# Quantum communication networks with defects in silicon carbide

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Quantum communication promises unprecedented communication capabilities enabled by the transmission of quantum states of light. However, current implementations face severe limitations in communication distance due to photon loss. Silicon carbide (SiC) defects have emerged as a promising quantum device platform, offering strong optical transitions, long spin coherence lifetimes and the opportunity for integration with semiconductor devices. Some defects with optical transitions in the telecom range have been identified, allowing to interface with fiber networks without the need for wavelength conversion. These unique properties make SiC an attractive platform for the implementation of quantum nodes for quantum communication networks. We provide an overview of the most prominent defects in SiC and their implementation in spin-photon interfaces. Furthermore, we model a memory-enhanced quantum communication protocol in order to extract the parameters required to surpass a direct point-to-point link performance. Based on these insights, we summarize the key steps required towards the deployment of SiC devices in large-scale quantum communication networks.

#### INTRODUCTION I.

The advent of the information age is not driven by computers alone, but increasingly by the connection of many computers into ever-growing computer networks. Similarly, quantum technologies will reveal their full potential only by harnessing connections between distant quantum processors [1]. While linking quantum processors will prove essential in quantum computing and distributed quantum sensing [2], an intermediate goal is the exploitation of quantum properties in the communication process itself.

The exchange of photons in quantum communication enables communication primitives unachievable in the classical realm. In quantum cryptography, for example, quantum states of light are used to exchange cryptographic keys which are inaccessible by a third party by virtue of the no-cloning theorem [3, 4]. The main roadblock towards widespread deployment of quantum cryptography is the limited communication distance of a few 100 km in optical fiber due to the nonexistence of a quantum amplifier. Currently, there are two approaches of extending the transmission distance of flying qubits. The first one involves free-space links between optical ground receivers and satellites, an approach which has seen the first in-field demonstrations in recent years [5]. Satellitebased quantum communication enables exchange of cryptographic keys around the globe [6, 7], where the loss is dominated by diffraction instead of absorption. The second approach relies on intermediate nodes in fiber-based networks, which promise to overcome the fundamental limit of point-to-point connections [8]. These nodes interface flying qubits with stationary qubits. Not only do stationary qubits act as quantum memories to extend the transmission distance of quantum states, but they also

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facilitate processing and routing of quantum information in complex network topologies.

Quantum nodes should therefore simultaneously fulfill several requirements. First and foremost, the transfer of quantum information to and from the nodes should be faithful and efficient [9]. Secondly, the storage time, which is limited by decoherence effects of the underlying physical system is crucial. In particular, it should be long enough to enable local quantum processing in addition to quantum and classical communication, both of which are limited by the travel time of the photons over global distances and the success probability of photon transmission. Ideally, the state can be transferred from the spin memory to a long-lived quantum register which has orders of magnitude longer storage times [10]. Crucially, the memories should emit in one of the telecommunication wavelength bands in order to minimize transmission losses and guarantee compatibility with existing fiber infrastructure. While quantum frequency conversion is a viable solution for shifting frequencies to the telecommunication band [11–13], noise and loss are inevitably added in the process. In addition, the nodes should be hosted on a scalable and integrated platform for parallelization and multiplexing purposes.

While several candidate systems such as atomic ensembles [14], quantum dots [15, 16], rare-earth-doped solids [17, 18] and trapped ions [19] are currently investigated, a particularly promising platform are defects in semiconductor materials. Among those, a number of defects in silicon carbide have gained attention due to their strong optical transitions, long spin coherence lifetimes and the fact that they are hosted on a standard material in the semiconductor industry [20]. The latter allows for a high level of integration, electrical spin read-out, electrically driven single photon emission and tunability via microcavity integration [21]. Additionally, spin centers can be interfaced with time-bin qubits as well as polarization qubits [22], making them versatile and deployable both for free-space and fiber-optical quantum communication.

A central concept in the deployment of semiconductor defects for quantum networks is spin-photon entanglement. These hybrid entangled states between a stationary and a flying qubit facilitate heralded entanglement between two quantum memories via Bell state measurements (BSM). To this end, two photons are interfered on a beamsplitter in a synchronous BSM, or a single defect is read out after two consecutive writing processes, which constitutes an asynchronous BSM [23]. BSMs are also key in entanglement swapping, which in turn is an essential building block of the quantum repeater protocol [8]. While first laboratory experiments have demonstrated heralded entanglement distribution between quantum memories and basic quantum network operations [17, 18, 24, 25], full-fledged quantum repeater chains which outperform point-to-point connections in quantum cryptography are still a long way off. However, several quantum cryptography protocols exhibit a substantial benefit over the direct transmission of photons

with only a single intermediate network node. One of these protocols is memory-assisted quantum key distribution (MA-QKD) [26], which is regarded an important milestone on the path to outperforming direct transmission [27].

In this white paper we present the results of MA-QKD simulations with parameters from state-of-the-art SiC devices. This serves as a testbed for the performance of SiC memories in a relevant quantum communication setting. Crucially, the results of this study provide the basis for the development of a roadmap for SiC devices. Furthermore, we discuss advanced quantum communication scenarios which benefit from the SiC platform. This paper is organized as follows. In Sec. II A we introduce the silicon carbide platform and the defects which are of interest, while Sec. II B is devoted to the photonic properties of the defects and their integration in quantum devices. Further on, we describe how these quantum devices based on SiC are suited as quantum nodes in Sec. III A. After a short introduction to quantum cryptography, Sec. III B is dedicated to a particular memory-assisted QKD protocol, with secure key rate simulation results presented in Sec. III C. We draw a roadmap for necessary improvements of SiC devices for quantum link deployment in Sec. IV and summarize our white paper in Sec. V.

