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Nanoscale design for large-scale challenges

From efficient power electronics to effective thermal management for wide-band-gap semiconductors

Elison Matioli, POWERlab, EPFL

Motivation

Electricity is the fastest growing form of end-use energy, but a significant portion is wasted in power conversion, especially in power semiconductor devices. The outstanding properties of Gallium Nitride semiconductors for power electronic devices can enable significantly more efficient and compact future power converters. Despite the exceptional recent progress, the performance of current GaN power devices is still far below the limits of this material. Further improvements require the reduction of the on-resistance, while maintaining large voltage-blocking capabilities, and an improved thermal management, which will enable higher efficiency, larger power density and smaller devices.

Efficient power electronics

We have demonstrated the novel concept of multiple highly-conductive channels, vertically stacked within the GaN semiconductor, resulting in over 4x-smaller sheet resistances. To achieve high-voltage operation in such ultra-conductive structures, we demonstrated the concept of lateral slanted field-plates, consisting of nanostructuring regions of the device to effectively manage high electric-fields. This technology can significantly increase the efficiency of power devices for future power conversion applications [1].

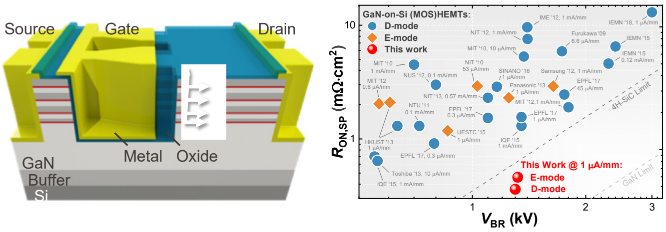

Figure 1. (left) Schematic of the multichannel slanted tri-gate MOSHEMTs. (right) $R_{ON,SP}$ versus V_{BR} benchmarks of multi-channel MOSHEMTs against conventional single-channel GaN (MOS)HEMTs in the literature, showing a substantial improvement by the multi-channel power devices.

References:

1. J. Ma, C. Erine, M. Zhu, L. Nela, K. Cheng, E. Matioli, "1200 V Multi-Channel Power Devices with 2.8 Ω·mm ON-Resistance", **IEEE International Electron Devices Meeting** (2019)
2. R. Van Erp, R. Soleimanzadeh, L. Nela, G. Kampitsis and E. Matioli, "*Co-designing electronics with microfluidics for more sustainable cooling*", **Nature** 585, 211–216 (2020)

Effective thermal management

By co-designing microfluidics and electronics within the same semiconductor substrate, a monolithically integrated manifold microchannel cooling structure was produced with efficiency beyond what is currently available. Our results show that heat fluxes exceeding 1.7 kW/cm² could be extracted using only 0.57 W/cm² of pumping power. An unprecedented coefficient of performance (exceeding 10,000) for single-phase water-cooling was shown, corresponding to a 50-fold increase compared to straight microchannels. The proposed cooling technology should enable further miniaturization of electronics, potentially extending Moore's law and greatly reducing the energy consumption in cooling of electronics. Furthermore, by removing the need for large external heat sinks, this approach should enable the realization of very compact power converters integrated on a single chip [2].

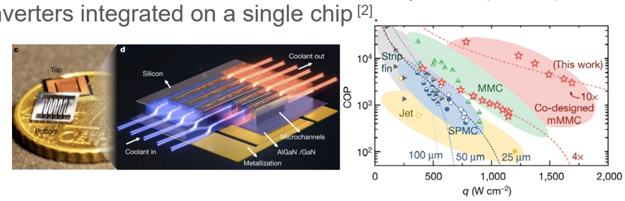

Figure 2. (left) Picture of the co-designed devices, from the top and bottom sides, with the 10×-manifold mMMC cooling. The top side shows the electronic structure and the bottom shows the manifold etched in the silicon substrate. Illustration of the fluid flow through the mMMC structure. Blue lines indicate the cold coolant flow entering the chip, and red lines indicate the hot coolant leaving the chip. (right) Benchmark of the experimentally demonstrated coefficient of performance (COP) versus the maximum heat flux q for a temperature rise of 60 K. Shown are the SPMC (blue), the MMC (green), the impinging jet (yellow), the strip fin (grey) and the mMMC (red). A large improvement in COP for a given heat flux is achieved with our proposed mMMC structures (red).

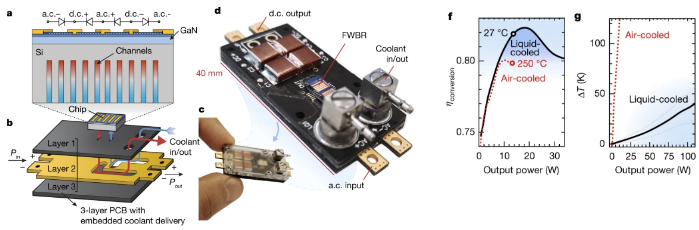

Figure 3. a, Schematic illustration of the super-compact liquid-cooled power integrated circuit based on four GaN power Schottky barrier diodes integrated in a single chip in a full-bridge configuration. b, A PCB-embedded coolant delivery was developed to feed the coolant to the device. The PCB consists of three layers, where the middle layer contains a fluid distribution channel. c, Photograph of the full 120-W AC–DC converter with coolant delivery to the liquid-cooled power integrated circuit. d, Converter without encapsulation, revealing the monolithically integrated full-wave bridge rectifier (FWBR) integrated circuit. f, Efficiency versus output power for the air-cooled and liquid-cooled AC–DC converter. At identical output power, the liquid-cooled converter exhibits substantially higher efficiency owing to the elimination of self-heating degradation. g, Temperature rise versus output power, showing a much higher temperature at equal output power for the air-cooled device compared to the embedded liquid cooling, which causes a large self-heating degradation. The black line shows the mean surface-temperature rise and the highlighted area shows the range between the minimum and maximum temperatures over the device's surface.

Key Results

- Ultra-low on-resistance power electronic devices based on multichannel GaN structures with Ron of 2.8 ohm mm and 1200 V
- Embedded cooling channels to cool heat fluxes exceeding 1.7 kW/cm² using only 0.57 kW/cm2 of pumping power, presenting an unprecedented coefficient of performance exceeding 10,000 for single-phase water-cooling.
- A super-compact 120 W ac-dc converter, based on an integrated GaN-on-Si Schottky barrier diode bridge rectifier with embedded cooling channels, was fabricated and experimentally evaluated.

These technologies show a promising pathway for efficient power electronic devices

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