Single photon emission and quantum photonics with silicon carbide

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Silicon carbide has recently emerged as a platform for quantum technologies, as it is a host for optically addressable spin defects, emitting from the visible to the NIR and even at telecom wavelengths.[1] Some of these color centers possess optically accessible and controllable high spin number with a very long coherence time (up to 20 ms) at ambient conditions and are characterized by quantum properties associated with their single-photon emission and their coherent spin state control, and the mechanisms to achieve spin-to-photon interfaces for remote entanglement of multiple spins, which make them ideal for quantum technology, such as quantum communication, and computation.[2] SiC exists in over 250 polytypes which are commercialized in wafer-scale allowing integration of quantum systems in large scale wafers as well as suitability for nanofabrication and potentials for scalable and integrated quantum photonics.

The most popular defects are neutral divacancy ($V_{Si}V_C^0$), the negatively charged silicon vacancy (V_{Si}^{-1}) and the carbon-antisite vacancy pair ($V_CC_{Si}^{+1}$). These defects have different photoluminescence (PL) and other spin properties which are polytype dependent. The defect properties also vary within the same polytype depending on its lattice position; they can either occupy an axial position or can be off-axis. The $V_{Si}V_C^0$ has spin-triplet ground state exhibiting electron coherence times T_2 exceeding 1 ms and has the same number of electrons as the nitrogen vacancy center in diamond, leading to similar spin and optical structures.[3] The longer coherence despite higher fractions of nuclear spins than diamond comes from the larger lattice spacing in SiC. PL from $V_{Si}V_C^0$ defects (Figure 1b) is attributed to its neutral charge state, 4H-SiC polytype is associated with four specific PL lines (PL1-4).[4] The zero phonon lines (ZPLs) of divacancies at near-infrared wavelengths (~1.12 eV), leads to lower attenuation in optical fiber and will therefore facilitate entanglement generation over long distances.[3,4]

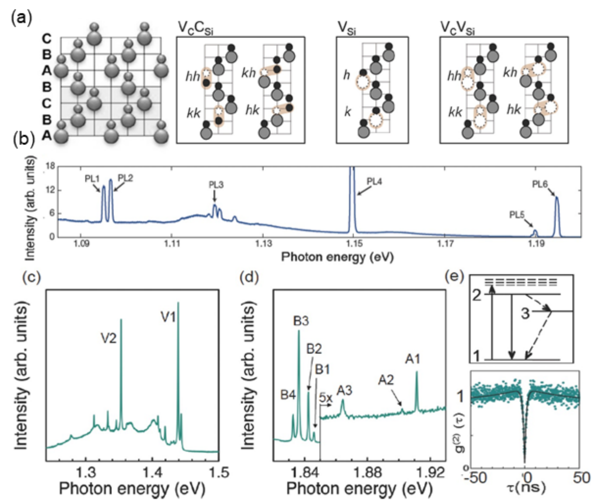

Figure 1: Electronic and optical properties of defects in 4H-SiC. **(a)** The atomistic structures with shaded, filled and empty circles signifying the Si, C, and vacancies. **(b)** divacancy (PL1–PL4 lines) with PL5 and PL6 being of unknown origin. **(c)** Silicon vacancy (V1 and V2 PL lines). **(d)** Antisite vacancy PL. (e) Representation of a 3-energy level system found in 4H-SiC.[7]

The negatively charged silicon vacancy has a different electronic structure compared to NV-type level due to its odd number of electrons, giving rise to a $S = 3/2$ ground state. Single silicon vacancy can occupy inequivalent lattice sites (hexagonal V1 or cubic V2) exhibiting differences in the ZPL emission and the zero-field splitting.[5] The carbon-antisite vacancy pair is an intrinsic defect with emission in the visible range, called AB lines and is found both in 4H and 6H-SiC polytypes. The visible PL is attributed to the positive charge state of this defect with S =

1/2.[6] Figure 1 shows the lattice structure of defect free SiC, defect structures and the defect PL spectra in 4H-SiC.

Optical stability at the single defect level and ease of manufacture are the requirements for implementing quantum technologies, making SiC one of the major quantum light–matter interfaces available, competing with diamond and quantum dots, especially as single-photon emitters. Castelletto *et al.* reported ultrabright, photostable SPS in SiC with carbon antisite defect which operates at room temperature.[7] A single defect was brought to an excited state by pumping with a laser and then it relaxes by emitting a single photon in a time scale of its lifetime. The single photon emission can be modelled by a 3-level system, with a metastable state. In high spin state defects, the decay into the intersystem crossing allows PL modulation, also by further excitation of the ground state using a microwave or RF source. This allows preparation of the defect in a particular spin state and measurement of polarization, a property that can be used to establish a spin-photon interface.