# II. THE SILICON CARBIDE PLATFORM

# A. Implementing spin-photon interfaces with defects in SiC

Single electron spins may be optically accessed through point defects in semiconductors, such as SiC [28]. The electron spin of the isolated paramagnetic defects in SiC can serve as a solid-state qubit once it can be initialized, read out and coherently controlled [29–35]. Furthermore, nuclear spins of the host crystal proximate to the point defects, e.g., <sup>13</sup>C and <sup>29</sup>Si in SiC, or introduced by the defect itself, e.g., <sup>14</sup>N or <sup>15</sup>N in nitrogenvacancy defects [33, 36–43] or <sup>51</sup>V in substitutional vanadium defects [44–46], can be used as quantum registers or ancilla qubits mediated by the hyperfine interaction between them (e.g., Refs. 47–49). The quantum states of the electron spin and nuclear spins can be typically controlled by microwave and radiofrequency alternating magnetic fields, if necessary, in the presence of a constant magnetic field.

A coherent spin-photon interface (SPI) can be created by exploiting spin-dependent atomic-like optical transitions [32, 35, 50, 51], typically available at cryogenic temperature. Spin-selective optical transitions, possibly in combination with microwaves for higher-spin systems [51], enable the preparation of specific spin states by optical pumping. They also enable readout by detection of the emitted photons under optical excitation [50], or by conversion of spin-states into different charge states [52–54]. Coherent SPI's also enable establishing a connection between the quantum memory of the solid-state qubit and the flying qubit encoded into the chosen quantum property of the photon [32]. This can be harnessed to setup entanglement-based quantum communication. Very recently, the first demonstration of spin-photon entanglement with a SiC defect was reported using the silicon vacancy in 4H-SiC [55].

Architectures based on single point defects in materials with a diluted nuclear spin bath have also shown the promising opportunity to coherently control a register of nearby weakly-coupled nuclear spins [56]. In this case, the hyperfine interaction acts on timescales longer than the electron spin dephasing time, so that it does not result in a separate transition visible in the electron spin resonance spectrum and cannot be driven directly. However, researchers have been able to address and coherently control such nuclear spins by applying pulse sequences such as dynamical decoupling on the electron spin, that extend its coherence time and can effectively isolate the contribution of a single weakly-coupled nuclear spin, filtering out all the other background. These techniques have enabled the implementation of multiqubit schemes [57], such as quantum error correction [58]. While most of this work has been done in diamond, some recent results show that it is also possible in SiC [49]. Given the higher abundance of isotopes with non-zero nuclear spin in SiC, however, isotopic engineering may be required to maximise the number of controllable nuclear spins [59].

We note that the reduction of the density of  $^{13}$ C and  $^{29}$ Si nuclear spins can be advantageous to extend the coherence times and reduce the optical linewidth of the coherent emission [35, 49] which occurs at the no-phonon or zero-phonon-line emission of the defects. It is imperative to fully characterize the magneto-optical properties of these point defects, in order to develop efficient quantum optics protocols for quantum information processing applications such as quantum communication.

The most mature polytype of SiC is 4H-SiC which has about 3.3 eV band gap. To realize a spin-to-photon interface, deep levels should be introduced by the point defect. This can typically be achieved by introducing dangling bonds of vacancies or dopants with d and f orbitals. We illustrate this by comparing three types of deep-level point defects in SiC: the silicon-vacancy (Sivacancy), divacancy and vanadium centres in 4H-SiC (see Fig. 1). These defects introduce multiple levels into the band gap where the excited state can be described by promoting an electron from the occupied in-gap level to the unfilled in-gap level. These defects have complementary ground state spin structure, with the negatively charged Si-vacancy having spin S = 3/2 in an orbital singlet, the neutral divacancy spin S = 1, and the neutral vanadium substituting silicon has spin S = 1/2 in an orbital doublet.

The electron-orbital and spin level structures are depicted for the three selected qubit species (see Fig. 1). For the negatively charged Si-vacancy in 4H-SiC, in-gap localized defect states are generated by the four carbon dangling bonds of the defect which lead to nondegenerate and triple-degenerate orbitals occupied by five electrons. The latter splits due to the  $C_{3v}$  symmetric crystal field of the defective 4H-SiC lattice. Finally, these defects states constitute an orbital singlet  ${}^{4}A_{2}(g)$  ground state and an orbital triplet  ${}^{4}T_{2}(e)$  excited state, where the latter splits to  ${}^{4}A_{2}(e)$  and  ${}^{4}E(e)$  states in ascending order for the reason as quoted above [60]. We note that the strength of the crystal field and the energy spacing between these levels depends on the actual defect site and in 4H-SiC the splitting is larger for the Si-vacancy defect at the quasicubic site [61]. We continue with that Sivacancy configuration in 4H-SiC. At low temperatures, the fluorescence is dominanted by the  ${}^{4}A_{2}(e) \rightarrow {}^{4}A_{2}(g)$ optical transition which results in the so-called V2 PL spectrum with zero-phonon-line (ZPL) wavelength at 917 nm (1.35 eV) (see Ref. 60 and references therein). The  $m_S = \pm 1/2$  and  $m_S = \pm 3/2$  states of the quartet spin slightly split by the so-called zero-field-splitting of about 70 MHz due to the crystal field. With optical excitation of this system, the electron spin can be pumped into the  $m_S = \pm 1/2$  in the electronic ground state, and the photoluminescence is brighter for the  $m_S = \pm 1/2$ states than that for  $m_S = \pm 3/2$  states. The origin of the spin-selective fluorescence comes from the spin-selective intersystem crossing between the  ${}^{4}A_{2}(e)$  state and the series of spin doublet excited states lying between the quartet states [62–70], see also Fig. 1(b). At zero external magnetic field, radiofrequency magnetic fields can rotate the electron spin in the ground state manifold. This electron spin resonance frequency can be increased to microwave region upon applying an appropriate external magnetic field aligned with the c-axis (defect symmetry axis or crystal stacking axis, see Fig. 1(a)) of 4H-SiC.

