Overcoming the limitations of gallium oxide through heterogeneous integration

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Power electronics, processing over 50% of world's electric energy, enables very efficient electric energy conversion for a wide range of applications such as electric vehicles, data centers, autonomous driving, robotics and smart grids. The availability of low-cost, efficient, and reliable power semiconductor devices that can conduct high current, block high voltage, and switch at high frequencies are key to improving the performance of power electronics systems.

While most of today's power devices are made of silicon (Si), the power devices based on semiconductors possessing a wider bandgap than Si, such as silicon carbide (SiC) and gallium nitride (GaN), have enabled numerous applications beyond the capabilities of Si. After three decades of relentless development, SiC and GaN devices have been commercialized. For example, high-performance, low-cost GaN-on-Si device technologies have allowed a significant boost in power conversion efficiency and a reduction in system form factors [1], emerging vertical GaN-on-Si devices are also under development [2].

On the horizon is a new generation of semiconductors possessing even larger bandgaps than GaN and SiC, i.e., the ultra-wide bandgap (UWBG) semiconductors. The major UWBG semiconductors include gallium oxide (Ga_2O_3), aluminum nitride (AlN), and diamond. Power devices based on these materials promise higher theoretical performance than their Si, SiC, and GaN counterparts. Among various

UWBG semiconductors, Ga_2O_3 is particularly promising owing to its controllable doping and the availability of large diameter wafers [3]. Ga_2O_3 devices have demonstrated high performance up to kilovolts classes.

Despite the initial success of Ga_2O_3 devices, they are faced with two fundamental material limitations. First, Ga_2O_3 has very low thermal conductivity (1/6 of Si, 1/10 of GaN, and 1/20 of SiC), which limits its heat dissipation and power handling capabilities. Second, there still lacks shallow acceptors for efficient p-doping in Ga_2O_3 . The absence of Ga_2O_3 PN junctions hinders the adoption of many advanced voltage-blocking structures for the development of high-voltage power devices.

Two recent papers [4,5] published in *Science China Physics, Mechanics & Astronomy* have showed good promise to overcome the above challenges through heterogeneously integrating Ga_2O_3 onto Si and GaN. In ref. [4], the heterogeneous Ga_2O_3 -on-Si substrate was demonstrated via an ion-cutting process. Benefitting from the higher thermal conductivity of Si than that of Ga_2O_3 , high-voltage (over 500 V) enhancement-mode Ga_2O_3 metal-oxide-semiconductor field-effect transistors exhibited stable operation at high temperatures up to 200°C. The demonstrated high-temperature voltage-blocking capabilities are among the best in all reported Ga_2O_3 transistors.

In ref. [5], Ga_2O_3 films are grown on the GaN substrate by metal organic chemical vapor deposition (MOCVD), the prevailing growth technique that enables the billion-dollar

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GaN optoelectronics and electronics markets. Such Ga₂O₃ films grown on the GaN substrate show significantly superior crystal quality, material homogeneity, and surface morphology compared with the Ga₂O₃ films grown on other foreign substrates. The fundamental understandings on the crystal and electronic structures of heterogeneous GaN/Ga₂O₃ interfaces have also been acquired. These results pave the road for demonstrating heterogeneous PN junctions based on p-type GaN and n-type Ga₂O₃, which could be an enabling building block for future high-voltage Ga₂O₃ power devices.

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