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A large-area multi-finger β-Ga_2O_3 MOSFET and its self-heating effect

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Abstract: The self-heating effect severely limits device performance and reliability. Although some studies have revealed the heat distribution of β-Ga_2O_3 MOSFETs under biases, those devices all have small areas and have difficulty reflecting practical conditions. This work demonstrated a multi-finger β-Ga_2O_3 MOSFET with a maximum drain current of 0.5 A. Electrical characteristics were measured, and the heat dissipation of the device was investigated through infrared images. The relationship between device temperature and time/bias is analyzed.

Key words: β-Ga_2O_3; MOSFET; multi-finger; self-heating effect

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1. Introduction

Ultra-wide bandgap β-Ga_2O_3 is a promising candidate for advanced high-power applications owing to its outstanding material properties, including a large bandgap of ~4.8 eV, a high critical breakdown field of 8 MV/cm and a large Baliga's figure of merit of 3444[1, 2]. Low-cost and scalable melting growth techniques such as edge-defined film-fed growth (EFG)[3] and Czochralski[4] methods give advantages to β-Ga_2O_3 over other wide bandgap materials such as SiC, GaN and diamond. Among these material properties of β-Ga_2O_3, low thermal conductivity (11–27 W/(m·K) at 300 K) can cause a severe self-heating effect (SHE) and affect device reliability and stability[5].

β-Ga_2O_3 power metal–oxide–semiconductor field-effect transistors (MOSFETs) have been investigated since 2012[6] and have achieved remarkable results[7–11]. Constructive methods have been proposed to minimize the SHE of β-Ga_2O_3 MOSFETs[12, 13], such as the ion-cutting technique[14], transfer to a foreign substrate[15, 16] and structural design[17]. Novel measurements have been used to characterize the transient temperature distribution of β-Ga_2O_3 MOSFETs[18]. Most reports on β-Ga_2O_3-based MOSFETs have focused on pursuing high PFOMs and exploring novel structures, yet large-area structures are needed to sustain a high on-state current for practical applications. For large-area structures, SHE will be more serious compared with small devices because of the smaller surface area-to-volume ratio, which is worth investigating. The main challenge of fabricating high performance large-area β-Ga_2O_3 transistor is the inhomogeneity of material growth and instable process flow. There have been reports that multi-finger β-Ga_2O_3 MOSFETs are capable of delivering 300 V switching transients with voltage slopes reach up to 65 V/ns[19], showing great potential. Nonetheless, the electrical and thermal properties of this technology remain to be thoroughly explored. In this work, we fabricated a multi-fingers β-Ga_2O_3 MOSFET with output current reach to 0.5 A. DC characteristics have been studied. We have employed optical thermography to investigate the impact of the self-heating effect on the multi-finger β-Ga_2O_3 MOSFET.

2. Experiment

A semi-insulating Fe-doped (010) β-Ga_2O_3 bulk substrate was used in this work. A β-Ga_2O_3 film with a concentration of ~2×10^{17} cm^{-3} was grown on the substrate by MOCVD. Before film growth, a 30-min wafer carrier bake was performed for cleaning at 860 °C. Details of growth and doping can be found in our previous report. Fig. 1 shows the cross-sectional schematic of the fabricated β-Ga_2O_3 MOSFET. The fabrication process started with mesa isolation was performed by BCl_3/Ar inductively coupled plasma (ICP) dry etching. Then, 300 nm of SiO_2 was grown by plasma-enhanced chemical vapor deposition (PECVD) at 300 °C, and source/drain areas were exposed by buffered oxide etching (BOE) for regrowth of the heavily doped ohmic contact region by MOCVD. After that, SiO_2 was fully removed by hydrofluoric acid solution for over 30 min. The Ti/Au (20/180 nm) metal stack was then deposited by electron beam evaporation and subjected to rapid thermal annealing at 470 °C for 1 min in a nitrogen atmosphere. Thereafter, 30 nm thick Al_2O_3 was deposited as the gate dielectric layer by atomic layer deposition (ALD) at 250 °C, and pad regions were opened by removing Al_2O_3 using ICP etching. Finally, Ni/Au (20/80 nm) gate metal was deposited by electron beam evaporation. Small-area transistors with a gate width (W_g) of 10 μm, a gate-to-source distance (L_{gs}) of 2 μm, a gate-to-drain distance (L_{gd}) of 7 μm and a gate length (L_g) of 2 μm were fabricated to evaluate the device properties. The device temperature distribution was characterized by a Fluke TiX580 infrared thermal imaging camera.