Recently, Marioka *et al.* showed emission of indistinguishable and distinguishable photons via coherent spin state manipulation from silicon vacancy centers.[8] Indistinguishable photons were generated by double excitation of single defects with an off-resonant laser and a Hong–Ou–Mandel model interference experiment was then performed on the two consecutively emitted ZPL photons. They observed a strong suppression in the coincidence peak at zero time delay, a signature of the indistinguishable photons (Figure 2a). A RF pulse was used to partially transfer the population from m_s =1/2 to m_s =3/2 state after initial laser excitation to generate distinguishable photons. The second excitation results in a photon of different energy and two interfering photons are maximally distinguishable as evident from their coincidence counts (Figure 2b). They were also able to tune the degree of photon indistinguishability by coherent spin state manipulation.[8]

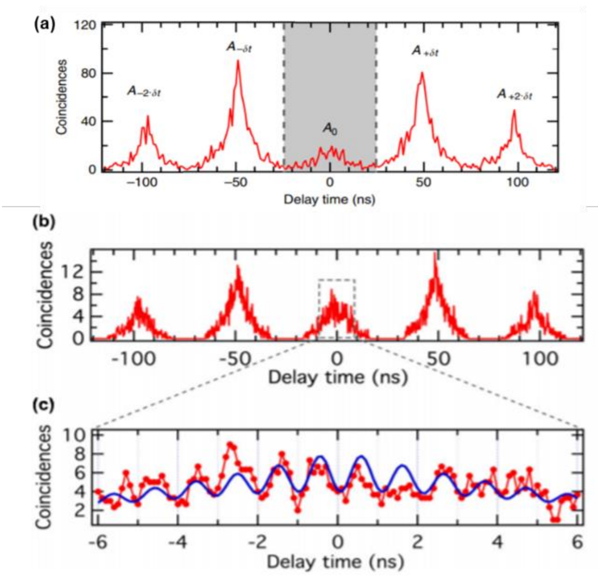

Figure 2: Hong–Ou–Mandel interference for photon indistinguishability study. (a) Schematic set-up for HOM interference with two photons from a single V_{Si}^{-1}. **(b)** Two-photon coincidence counts as a function of the delay The coincidence peak at zero time delay reappears. **(c)** Zoom-in of the HOM interference pattern revealing the fringe pattern.[8]

Defects in SiC have a weak luminescence which makes single photon detection rather difficult. Photon-collection efficiency and ZPL emission can be improved by the integration of these defects into photonic devices. Though several types of nanostructures can be fabricated in SiC, such as photonic crystal cavities that provide a strong photon confinement, their Q factor is still far from the theoretically predicted values. Bracher *et al.* showed a selective enhancement of two closely spaced ZPLs in one dimensional nanobeam photonic crystal cavities with embedded V_{Si}^{-1} point defects in 4H-SiC.[9] Purcell enhancements were calculated from lifetime measurements which showed a decrease from the bulk lifetime when the cavity mode was in resonance with the

ZPL. This was attributed to the increase in the photonic density of states. The emitter lifetime showed an increase when the cavity mode is off resonance. With slightly blueshifted cavity resonances, they observed an 80-fold Purcell enhancement and the value was supported by the increase in spontaneous emission fraction into the ZPL. Chen *et al.* showed that single defect centers can be fabricated and accurately positioned at predefined positions by using a femtosecond laser writing process to integrate them to photonic devices.[10] Similar to silicon vacancies, the divacancies coupled to nanobeam photonic crystal cavity also showed a selective enhancement of one PL branch and its spin state coherence can be extended through dynamical decoupling.[11] Microwave control plus cavity-emitter interactions resulted in an increase in the $V_{Si}V_C^0$'s ZPL emission, which would pave the way for scalable long-distance entanglement networks.[11]

In summary, SPS in SiC have remarkable properties and can be integrated into opto-electronic devices and for quantum photonic applications. The incorporation of these defects in photonics crystal could allow bridging the classical-quantum photonics gap, since it hosts promising optically addressable spin defects and can be processed into devices.

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