present in silicon carbide[10], it is likely that many other optically active single-spin centres will be found and addressed in the near future. Each of these defects can be expected to possess different spin states and Hamiltonians, potentially allowing for greater flexibility in engineering and addressing multi-spin registers. Finally, the measured spin coherence times of the defects in silicon carbide are remarkably long, both at ambient conditions and at cryogenic temperatures. The spin coherence times measured in these experiments are actually limited by the randomly fluctuating magnetic field produced by the nuclear spins of ^{13}C and ^{29}Si atoms in the vicinity of the vacancies. Therefore, and as already shown in diamond[6] and silicon[7], a further increase in spin coherence time might be achievable by removing the ^{13}C or ^{29}Si spins, an option that has recently become available also in silicon carbide[11].

Looking ahead, the accomplishment of single-spin control in silicon carbide paves the way for integrating highly coherent spins with a variety of optical and electronic structures. Silicon carbide is becoming an increasingly mature material platform for the fabrication of high-quality optical resonators[12] and photonic crystals[13], as well as high-power and high-frequency electronic devices. In the long term, one can envisage building spin-based quantum information processors by engineering arrays of spins coupled through cavity photons and locally addressed by electric or magnetic fields. As suggested by the room-temperature experiments conducted by Widmann and colleagues, this quantum processor could potentially operate in ambient conditions. In addition, the luminescence of the defects in silicon carbide is in the near-infrared, which is advantageous for integration with optical telecommunication systems.

There are still formidable difficulties to overcome before such defect-based quantum processors can become a reality. First among these are the deterministic creation of defects at precise locations, and the engineering of their mutual couplings. However, the now-demonstrated ability to coherently manipulate and optically read-out single spins in silicon carbide is a promising step towards integrating the most attractive features of carbon and silicon into a modern, flexible and high-performance material platform. ❐

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THERMAL TRANSPORT

Cool electronics

Although heat removal in electronics at room temperature is typically governed by a hierarchy of conduction and convection phenomena, heat dissipation in cryogenic electronics can face a fundamental limit analogous to that of black-body emission of electromagnetic radiation.

Jungwan Cho and Kenneth E. Goodson

For decades, miniaturization has been the hallmark of electronics. Efforts to make things smaller span an enormous range of dimensions, from nanoscale transistors and thumbnail-sized chips to smartphones, vehicle electronics and even server farms. Heat management is often the bottleneck in the further miniaturization of these technologies, leading to many examples where decreasing size and increasing functional density results in overheating. For transistors and semiconductor devices operating at cryogenic temperatures, the simple act of delivering heat into the substrate can be a big challenge because, at these temperatures, the phonon population density drops dramatically. Writing in *Nature Materials*, Austin Minnich and co-authors provide[1] an elegant demonstration of this limit of heat transfer for indium phosphate high-electron-mobility transistors.

At cryogenic temperatures, in the absence of backscattering and diffusion, that is, in the phonon ballistic limit, heat dissipation into the substrate is subject to the 'phonon black-body radiation limit', which is analogous to a similar limit for electromagnetic radiation[2]. In general, the rate at which phonons radiate heat away from a transistor heat source depends on the number and velocities of the populated phonon modes in the substrate. At cryogenic temperatures, where the phonon population is sparse and dominated by low-energy modes according to the Bose–Einstein distribution, the lattice temperature near the active region of electronic devices increases until higher-energy phonon modes are populated and can carry the heat away. Minnich and co-workers show that the limited rate of heat removal that can be achieved through phonon radiation into the substrate governs the lowest possible noise in cryogenic electronics. This finding has important implications in a variety of fields that utilize extremely low temperatures to obtain ultralow-noise environments, such as radio astronomy and satellite and space communication[3].

The phonon black-body radiation limit becomes important when relevant length scales, such as the device and substrate dimensions and the spatial extent of the heat source[4], are smaller than the mean free paths of phonons that dominate heat conduction. In crystalline dielectrics and semiconductors, these heat conducting phonons have a broad distribution of mean free paths, spanning several orders of magnitude[5–7], as illustrated in Fig. 1. The rapid increases of mean free paths at lower temperatures are due to the decreasing phonon population, which reduces phonon–phonon scattering, as well as to the increasing wavelengths of phonons and the associated weaker scattering on some types of defect. At cryogenic temperatures, in particular, the mean free paths of phonons are of the order of several hundred micrometres or even a millimetre, which is substantially larger than device and substrate dimensions. At higher temperatures, where phonon backscattering and diffusion processes become important, phonon black-body radiation no longer limits the cooling of electronic devices (Fig. 1). Phonon transport in the near vicinity of most electronic devices at room temperature and above is often quasi-ballistic, that is, some phonons travel ballistically between interfaces while others scatter internally due to defects and interfaces.