3. Results and discussion

The DC characteristics of the small-area transistor were

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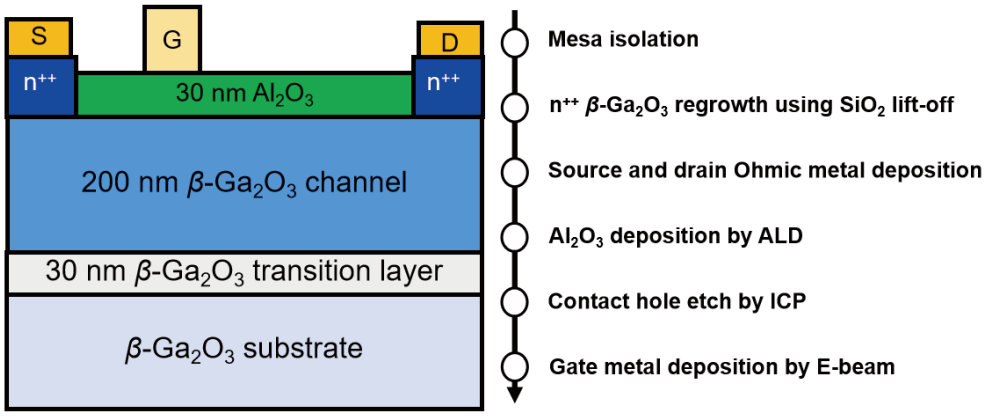

Fig. 1. (Color online) Cross-sectional schematic of the β-Ga_2O_3 MOSFET and its process flow.

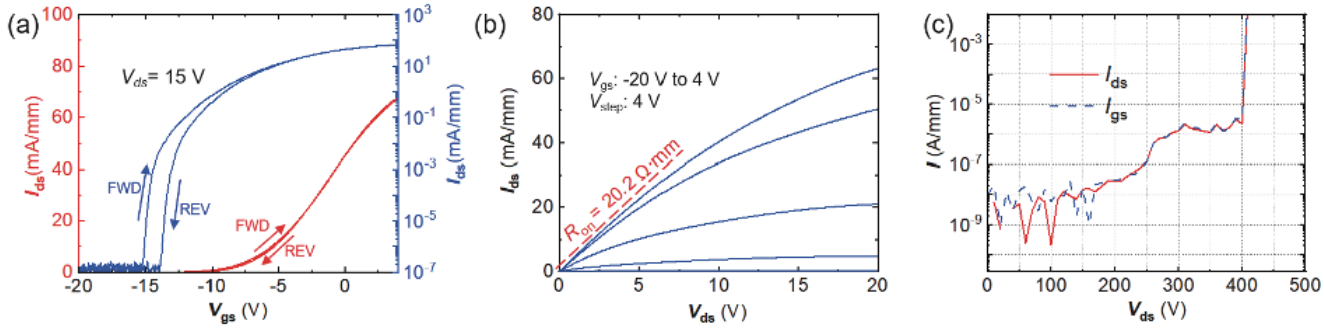

Fig. 2. (Color online) DC (a) transfer and (b) output characteristics of small-area MOSFET. (c) Three terminal leakage current under the off-state.

determined by a Keysight B1500A semiconductor device analyzer. Fig. 2(a) shows the transfer characteristics of the small-area MOSFET. A threshold voltage V_{th} = –11 V, subthreshold swing SS = 190 mV/dec and an on/off ratio $I_{on}/I_{off} > 10^8$ were extracted. Fig. 2(b) illustrates the output characteristics of the small-area MOSFET. The saturation drain–source current I_{ds} = 63 mA/mm and on-state resistance R_{on} = 20.2 Ω·mm were obtained. Fig. 2(c) shows the off-state characteristics of the small-area device, which was carried out by a Keysight B1505A power device analyzer. Gate bias was kept at –15 V during the test. A three-terminal breakdown voltage of 400 V was obtained.

