

Writing above the bandgap

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Above-bandgap, nanosecond laser pulses enable the localized in situ writing of spin defects in prefabricated nanophotonic cavities. The approach preserves defect and cavity mode properties, key requirements towards cavity–emitter coupling in quantum networks.

Quantum technologies have emerged as a critical area of research and development, which promises to reshape the technological landscape of computation, communication and sensing by exploiting concepts of qubits – quantum counterparts to classical bits that can store arbitrary superposition of two distinct states – and entanglement – quantum correlation between properties of qubits. A key challenge in quantum technologies is the development of a quantum repeater – hardware that creates quantum correlations between single photons carrying quantum information entangled to stationary qubits, enabling a long-range quantum communication network. Scalable quantum repeater platforms based on entangled long-lived solid-state qubits and photons suitable for efficient propagation in a fibre are hard to come by. The most promising systems in this space have been point defects in wide-bandgap materials called colour centres. The presence of such defects creates an available electron in a discretized set of energy levels whose spin can be used as a qubit and can be efficiently manipulated and read out using laser pulses. Silicon carbide (SiC) colour centres, in particular, have gained prominence among quantum platforms due to a unique combination of up to seconds-long quantum information storage, high uniformity among defect properties and suitable photon emission for long-distance fibre communication^{1,2}. As research in

this area progresses, the seamless integration of colour centres with nanodevices will be critical for the advancement of quantum technologies and their widespread adoption. Now, writing in *Nature Materials*, Aaron M. Day and collaborators³ report colour centre inscription in prefabricated SiC nanophotonic cavities employing a direct laser writing technique and demonstrating deterministic localization and real-time monitoring of the colour centres in the nanophotonic cavity.

The SiC colour centre platform has been extensively explored over the past two decades, including for spin manipulation, indistinguishable photon emission and nanodevice integration, and presents a promising avenue for realizing practical, compact quantum systems. By incorporating colour centres into nanostructures such as nanophotonic waveguides, nanocavities and plasmonic devices, researchers can enhance light–matter interaction and achieve efficient coupling of single photons to solid-state qubits. This integration can substantially improve the performance of quantum devices in terms of indistinguishable photon generation, entanglement creation and overall efficiency. Moreover, the combination of colour centres and nanodevices allows for the development of novel quantum components, such as single-photon sources and frequency converters, that can be integrated into larger, scalable quantum networks.

Among pressing issues in defect integration with nanodevices is the colour centre positioning. On one hand, the surrounding substrate should stay as pristine as possible, and on the other, the colour centre should be formed at an optimal location for light–matter interaction. Defects in bulk are traditionally generated using methods such as ion irradiation followed by high-temperature annealing or in situ doping during crystal growth. More controlled approaches are achieved via masked ion implantation⁴, focused ion beam exposure⁵ and direct laser writing^{6,7}. The direct laser writing technique is promising for achieving precise placement and control over the number of colour centres, and does not require an annealing step to activate the defect. However, laser

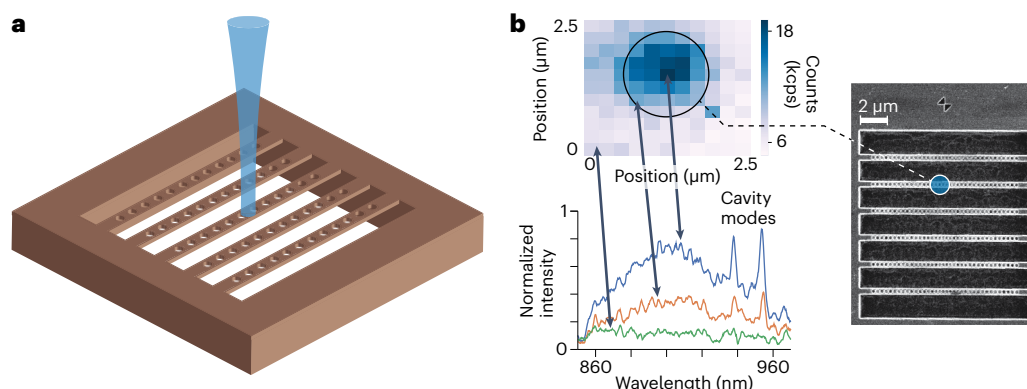


Fig. 1 | Above-bandgap laser inscription of colour centres in nanophotonic cavities. **a**, Schematic of the inscription method using an above-bandgap 337.1 nm, 4 ns pulsed laser (blue) focused onto the prefabricated nanophotonic cavities in a 4H polytype of silicon carbide (brown). **b**, Room temperature (300 K) photoluminescence heat map and corresponding spectra from an irradiated spot

on the nanophotonic cavity (blue circle on the scanning electron micrograph) showing that the silicon vacancy defects are incorporated into the cavity while preserving its resonant modes (peaks in the blue spectrum). Figure adapted with permission from ref. 3, Springer Nature Ltd.

writing demonstrations thus far have been limited to bulk material, as the surface properties posed a challenge to nanophotonic integration.

The work by Day and collaborators³ brings the direct laser writing of defects to a new level by directly generating the colour centres in prefabricated SiC nanophotonic devices (Fig. 1). In contrast to previous approaches, the authors generate defects using the above-bandgap nanosecond pulses, which have lower instantaneous pulse powers. This result is exciting because it enables real-time in situ monitoring of the defect formation by simply adding a pulsed laser to an existing confocal system. An optimal fluence was shown to exist for which the laser pulse efficiently generates defects while preserving their spin–optical properties as well as the device functionality, making this method suitable for nanophotonic integration of colour centres. Moreover, it was shown that this method can also be used for single-shot annealing of the background fluorescence originating from the already existing surface defects.

The demonstration of the direct laser writing method in this work offers the ability to deterministically generate and position defects inside a nanophotonic cavity. This is a critical step towards developing essential building blocks of quantum hardware such as quantum repeaters and quantum memories. Moreover, the real-time monitoring of the defect formation and the lack of additional processing steps to activate the defects substantially boost the throughput, which is necessary for integration of defects at scale. This method could be explored to generate colour centres with wavelengths close to the telecommunication range like the divacancy and nitrogen vacancy in SiC. In addition, the ability to generate defects with specific crystal orientations would

result in an increased coupling between the defect and nanophotonic device, required for achieving enhanced single-photon emission and collection. Additional studies of spin-coherence properties of the defects generated using this method will help to further optimize the experimental conditions for reliable deployment in quantum information technologies. Finally, SiC is compatible with existing semiconductor fabrication processes, which can facilitate the integration of quantum devices with classical electronics and, combined with targeted colour centre generation, accelerate the development of practical, large-scale quantum systems.

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Competing interests

The authors declare no competing interests.