The neutral divacancy [29, 71–75] in SiC consists of neighbouring Si and C vacancies in the SiC lattice [see Fig. 1(c)]. The electronic structure is identical to the NV centre in diamond, with  $C_{3v}$  symmetry and a S = 1electronic spin, so that spin-conserving cyclic transition between  ${}^{3}A_{2} \rightarrow {}^{3}E$  can be used for spin-photon interfacing [32]. Difference from the NV centre are the emission wavelength in the near-infrared (with zero-phonon lines around 1030-1130nm) and a zero-field splitting of about 1.3 GHz. Experimental progress on the divacancy has been quite fast with several breakthroughs, such as long spin coherence time, single-shot electron spin readout [54] and control of associated nuclear spins [49] demonstrated in just a few years.

Another configuration of interest is an electron with S = 1/2 within a doublet orbital state. This provides altogether  $2 \times 2$  quantum states that split into two doubly degenerate Kramers states due to spin-orbit coupling. The Kramers degeneracy can be further split by magnetic fields. Neutral vanadium substituting the silicon in the SiC forms such a system. The in-gap defect states come from the vanadium d orbitals, which are five-fold degenerate under spherical symmetry. The crystal field provided



FIG. 1. (a) 4H-SiC crystal lattice with its stacking sequence, (b) Silicon-vacancy and its electronic structure in the negative charge state at the quasicubic site, (c) the neutral divacancy with a neighboring Si and C vacancy with its electronic structure and (d), Vanadium substituting Si and its electronic structure in the neutral charge state at the quasicubic site.

by the SiC crystalline lattice splits these d orbitals into a low-energy orbital doublet – which interacts weakly with the lattice – and an orbital triplet higher in energy that hybridizes with the neighboring carbon orbitals. This orbital triplet is further split into a doublet and a singlet due to the  $C_{3v}$  symmetry of the crystal field. In the neutral vanadium center the lower-energy double degenerate in-gap state is occupied by a single electron which manifests the  ${}^{2}E(g)$  ground state. The strength of the spinorbit splitting in the  ${}^{2}E(q)$  state depends on the specific defect site which is as large as 529 GHz for the quasicubic configuration. The orbital triplet  ${}^{2}T_{1}(e)$  excited state splits to  ${}^{2}E(e)$  and  ${}^{2}A_{1}(e)$  levels where the order of these levels also depend on the defect site; the ascending order is  ${}^{2}E(e)$  and  ${}^{2}A_{1}(e)$  at the quasicubic site [20]. The optical transition can be described as  ${}^{2}E(e) \rightarrow {}^{2}E(q)$ which is associated with the  $\alpha$  vanadium photoluminescence (PL) center in 4H-SiC [20, 46]. As the excited state is less localized than the ground state and the excited state partially loses its d orbital character, the radiative lifetime occurs in the region of 100 ns [20].

A similar electronic structure and optical transition  ${}^{2}E_{u}(e) \rightarrow {}^{2}E_{g}(g)$  is known for the negatively charged silicon-vacancy PL center [76–80] and akin group-IV-vacancy PL centers (see Refs. 81 and 82 and references therein) in diamond, where resonant excitation between the selected states in the ground state and optical excited state manifolds results in a coherent population trapping, and the so-called  $\Lambda$ -scheme is employed to initialize and readout the qubit state [83, 84]. The most developed control and realization of the SPI have been demonstrated for the negatively charged silicon-vacancy PL centers among the diamond group-IV-vacancy PL centers [23, 85–90]. This center has a ZPL at 738 nm

(1.68 eV) which requires a conversion to the telecommunication wavelengths for efficient entanglement distribution over optical fibers [91]. Based on the similarities in the nature of optical transitions of the diamond silicon-vacancy PL center and the  $\alpha$  vanadium PL center, the  $\Lambda$ -scheme can be carried out to realize the SPI [see Fig. 1(d)]. It comes with a significant advantage over the diamond group-IV-vacancy centers, as the  $\alpha$ center's ZPL at 1278 nm (0.97 eV) falls into the telecommunication O-band, removing the need for complex and inefficient nonlinear wavelength conversion systems. We note that standard SMF-28 telecom fibers enable singlemode propagation both for O- and C-band photons: this is practically very convenient as the (largely unoccupied) O-band can be used for the single-photon-level quantum channel, and the C-band for the required classical channel, avoiding cross-talk.

Single-photon emission from vanadium PL centers in SiC has been observed [34, 35], where the interpretation of the fine structure PL requires the details of the vanadium hyperfine interaction with the electron spin and the double degenerate orbital [92, 93]. The interaction of the magnetic field with this system is a complex interplay between the electron-phonon coupling, spin-orbit coupling and the specific selection rules of the d orbitals of vanadium [94]. Understanding the fine details of the spin Hamiltonian was an inevitable step to design quantum optics protocol for optical control of the vanadium nuclear spin [92, 95, 96]. The observed  $T_1$  time reaches 25 s at 100 mK [96] which enabled to characterize the hyperfine level structure of the  $\alpha$  center via two-photon magneto-spectroscopy. For ensemble  $\alpha$  centers, the observed spin dephasing  $T_2^*$  time from Ramsey interference measurements is 7.2  $\mu$ s at 2 K (Ref. 97). The observed 150 counts/s from single vanadium emitters [35] may be substantially improved by engineering the single vanadium defects into solid immersion lenses [98], photonic crystals or optical waveguides and open microcavities [99–101]. These parameters and properties make  $\alpha$  vanadium center in 4H-SiC very promising candidate to realize a practical SPI with a programmable nuclear spin quantum memory.

We note that the single vanadium centers were created in SiC by vanadium ion implantation, followed by high-temperature annealing to repair lattice damage of the crystal lattice [34, 35]. The residual parasitic defects after annealing may create strain and fluctuating charge environment upon illumination. This is an important issue in securing stable emission from single vanadium centers and produce indistinguishable quantum emitters for quantum communication. The fluctuating charges may be flushed by integrating the vanadium centers into p-i-n junction of 4H-SiC and applying an appropriate electric field on it, a method which is already established for isolated divacancy qubits [102]. A recent study on single vanadium centers in 4H-SiC has shown that the photostability of single  $\alpha$  centers upon illumination can be significantly improved by compensating the residual n-type and p-type dopants of SiC and pinning the Fermi-level to the middle of the band gap [35].