Figs. 3(a) and 3(b) give an optical microscope image of a multi-finger β-Ga_2O_3 MOSFET and its layout. The multi-finger MOSFET featured a finger-to finger distance of 20 μm, which is composed of L_{gs} = 4 μm, L_g = 4 μm and L_{gd} = 12 μm. Each finger has a width of 20 μm. The large-area transistor showed an on-state current of 0.5 A and an on-resistance of 13 Ω, as shown in Fig. 3(d). The different threshold voltages between large-area and small-area devices can be ascribed to epitaxial β-Ga_2O_3 film. The current and voltage level is still lagging behind the small-area device due to uniformity issues in material growth and the device fabrication process. Upon the establishment of mature material growth and fabrication process, the inherent advantages of the material can be fully demonstrated.

The temperature distribution images measured by the infrared camera are shown in Figs. 4(a)–4(d). The gate electrode was kept floating during the test. According to the results, the heat was mainly generated in the β-Ga_2O_3 channel between the source and drain and then mainly dissipated through the metals, which explains why the metal possessed a lower temperature during the tests. This phenomenon became more obvious in the thermal equilibrium state (see Fig. 5(a)). The maximum temperature in the β-Ga_2O_3 channel almost reached 250 °C under an applied voltage of 8 V, showing the severe self-heating effect of the large-area transistor. The primary reason for the comparatively reduced temperature of the metal pad is primarily ascribed to its superior conductivity in comparison to β-Ga_2O_3. It is worth noting that the reflectivity and emissivity of the metal surface could potentially impact the precision of temperature measurement. To alleviate SHE, effective cooling mechanisms are necessary to regulate the SHE, including the implementation of high-thermal-conductivity carrier wafers[15] for top-side or flip-chip integration[20], as well as the utilization of heat sinks[12].

4. Conclusion

In summary, we present a multi-finger β-Ga_2O_3 MOSFET with a saturation current over 0.5 A. The self-heating effect was investigated by infrared images. The generation and dissipation actions were analyzed. This work provides a better understanding of the self-heating effect of large-area β-Ga_2O_3 MOSFETs and is significant for high-power applications.

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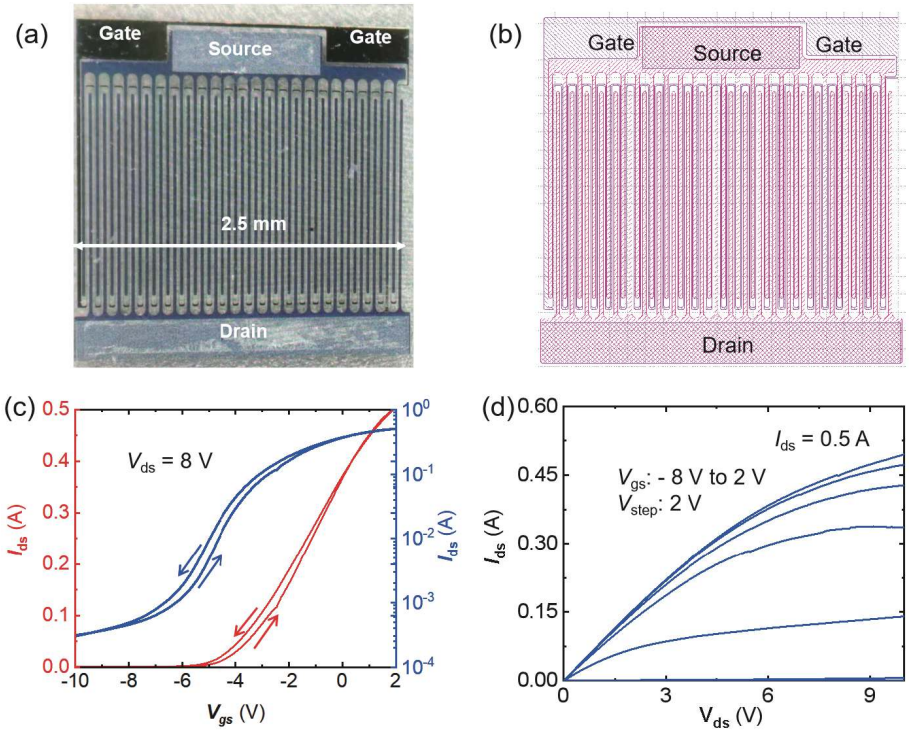

