Device cooling

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Advancing cooling limits with 3D embedded microchannels

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A system that incorporates manifold structures, microjets and microchannels can effectively cool electronic devices at a heat flux of 3,000 W cm^{-2}.

As the electronics industry continues its drive towards ever more compact devices, the resulting device heat fluxes can now reach several kilowatts per square centimetre. It is thus increasingly critical to replace traditional air cooling technology with liquid cooling, which can enhance computational efficiency and capacity while reducing energy consumption and greenhouse gas emissions[1]. Liquid cooling has evolved from external cold plates with two-dimensional (2D) channels to 3D microfluidic structures embedded directly on the backside of a chip. This approach brings the coolant closer to on-chip hotspots, shortening thermal paths and reducing conduction thermal resistance.

Such embedded cooling offers optimal thermal performance while preserving electrical connections above the device pads[2]. However, in order to continue to advance cooling limits and reduce energy consumption, it is necessary to integrate auxiliary functional layers and to optimize the microchannels. Writing in *Nature Electronics*, Bai Song and colleagues now report an integrated 3D embedded cooling strategy that combines tapered manifolds, microjets and sawtooth microchannels[3]. The approach enables dissipation of heat fluxes up to 3,000 W cm^{-2} with a low pumping power.

Microchannel cooling technology initially focused on flow path design with planar configurations. Although this approach could achieve dissipation of heat fluxes up to 790 W cm^{-2}, it required prohibitively high pumping power[4]. Recent research has directed attention towards manifold-integrated 3D embedded microchannel architectures. This configuration uses forced flow distribution to increase heat dissipation capabilities to 1,000 W cm^{-2}, while reducing pressure drop and energy consumption. In 2020, single-wafer monolithically integrated 3D manifold microchannels[5] achieved a heat dissipation exceeding 1,700 W cm^{-2} due to greatly reduced conduction thermal resistance.

Building on this foundation, the researchers — who are based at Peking University — designed jet-enhanced manifold sawtooth-sidewall microchannels with a three-layer integrated structure. In particular, the structure is composed of a wafer with the electrical circuits on top and the microchannels in the backside of the substrate; a second wafer that contains a manifold layer and microjet plate; and finally a glass lid that is used to seal the assembly (Fig. 1). The embedded 3D structures are fabricated using standard silicon micromachining. The manifold layer has a staggered inlet–outlet configuration, which shortens the fluid flow paths and effectively reduces the pressure drop and power consumption. The microjet layer uses high-velocity fluid to directly impinge on hotspot regions (such as near the chip junction), enhancing

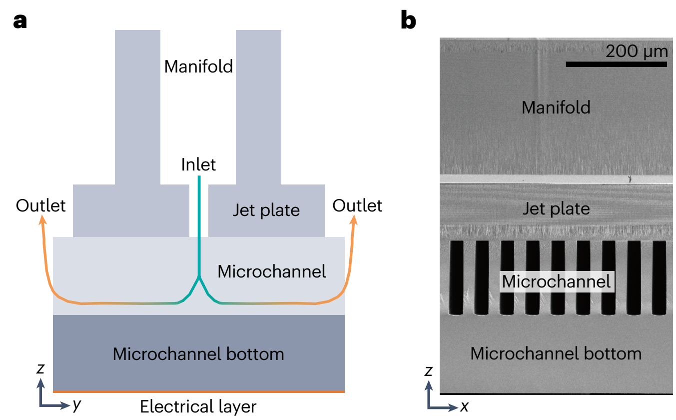

Fig. 1 | 3D embedded microchannel cooling strategy. a, The system has a three-layer structure that integrates a tapered manifold, microjets and sawtooth microchannels. Cold water (blue) enters the manifold inlet channel, is accelerated through the jet plate within the intermediate layer, and impinges on the bottom of the microchannels, then returns to the manifold outlet channel (orange). **b**, Cross-section scanning electron microscopy image showing the profile of the microfluidic structure in **a**. Figure adapted from ref. 3, Springer Nature Limited.

local heat transfer. This impingement promotes fluid mixing and accelerates heat transfer from the solid surface to the coolant.

The team also performed numerical simulations to optimize the microchannels, and found that replacing the traditional straight microchannels with sawtooth-sidewall microchannels reduced coolant velocity and pressure at the inlet and augmented convective sidewall heat transfer. Small vortices generated within the sawtooth structures promote fluid mixing and decrease the boundary layer thickness within the microchannels. The combined design achieves a heat dissipation capability of around 3,000 W cm^{-2} with a pumping power of only 0.9 W cm^{-2}.

The work of Song and colleagues provides a valuable advance for 3D embedded microchannel design. Nevertheless, as the power densities of future wide-bandgap electronic devices continue to rise, substantial challenges persist in extending cooling limits. Key areas for development include structural optimization, manufacturing processes, coolant selection, heat transfer mechanisms and multiscale thermal management. Further optimization of the microjet–manifold co-design, as well as exploring complex microchannel architectures (such as biomimetic structures), could better balance thermal resistance versus flow resistance. Novel cooling technologies are also needed to enhance advanced transistor performance[6] and integrate high-thermal-conductivity materials (diamond layers[7], for example) for local heat dissipation.

The current approach used water as the coolant, but future work could examine alternative liquids[8] such as liquid metals, fluorinated dielectric fluids and engineered nanofluids. Additionally, two-phase cooling that combines microjets with phase-change mechanisms should be investigated. Successfully addressing these challenges would allow current cooling limits to be surpassed, leading to advanced electronics with higher performance, power densities and energy efficiencies.

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Competing interests

The authors declare no competing interests.