#### B. SiC devices

SiC is a mature platform for microelectronics, in particular for power application. Capitalising on a wider bandgap, higher thermal conductivity, and larger critical electric field than silicon, SiC devices can operate at higher temperatures, higher current density, and higher blocking voltage and are becoming more and more widespread in applications such as power conversion in electric vehicles [103, 104]

Recently, researchers have started exploring SiC applications beyond power devices [105, 106]. While it is not a material widely utilised in photonics applications, it exhibits quite promising optical properties [107]. Due to its wide bandgap, SiC features a large transparency range, between 0.37 - 5.6  $\mu$ m for the 4H polytype [108–110].

SiC also features quite strong nonlinear coefficients, not far from values reported for silicon and lithium niobate. The quadratic nonlinearity  $\chi^{(2)}$  has been measured to be  $\approx 12.5 \text{ pm/V}$  in the hexagonal polytypes [111], while the third order (Kerr) nonlinearity  $\chi^{(3)}$  is about  $6.9 \times 10^{-19} \text{m}^2/\text{W}$  at 1550 nm [112] for 4H-SiC. Strong nonlinear coefficients are crucial to implement on-chip modulators and frequency converters [113–116].

Given its outstanding electronic and photonic properties, SiC provides a formidable platform for integration of different functionalities into the same chip. One could envision a single quantum photonic chip integrating SPI's with all the photonic elements required to process quantum states of light (such as optical modulators, beamsplitters, etc), all electrically controlled.

One crucial step for high-rate spin-photon interfacing is to enhance light-matter interaction with an optical cavity. Enhancement of light-matter interactions in cavities can broadly be divided into two approaches: on the one hand, cavities can increase the photon emission from defects into a desired spatial mode, on the other hand a cavity can enhance interaction of an incoming light pulse with the optical dipole. We will briefly describe both approaches below.

The enhancement factor for the spontaneous emission into the cavity,  $F_{SE}$  is given by

$$F_{SE} = \frac{3}{4\pi^2} \Upsilon \frac{\gamma_{ZPL}}{\gamma_{tot}} \zeta^2, \text{with } \Upsilon = \left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}, \qquad (1)$$

with the free-space wavelength  $\lambda$ , the refractive index of the material n, the quality factor Q, and the mode volume V. We have furthermore defined the optical enhancement factor  $\Upsilon$  which collects the performance parameters of the cavity. The value  $\zeta \in [0, 1]$  gives the overlap of the defect's dipole with the electric field mode, relating both to the relative orientation of the dipole and its position within the spatial distribution of the mode, while  $\gamma_{ZPL}$  and  $\gamma_{tot}$  are the decay rate into the zero-phonon line and the total decay rate, respectively [117, 118].

Further, an incoming light pulse will interact more strongly with the optical dipole transition of the defect if it is placed in a suitable cavity. If transitions of different spin states can be resolved, the latter mechanism can be implemented for spin-dependent absorption, reflection, or phase shifting of the incoming light. For a symmetric, lossless cavity, the fractions of the resonant optical power reflected and transmitted by the coupled system are given by [119]

$$R_C = \left(\frac{2C}{2C+1}\right)^2 \text{ and } T_C = \left(\frac{1}{2C+1}\right)^2, \quad (2)$$

where  $C = F_{SE}/2$  is the cooperativity of the system. For finite cooperativity, a fraction of the light will be scattered and lost by the system and is given by  $S_C = 4C/(2C+1)^2$ . Such scattering processes can further lead to undesired spin flips. These expressions assume lowpower excitation, i.e. far below the saturation power of the system.

The last few years have seen great progress in the development of SiC microcavities [10, 107]. An important starting point is the fabrication of thin SiC membranes. Few-microns thick membranes on a high-reflectivity Distributed Bragg Reflector (DBR) can be used for open microcavities, positioning a second concave DBR on top of the emitter [120]. Thinner suspended membranes (few hundred nanometers thick) are required to fabricate photonic crystal devices such as photonic crystal nanocavities and nanobeams. Seminal papers have demonstrated the fabrication of membranes and cavities [99, 121–123] by electro-chemical etching, exploiting the etching selectivity between regions of different doping. More recently, researchers have developed thin-film SiC on insulator, by bonding SiC on a SiO2-on-Si wafer, and grinding/polishing the SiC to the desired thickness [10]. This technique can deliver wafer-scale thin-film SiC with low roughness, and has been used to fabricate different types of microcavities [124, 125]. However, the yield in such processes is currently hampered by non-uniformity of the SiC thickness, leading to low yield in photonic device fabrication.

SiC photonic crystal cavities have reached extremely high quality factors of  $6.3 \times 10^5$  while maintaining a small mode volume of 2.1  $(\lambda/n)^3$ , corresponding to  $\Upsilon = 3 \times 10^5$ [126]. While no integration with Fabry-Pérot resonators has been reported for SiC, devices using membranes of other materials have yielded promising results. As an example, a Fabry-Pérot microcavity containing an yttrium orthosilicate (YSO) membrane reached  $\Upsilon = 7 \times 10^3$  [127]. Recently, microcavities with smaller mode volume and higher finesse have been demonstrated, indicating that  $\Upsilon = 2 \times 10^4$  could be reached for SiC [120]. While the enhancement factor is expected to be lower than for optimized photonic crystal cavities, Fabry-Pérot microcavities offer highly efficient coupling to single-mode fibers and integration with micro-electro-mechanical systems for individual tuning in large-scale systems [21].

From a combination of measurements and *ab-initio* calculations, vanadium on the  $\alpha$  site of 4H SiC is expected to have a branching ratio of  $\gamma_{ZPL}/\gamma_{tot} \simeq 9\%$  [20], giving *C* approaching 100 for the best reported Fabry-Pérot microcavities, and even approaching 1000 for the best reported photonic crystal cavities, respectively. In both cases, a high contrast between coupled and uncoupled spin states can be expected.