Fig. 3. (Color online) (a) Optical microscope image and (b) layout of a multi-finger β-Ga_2O_3 MOSFET. (c) Transfer and (d) output characteristics of multi-finger MOSFET.

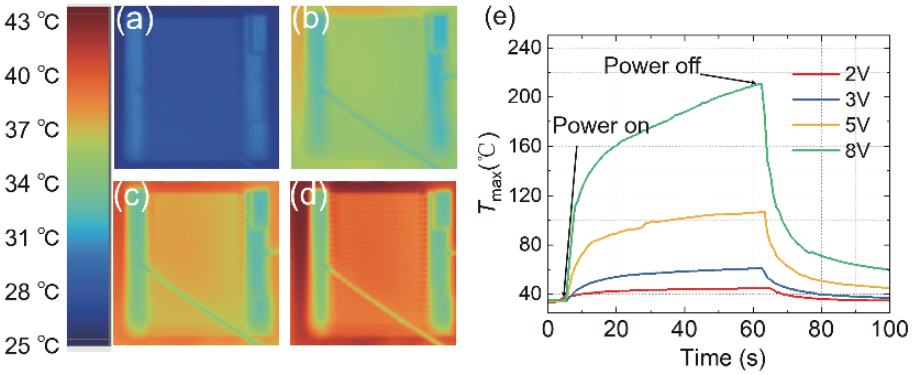

Fig. 4. (Color online) Temperature distribution images with biased time of (a) 0 s, (b) 10 s, (c) 20 s and (d) 50 s. The drain bias was set as 2 V. (e) Time dependence of the maximum temperature in the β-Ga_2O_3 channel with different drain voltages.

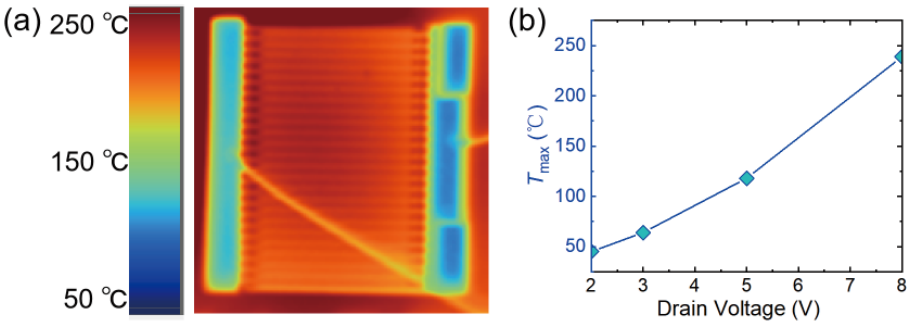

Fig. 5. (Color online) Thermal equilibrium state: (a) temperature distribution image with a drain voltage of 8 V and (b) maximum temperature in the β-Ga_2O_3 channel versus applied drain voltage.

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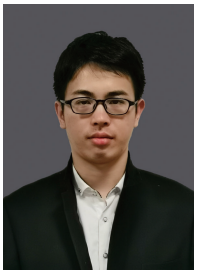

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