

Joule Heating in Two-dimensional Materials Based Transistors

Faisal Ahmed¹, Bilal Anjum Ahmed^{1*}, Abbas Saeed Hakeem²

¹Department of Mechanical Engineering, Pakistan

²Center of Excellence in Nanotechnology, Saudi Arabia

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***Corresponding author:** Bilal Anjum Ahmed, Department of Mechanical Engineering, College of Electrical and Mechanical Engineering, National University of Science and Technology, Islamabad-44000, Pakistan

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Abstract

Recently, two-dimensional electronic materials such as graphene, transition metal dichalcogenides and black phosphorus are persuaded as a possible alternative to the conventional silicon based electronic technology due to their exceptional characteristics. Interestingly, the two-dimensional materials exhibit drastically different electrical, mechanical, thermal and physical properties compared to their bulk counterpart materials due to the quantum confinement effect. The two-dimensional materials have been extensively studied under ambient or cryogenic operating conditions in order to explore their intrinsic characteristics and materials' physics. However, the practical electronic devices are operated under aggressive operating conditions like large electrical and thermal stresses, where heat dissipation and its management become critical. Therefore, in this report we sought to review the progress made towards Joule heating effect and remedies for efficient thermal spreading in functional two-dimensional materials-based transistors.

Keywords: Joule heating; Two-dimensional materials; Graphene; High electric field

Mini Review

Transistor is considered as a building block for electronic circuitry, as it is used to control the flow of electric current across its semiconducting channel while applying potential difference along its metallic electrodes (the source and the drain). The flow of current is regulated by a third electrode called the gate, that is separated from a semiconducting channel by an electrically insulating material, as shown schematically in Figure 1(a). When a large amount of electric field (F) [electric potential (V) normalized by channel length (L), $F = V/L$], is applied to a transistor, the kinetic energy of electronic charge carriers in semiconducting channel increases, resulting in the aggressive interaction of carriers with each other and with immediate environment. These charge collision events in association with atomic oscillations, also called phonons, increase the device operating temperature, and this effect is called Joule heating [1]. The extent of Joule/thermal power (P) generated depends on the electrical resistance (R) of a material and the square of current (I) passed across it, as $P=I^2R$ [2]. In a typical integrated circuit, there are over a billion transistors that generate significant amount of thermal energy. If the Joule energy is not dissipated properly, it may lead to malfunction or eventual burning of transistors hence circuits [3].

Silicon is widely used semiconducting channel material for electronics thanks to its abundant availability, cheap and highly suitable electronic properties. Recently, there has been an aggressive push from public as well as industry for flexible, portable and high-performance electronic devices [1]. Silicon fails to meet the daunting criteria since it degrades its properties when scaled to sub-nanometer node. However, other nano materials having fascinating electrical, mechanical and thermal properties have been reported in literature [4-6]. In the emerging two-dimensional (2D) electronic materials graphene, transition metal dichalcogenides (TMDCs) and black phosphorus are considered as most suitable alternatives [2]. The naturally layered structure of these 2D materials enables them to scale down to single layer thickness that is merely $<1\text{nm}$ in z-axis. The thinner physique of 2D materials means that they can easily accommodate a greater number of transistors in the vertical direction unlike bulk silicon devices thereby increasing packing density. It is pertinent to note that the greater packing density leads to the greater thermal power density in functional circuits

based on 2D materials. In addition to this, except graphene, the semiconducting 2D materials exhibit smaller thermal conductivity values ($k < 100 \text{ W/m}^2\text{K}$) at room temperature, that is the bottleneck to the efficient dissipation of thermal energy [7]. To address this issue, there has been a number of reported studies. In this outlook, a systematically review of Joule heating effect in 2D materials based on electronic devices.