## III. BEYOND POINT-TO-POINT QUANTUM KEY DISTRIBUTION WITH SIC DEVICES

In the following, we will focus on applying SiC devices in quantum key distribution (QKD), which is arguably the most mature family of quantum communication protocols. This approach is particularly useful, since the performance of SiC devices in quantum networks can now be assessed and optimized based on a single parameter, namely the secure key-rate (SKR) in QKD, which is the rate of distributed bits that can be used for encryption purposes. The SKR can be used as an overall performance parameter of quantum networks, since it not only depends on the achievable throughput of photons, but also crucially on errors during transmission. In direct transmission, the limiting factors of the SKR are the achievable photon repetition rate of the source and the time resolution of the detection system, whereas the SKR in memory-enhanced quantum networks is mainly limited by the processing time, communication latency and efficiency of the quantum nodes as will be discussed

in this chapter.

The two parties involved in QKD, called Alice and Bob, exchange secret keys in an information-theoretic secure way. Typically, the secret key is encoded in two randomly chosen conjugate bases by Alice, and only Bob can obtain the key by randomly measuring in the same conjugate bases. Due to the no-cloning theorem [3, 4], a third party is fundamentally incapable to obtain the key without prior knowledge of Alice's or Bob's basis settings. All eavesdropping attempts disturb the quantum state and signal the presence of an adversary. There are two families of QKD protocols. In the prepare-and-measure type (e.g. the BB84 protocol [128]), Alice prepares the quantum states and sends them to Bob, who performs measurements. Entanglement-based protocols (e.g. the BBM92 protocol [129]) consist of a central node which distributes pairs of entangled photons to Alice and Bob, both of which perform measurements on their received photon.

Practical implementations of QKD over long distances are mainly impeded by photon loss in optical fiber. The loss of photons leads to an exponential decrease of the secure key rate with fiber distance, limiting the maximal key exchange distance to a few hundred km in optical fiber [130]. This is the case for a direct fiber connection between Alice and Bob. An alternative approach is the division of the total distance between Alice and Bob into several segments. The loss in each of these segments is now exponentially reduced, which overall leads to a substantial improvement in the secure key rate between Alice and Bob. There are two fundamentally different approaches which make use of this segmentation. The first approach is known as a trusted repeater, where each of the nodes connecting two segments performs a full QKD protocol and the resulting key is relayed to other segments. While this indeed increases the possible transmission distance indefinitely, each node reads out the key, which necessitates absolute trust in each node. The second approach is known as a quantum repeater [8]. Here, adjacent nodes are supplied with entangled photons which are stored in quantum memories. Once the quantum memories of all nodes are loaded, nested entanglement swapping is performed in order to entangle the end nodes which belong to Alice and Bob. With entanglement at hand, Alice and Bob can now perform any quantum communication protocol using entanglement as a resource.

SiC devices are natural candidates for this purpose, since quantum repeater stations must facilitate the storage of qubits over long periods of time and process stored qubits for entanglement distillation [131]. Despite their potential, current SiC devices, as well as other quantum memory platforms, are unable to fulfill the stringent requirements of quantum repeaters, let alone the necessary error correction or entanglement distillation overheads, and therefore fail to outperform direct transmission of photons. However, there are QKD protocols which exhibit a quantum memory enhancement without requiring



FIG. 2. SiC device configuration enabling a heralded quantum memory and an asynchronous Bell state measurement. The time-bin state of an incoming photon is converted into spin-photon entanglement between the SiC defect electron spin and an outgoing time-bin encoded photon. A measurement of the outgoing photon in an imbalanced Mach-Zehnder interferometer with imbalance  $\Delta t$  teleports the state of the initial photon into the spin state of the SiC defect, heralded by a single-photon detection.

a full-fledged quantum repeater chain [27, 132].

Within the scope of this white paper, we want to focus on one particular protocol, so-called memoryassisted measurement-device-independent QKD (MA-MDI-QKD) [26], which requires only a single quantum repeater node. At first, we cover the deployment of SiC devices as quantum nodes and discuss to what extent they fulfill the requirements for quantum communication. We then go through the MA-MDI-QKD protocol in greater detail and simulate the protocol based on realistic parameters of state-of-the-art SiC devices. Additionally, we discuss the opportunities of SiC devices for advanced quantum network architectures.

#### A. SiC devices as quantum nodes

SiC devices serve as an SPI, allowing the quantum state of a photon to be transferred to an electronic spin state, and vice versa. A device configuration implementing this interface is sketched in Fig. 2 and discussed below. After the qubit is stored in the spin state, we can apply arbitrary unitary operations using microwave pulses. To connect two quantum links, we need to perform at least two-qubit gates in the quantum node.

The SPI primarily relies on spin-photon entanglement. Let us consider the writing process of a photonic qubit state into the quantum memory. We use a time-bin encoding of the photon, although it is worth noting that SiC memories can also be connected to other degrees of freedom, like the polarization domain [22]. A time-bin qubit

$$\left|\Phi_{\rm Photon}\right\rangle = \frac{1}{\sqrt{2}} \left(\left|t_0\right\rangle + e^{i\phi}\left|t_1\right\rangle\right),\tag{3}$$

is realized as a coherent superposition of two orthogonal states, namely the presence of a photon at time  $t_0$  and at

a later time  $t_1$ . The electron spin is initialized in state

$$|\Psi\rangle_{\rm Spin}^{\rm init} = \frac{1}{\sqrt{2}} \left(|\downarrow\rangle + |\uparrow\rangle\right),\tag{4}$$

where  $|\downarrow\rangle$  ( $|\uparrow\rangle$ ) corresponds to the spin down (up) state of the electron. Based on the non-degenerate level structure [133], a photon arriving at time  $t_0$  is now only resonant with the optical transition of state  $|\downarrow\rangle$  and is thus reflected off the defect-cavity system, resulting in the joint spin-photon state  $|\downarrow t_0\rangle$ . Between  $t_0$  and  $t_1$ , a  $\pi$ -pulse is applied to the microwave transition, which inverts the electron spin state from  $|\downarrow\rangle$  to  $|\uparrow\rangle$  and vice versa. The later time-bin  $|t_1\rangle$  is now resonant with the optical transition of state  $|\uparrow\rangle$ , and upon successful reflection results in state  $|\uparrow t_1\rangle$ . Both the population transfer between the electronic spin states and the time-bin state are coherent processes, which results in a coherent superposition of the spin-photon states

