed model and simulation, respectively

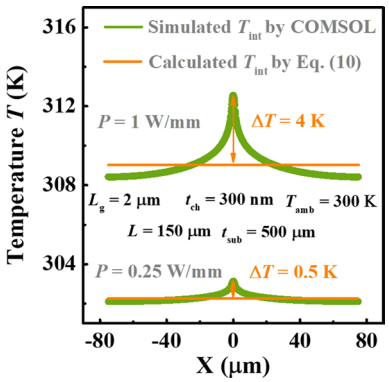

Fig. 5 Comparison of T_{int} between simulated and calculated by Eq. (10) at different P

as plotted in Fig. 5. It is found that the Joule heating becomes more concentrated in the middle of device as P increases. There are 0.5 K and 4 K ΔT between the model and simulation at this location when $P=0.25$ and 1 W/mm, respectively. This is the reason that our model fails to accurately predict T_{max}. Therefore, a more reasonable hypothesis of T_{int} is needed to obtain higher accuracy in future. Nevertheless, the T_{max} is predicted by model to be only < 4 K lower than that by simulation even under 1 W/mm power dissipation density. That is to say, although the hypothesis of uniform T_{int} is inconsistent with fact, our model can provide an estimation of T_{max} with enough accuracy.

Conclusions

An accurate analytical model to estimate the T_{max} of Ga_2O_3 MOSFETs involving the temperature- and direction-dependent of thermal conductivity is presented. A simple expression based on device geometry and material parameters has been derived. An excellent agreement has been obtained between the model and COMSOL Multiphysics numerical simulations by varying different power consumption. The proposed model for the T_{max} is of great importance for effective thermal management power devices especially Ga_2O_3 MOSFETs.

Abbreviations

Ga_2O_3: Gallium Oxide; MOSFETs: Metal–oxide–semiconductor field-effect transistors; AlGaN: Aluminum Gallium Nitride; GaN: Gallium Nitride; SiC: Silicon Carbide.

Acknowledgements

Not applicable.

Authors' contributions

XLJ carried out the calculations and simulations. XLJ and HDH drafted the manuscript. GQH and YL helped to revise the manuscript. YH supported the study. All the authors read and approved the final manuscript.

Funding

The authors acknowledge support from the National Key Research and Development Project (Grant No. 2018YFB2200500, 2018YFB2202800) and the National Natural Science Foundation of China (Grant No. 62025402, 91964202, 61874081, 61851406, 62004149, and 62004145).

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Competing interests

The authors declare that they have no competing interests.

Received: 24 November 2020 Accepted: 28 January 2021
Published online: 10 February 2021

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