This situation begs the question: are there cooling limits for the wealth of semiconductor technologies operating at room temperature and above? For many modern nanotransistor technologies, which feature dimensions well below the mean free paths depicted in Fig. 1, ballistic phonon transport is already playing a big role within devices and the nearby substrate. In this way, deep dimensional scaling brings to room temperatures the ballistic transport physics reported for substrates at cryogenic temperatures by Minnich and co-authors. As devices are miniaturized to ångström scales, thermal conduction will be strongly sub-continuum and governed by the phonon properties of the materials, electron–phonon scattering details, and geometry.

The limits to heat dissipation in electronics at higher temperatures than the ones considered in the study by Minnich and co-authors are closely linked to materials research, which has resulted in an expansion of the palette of possible substrate and packaging materials in electronic devices. Recent examples involve 1D and 2D thermal conductors, such as carbon nanotubes and graphene, which can offer exceptionally high effective thermal conductivities. Few-layer graphene has been used as a top-surface lateral heat spreader for high-power GaN transistors[8], and carbon nanotubes have been used as part of composite materials to help connect semiconducting chips to heat sinks[9]. Research on synthetic diamond is aiming to integrate this material, which has the highest measured 3D thermal conductivity at room temperature, within tens of nanometres of active semiconducting regions[10]. Nanofabrication and surface structuring have enabled control of liquid wetting/nonwetting behaviour and are playing a pivotal role in the development of next-generation heat pipes and microfluidic heat sinks[11].

The limits of room-temperature cooling of electronics are therefore likely to involve materials innovation across a hierarchy of length scales. The 'coolest' electronics a decade from now might include novel materials in close proximity with semiconducting regions, nanostructured packaging, and engineered surfaces for liquid–vapour phase management at the heat sink level. ❒

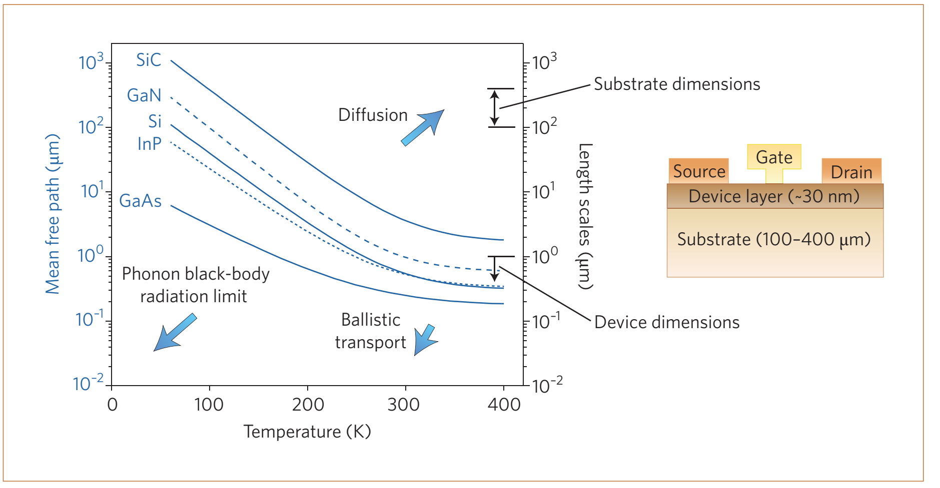

Figure 1 | Temperature dependence of the mean free paths of phonons in a variety of substrate materials[5–7]. At low temperatures and small dimensions (bottom left blue arrow), ballistic emission into the substrate can be important for heat removal. For some cryogenic electronics, this yields the phonon black-body radiation limit[1]. The plot also shows that ballistic transport can be important in many aggressively scaled semiconductor devices even at room temperature (bottom right blue arrow). At high temperatures and large dimensions (top right blue arrow), heat diffusion governs the cooling of electronics. The schematic indicates the typical dimensions of a semiconductor device.

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FERROELECTRICS

Negative capacitance detected

The experimental detection of negative capacitance in ferroelectrics rekindles hopes that the phenomenon could be used to further push the miniaturization of conventional transistors.

Gustau Catalan, David Jiménez and Alexei Gruverman

A capacitor is a charge-accumulator device that consists of two metallic electrodes separated by a dielectric material. When a voltage is applied to the electrodes, the dielectric responds by polarizing, that is, by exhibiting a separation of positive and negative charges. In this context, ferroelectric materials are excellent dielectrics as they can display phase transitions between polar and nonpolar states, near which the polarizability (expressed by the relative permittivity or dielectric constant) increases enormously. The large polarizability of ferroelectrics has been successfully exploited in a variety of electronic devices manufactured on a large scale[1]. It is therefore ironic that the materials with the highest dielectric constants (which