$$\left|\Psi\right\rangle_{\text{Spin-photon}} = \frac{1}{\sqrt{2}} \left(\left|\downarrow t_{0}\right\rangle + e^{i\phi} \left|\uparrow t_{1}\right\rangle\right), \qquad (5)$$

describing a spin-photon-entangled state. An optical circulator now redirects the reflected photons into a detection unit, which consists of a Mach-Zehnder interferometer with imbalance  $\Delta t = t_1 - t_0$  and single-photon detectors (see Fig.2). This Mach-Zehnder interferometer realises a probabilistic measurement in the X-basis  $\{1/\sqrt{2}(|t_0\rangle + |t_1\rangle), 1/\sqrt{2}(|t_0\rangle - |t_1\rangle)\}$ . A measurement of the photon in this basis transfers or teleports the initial photon state onto the spin state, resulting in

$$\left|\Psi\right\rangle_{\text{Spin}}^{\text{final}} = \frac{1}{\sqrt{2}} \left(\left|\downarrow\right\rangle + e^{i\phi}\left|\uparrow\right\rangle\right),\tag{6}$$

where the measurement-induced phase ambiguity, resulting from the probabilistic registration in one of the two single-photon detectors after the Mach-Zehnder interferomter, has already been compensated [134]. The detection of a single photon after the interferometer therefore heralds the successful writing process of the initial photon state into the spin state memory. The overall efficiency of the writing process is limited to a maximum of 25%. This is because the state-dependent reflection of the photon fails in 50% of the cases, and the projective measurement in the Mach-Zehnder interferometer also fails in 50% of the cases [135].

Two-qubit gates play a crucial role in quantum communication, especially for achieving a BSM between two incoming photons. SiC devices provide a suitable approach to perform this BSM asynchronously using a single defect [23]. After writing the first photon in the spin memory, a second photon with phase  $\phi'$  can be loaded into the same defect memory. The resulting spin state

$$|\Psi\rangle_{\text{Spin}}^{\text{BSM}} = \frac{1}{\sqrt{2}} \left( |\downarrow\rangle + e^{i(\phi + \phi')} |\uparrow\rangle \right), \tag{7}$$

inherits the sum of the phases of both photons. Once more, the phase ambiguity that arises after photon measurement has already been compensated for. The BSM



FIG. 3. Comparison between different QKD schemes. a) In prepare-and-measure-type QKD protocols (e.g., BB84), Alice produces quantum states and sends them to Bob, who performs measurements. b) In measurement-device-independent (MDI)-OKD protocols. Alice and Bob each prepare quantum states and send them to Charlie, an untrusted third party. Charlie performs a Bell state measurement (BSM) on both quantum states and based on the outcome of this measurement, Alice and Bob agree on a secret key. c) In memoryassisted measurement-device-independent (MA-MDI)-QKD, both Alice and Bob produce quantum states and send them to Charlie. Prior to the BSM, Charlie synchronises the arrival of the quantum states with the help of quantum memories (QM). Upon successful Bell state measurement (BSM), Charlie announces the outcome of the measurement which leads to the establishment of a secret key between Alice and Bob.

is concluded by reading out the spin state in the X-basis. Depending on the measurement outcome, two Bell states, namely the  $\Phi^+$  or the  $\Phi^-$  state, can be discriminated. While the asynchronous BSM is resource efficient – only a single quantum memory is required – both photons enter the cavity via the same single-mode fiber. To prevent additional losses caused by probabilistic routing with a beamsplitter [23], one can opt for active optical switching instead.

#### B. Memory-assisted measurement-device-independent QKD

Measurement-device-independent (MDI) OKD can be viewed as an entanglement-based QKD protocol in reverse. In entanglement-based QKD a central source produces pairs of entangled photons and transmits them to the communicating parties Alice and Bob. In MDI QKD, both Alice and Bob randomly and independently prepare photons in one of the four BB84 states [128] and send them to a third, untrusted party, called Charlie (C) (see Fig. 3). Charlie performs a BSM which projects the separable state of Alice's and Bob's photon on a joint state in the Bell basis. After C announces the outcome of the BSM, Alice and Bob announce the bases of their respective BB84 state  $\{|0\rangle, |1\rangle, 1/\sqrt{2}(|0\rangle \pm |1\rangle)\}$ . Depending on the announcement, Alice or Bob either swap the bit value in their record or keep them as they are to make sure their bits are always correlated. This protocol is



FIG. 4. Two SiC devices receiving photons from Alice and Bob via an optical switch. Each of the SiC devices can perform asynchronous Bell state measurements. In order to avoid idle times of the node, the optical switch toggles Alice's and Bob's fibers after successful detection of one photon either from Alice or Bob.

measurement-device-independent, since it avoids known side-channel attacks and vulnerabilities of the detectors [136]. The protocol requires that both Alice's and Bob's photon arrive simultaneously at the BSM. With increasing channel loss, the probability of two photons arriving simultaneously decreases exponentially. For this reason, MDI-QKD does not scale favorably compared to direct transmission.

Nonetheless, the protocol's efficiency can be significantly bolstered through the preliminary storage of photons at the central node before the BSM. The photon storage can serve the vital function of synchronizing the channels between Alice and Bob [26]. This alleviates the need for precise simultaneous photon arrival. The BSM is executed asynchronously, exclusively upon the complete loading of both memories. In essence, this scheme merges ideas from quantum repeaters and MDI-QKD and is thus among the simplest QKD protocols involving quantum memories.