Micro-Raman spectroscopy is widely employed to measure the localized Joule temperature in a device since Raman spectra depict the population of specific phonon modes (thermal carrier) modes of the material. Therefore, the relative position of Raman modes is considered as micro-thermometer to compute the operating temperature at a small scale [7]. In 2D materials, Joule heating was firstly reported by IBM [8]. They employed spatial Raman spectroscopy to compute the temperature distribution in functional graphene device under electrical stress. Their result showed that the center of graphene device is heated up to 1050K temperature and lateral ends are relatively cooler as the metallic electrodes function as heat sink, as shown in Figure 1(b). Similarly, operating temperature of 2D semiconducting materials MoS_2 and black phosphorus was also reported by micro-Raman spectroscopy [4,9-11]. In another study, Grosse et. al. [12] studied thermal spreading in graphene device by using thermal atomic force [12]. However, Bae et al. [13] employed thermal infrared camera to capture the heat

distribution in a graphene device. However, this approach needs ultra-high-resolution IR camera to detect the thermal signals [13]. From all the reported studies it was suggested that the channel-dielectric interface is the thermal bottleneck since commonly used dielectric material, SiO_2 , exhibit very low $k \sim 1.4 \text{ W/m}\cdot\text{K}$ at room temperature. Therefore, dielectric engineering and device structure engineering was proposed as a remedy for facile thermal spreading [14,15]. Graphene and black phosphorus devices fabricated on an insulating hexagonal boron nitride (hBN) substrate, showed better electrical endurance and thermal susceptibility compared to that of SiO_2 supported devices due to better thermal properties of hBN [4,16]. Kim et al. [16] sandwiched graphene with hBN and applied a very high electrical field, in result, they observe that graphene can sustain ultra-high electrical stress and exhibited around 2800K temperature [17]. Surprisingly, at very high field graphene emit visible radiations. Similarly, in another report they reported bright visible light emission from graphene by suspending it over SiO_2 trench, as the thermal energy was accumulated along the center of channel, that leads to radiation emission, as shown in Figure 1(c) [18]. This was partially attributed to ultra-high k and very small heat capacity of graphene at room temperature. Similarly, the suspended MoS_2 also exhibited similar light emission property. Ali et al. [15] proposed device structure engineering to smoothly dissipate the heat in semiconducting BP device [15].

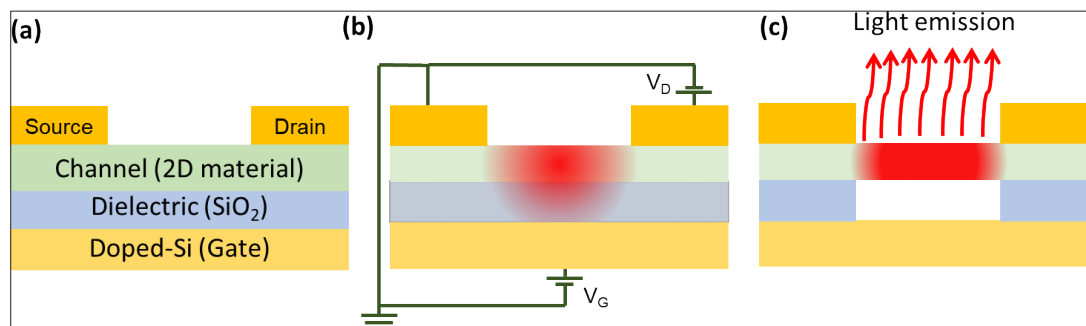


Figure 1:

- (a): Schematic of a back-gate field effect transistor.
 (b): Electric connection and Joule heating effect in a functional device.
 (c): Schematic of light emission from the suspended device.

Conclusion

In conclusion, Joule spreading phenomenon is highly critical for practical and reliable device functionality, because Joule heating induced thermal stresses may lead to device breakdown. Although number of aforementioned studies are carried out in this area, but still, there is still ample opportunity available for future studies. For example, there is a dire need to directly measure the spatial operating temperature of the device because micro-Raman is limited to point-by-point data measurements. Furthermore, new device concepts like ballistic devices [19] and thermal rectifiers [20] are to be investigated in detail. Also, Joule heating phenomenon in many emerging 2D materials like TMDCs, hBN, transition metal carbides, nitrides and carbonitrides need to be investigated.

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