The asynchronous BSM introduced in the last section is perfectly suited for MA-MDI-QKD with some slight adaptations. Since both Alice's and Bob's photon must be guided to the same SiC device, some kind of optical switching must be employed. An efficient solution to this problem is to use two SiC devices and an optical switch which re-routes the fibers after the first detection event (see Fig. 4). This toggling prevents the node C from being idle and is a first step towards parallelization (see Sec. IV). This is one crucial technological step beyond the first demonstration of a memory-assisted QKD protocol in Ref. [23], where the authors employ a probabilistic routing of the photons.

#### C. Results and main limitations

In this section we will analyze the key parameters of SiC devices and their impact on the performance of quantum nodes in MA-MDI-QKD. Along with link loss, the primary factor limiting the SKR over long distances is the combination of the photon rate, time resolution, and dark count rate of the single-photon detectors [137]. Unlikely events in which an undetected photon projects the spin state, while two further photons are detected, are not considered.

For memory-assisted QKD to surpass the direct point to point key rate, the advantages gained from using quantum memories must outweigh the costs in efficiency, processing time, and fidelity associated with realistic SiC devices. Hence, we focus on parameters critical to the performance of the asynchronous BSM. To achieve a high SKR, efficiency, fidelity, communication latencies, and processing time are the most important factors to consider. In App. A, we provide a set of values for the most important parameters that are used in our simulations. Chiefly, we assume high cooperativity resulting in unit contrast for the two different spin states.

Based on our previous analysis, we have determined that the memory writing success rate has a lower limit of 25%, resulting in a maximum achievable efficiency of 6.5% for the asynchronous BSM. This sets a fundamental baseline, but the SiC-cavity system itself introduces additional imperfections, including a finite cooperativity of the cavity, leading to further losses. Other factors contributing to losses include the quantum efficiencies of the single-photon detectors and the insertion losses of the optical switch and optical circulator. Although the fidelity of the spin read-out is generally high [27], the fidelity of the spin-photon entanglement used in the writing process is significantly lower. This lower fidelity arises from the involvement of single-photon interference as a heralding mechanism.

Writing a photonic qubit into the quantum memory presents a time-consuming process when compared to the timescales of photon sources, which typically operate in the GHz regime. The primary constraint arises from the microwave pulse employed to perform unitary operations on the electron spin. The duration of a  $\pi$ pulse, denoted as  $\tau_{\pi}$ , determines the minimum separation between the time-bins of a qubit  $\Delta t$ , requiring  $\Delta t > \tau_{\pi}$ . Due to the probabilistic heralding measurement, photons are detected outside their initial temporal qubit space. Consequently, the time-bin separation of a single qubit also restricts the spacing between two successive timebin qubits. Thus, the photon repetition rate of the QKD transmitter is bounded by  $1/(2\tau_{\pi})$ , where a typical  $\pi$ pulse duration of  $\tau_{\pi} = 100 \,\mathrm{ns}$  yields a maximum photon repetition rate of 5 MHz. Furthermore, the photon repetition rate incurs an additional penalty resulting from the temporal spread of the time-bins  $\tau_p = 11.2 \,\mathrm{ns}$ , which is constrained by the bandwidth of the quantum memory as determined by the time-bandwidth product



FIG. 5. MA-MDI-QKD implemented with realistic SiC devices and varying  $\pi$ -pulse durations  $\tau_{\pi}$ . Secure key rates are plotted as a function of transmission distance through a single-mode optical fiber (Corning SMF-28). The solid lines correspond to different  $\pi$ -pulse durations of the electron spin, which are inversely related to the achievable photon repetition rate of the protocol with a dephasing time  $T_2 = 10 \text{ ms}$ . The BB84 and the MDI-QKD protocols are also plotted at different photon repetition rates (4.5 MHz and 5 GHz). Three distinct regions can be identified based on different secure key rate versus distance scalings. In Region I, the implemention of MA-MDI-QKD with SiC devices outperforms point-to-point QKD. Region II is dominated by dephasing of the electron spins, while region III is dominated by noise induced by accidental coincidence counts. The secure key rates are calculated in the asymptotic limit.

of a transform-limited pulse. Including this contribution, the photon repetition rate is ultimately bounded by  $1/(2\tau_{\pi} + 2\tau_{p}) = 4.5$  MHz. Once a successful BSM is heralded, the readout of the electron spin necessitates a microwave  $\pi/2$ -pulse and re-initialization of the spin followed by a second  $\pi/2$ -pulse, rendering the electron spin unavailable during this interval. Similarly, the electron needs to be reset and rotated into a superposition once the memory time has elapsed.

The strong influence of the  $\pi$ -pulse duration on the SKR can be observed in Fig. 5. We simulated the secure key rate in MA-MDI-QKD for four different  $\pi$ -pulse durations (10 ns, 25 ns, 50 ns and 100 ns), as a function of the link distance in standard telecommunication fibers (Corning SMF-28). Here it can be seen that one of the primary factors limiting the rate of long-distance quantum communication is the sequence duration for spinphoton generation, which is limited by the  $\pi$ -pulse duration of the electron spin and, to a lesser extent, by the optical bandwidth of the spin-dependent response of the cavity-defect system. Shorter  $\pi$ -pulses would result in key rates which could easily outperform a point-topoint communication, even for short-distance links. For comparison purposes, we simulated the MDI-QKD pro-



FIG. 6. MA-MDI-QKD implemented with realistic SiC devices and varying dephasing times  $T_2$ . Secure key rates are plotted as a function of transmission distance through a single-mode optical fiber (Corning SMF-28). The solid lines correspond to different dephasing times of the electron spin with a  $\pi$ -pulse duration  $\tau_{\pi} = 100$  ns. The BB84 and the MDI-QKD protocols are also plotted at different photon repetition rates (4.5 MHz and 5 GHz). The secure key rates are calculated in the asymptotic limit.

tocol (dashed lines) and the BB84 protocol (dash-dotted line) along with the MA-MDI-QKD protocol (solid lines). Two different photon repetition rates were employed in simulating each of the protocols that are not assisted by quantum memories. The lower photon repetition rate (4.5 MHz) corresponds to the  $\pi$ -pulse-limiting rate of MA-MDI-QKD, while the higher photon repetition rate (5 GHz) corresponds to the scenario, where the timeresolution of the detectors is the limiting factor. Similar to the photon repetition rates, also the resulting SKR differ by three orders of magnitude, indicating the huge potential of an increased photon repetition rate.

The efficiency-penalty of our implementation of the MA-MDI protocol can be observed at a fiber distance of 0 km. While the memory-assisted protocol should result in the same rate as the MDI protocol at zero transmission loss, there is still a difference in the SKR due to the different efficiencies of the BSM (6.5% in MA-MDI-QKD compared to 50% in MDI-QKD).

In general, the SKR in MA-MDI-QKD exhibits three distinct scalings, which are separated by dashed vertical lines in Fig. 5. In region I, the scaling of the SKR with fiber distance is dominated by the utilization of a quantum memory. This is the region, where the memoryassisted protocol outperforms point-to-point QKD protocols. In region II, the scaling of the SKR with fiber distance is dominated by decoherence. Here, the distances and the accompanying losses become large enough, such that the quantum states stored in the electron spin start to decohere according to a specific dephasing process [26], rendering the quantum memory useless. The resulting key-over-distance-scaling is now similar to the scaling of MDI-QKD, where both photons are required to arrive simultaneously at the central node. In region III, the scaling of the SKR with fiber distance is dominated by accidental coincidences, which is accompanied by a rapid decrease of the SKR towards zero. Accidental coincidences arise from dark counts of the heralding detectors, which are counts that are not triggered by an incoming photon. This ultimately limits the maximal achievable communication distance in any QKD protocol.

Memory-assisted quantum networks demand long storage times. On the other hand, they are required due to low transmission probabilities inherent to long-distance quantum links and the resulting synchronization times of the two incoming photons. Another noteworthy limitation of MA-MDI-QKD therefore pertains to the dephasing of the electron spin. If the dephasing time of the defect is exceeded, the memory must be re-initialized, resulting in the loss of the stored qubit and detrimentally impacting the achievable communication distance. While this predicament could be circumvented by transferring the state from the electron spin to the long-lived nuclear spin, typical conversion times fall within the microsecond regime and the nuclear spins do not couple to the cavity mode, rendering quantum registers impractical for this protocol.

In Fig. 6, the dephasing time  $T_2$  of the spin defect assumes the values 10 ms, 100 ms, 1 s and 10 s. The region where the scaling is dephasing-limited (region II) shifts to longer transmission distances with increasing dephasing time. Specifically, a tenfold increase of the dephasing time results roughly in additional 50 km of maximal transmission distance. Therefore, prolonging dephasing times to  $T_2 \gg 100$  ms would be an important step to significantly outperform point-to-point QKD protocols operating at optimal photon repetition rate.

A further bottleneck of our proposed scheme is the low vield of the writing process, constrained by a 25% upper limit, which sets a fundamental baseline for the efficiency of the asynchronous Bell state measurement in its current implementation. This efficiency limit can be eliminated via two measures. Firstly, the heralding measurement for teleporting the photonic qubit into the spin qubit in its current form employs a passive and imbalanced Mach-Zehnder interferometer. Due to the probabilistic nature of the interferometer, half of the photons are lost. One can replace the passive interferometer by an activelyswitched interferometer which, given sufficiently low insertion loss, can mitigate this photon loss. Secondly, in the scheme described above, only photons which are reflected off the cavity are post-selected on. By including the transmitted photons, projections on other Bell states can be utilized, avoiding this photon loss channel.

Additionally, multiplexing techniques, such as wavelength multiplexing, which are common in modern telecommunication networks, can be harnessed for achieving higher rates in quantum networks. Wavelength



FIG. 7. MA-MDI-QKD implemented with realistic SiC devices, varying  $\pi$ -pulse durations  $\tau_{\pi}$  and 172-fold multiplexing. The multiplexing is achieved through 88 wavelength channels and two polarization channels. Secure key rates are plotted as a function of transmission distance through a single-mode optical fiber (Corning SMF-28). The solid lines correspond to different  $\pi$ -pulse durations of the electron spin, which are inversely related to the achievable photon repetition rate of the protocol with a dephasing time  $T_2 = 10 \text{ ms}$ . The BB84 and the MDI-QKD protocols are also plotted at different photon repetition rates (4.5 MHz and 5 GHz). Three distinct regions can be identified based on different secure key rate versus distance scalings. The secure key rates are calculated in the asymptotic limit.

multiplexing in fiber networks is highly standardized, with plenty of cheap off-the-shelf components. The SiC platform is ideally suited for wavelength multiplexing due to the high level of integration possible with silicon microelectro-mechanical systems and the resulting frequency tunability of each cavity. In Fig. 7, the SKR in MA-MDI-QKD is plotted with 172-fold multiplexing, leading to 172-fold increase of the SKR. We assume 88 wavelength channels and additional two-fold multiplexing in the polarization degree of freedom. While only a single optical fiber is required between the communicating parties, the resources required at the nodes scale linearly with the number of multiplexed channels.

Finally, it should be mentioned that photon losses could be further reduced by utilizing a different optical frequency. The photon loss at the telecommunication O-band (~ 0.3 dB/km), investigated here, is much lower than at optical wavelengths emitted from other defect platforms [138]. However, the band with the lowest loss, which is primarily used in optical telecommunication systems nowadays, is the C-band, with a loss of ~ 0.2 dB/km. While the difference between these two bands is seemingly small, it accumulates to an order of magnitude loss difference after 100 km of propagation.

#### IV. ROADMAP FOR SIC QUANTUM LINKS

We now summarize the required technological steps for SiC photonics towards full deployment based on the example of repeater-extended quantum communication. In order to be competitive with competing approaches, this target needs to be reached within the next decade (see Fig. 8). As underlined by the preceding calculations, this application requires high-rate spin-photon entanglement with high fidelity and long ( $\gg 100 \text{ ms}$ ) spin coherence lifetime, with hundreds of addressable sites at each repeater node for multiplexing, to usefully exceed the rates provided by direct links.

#### 1. Prerequisites

Regarding *materials development*, the properties of most defects in SiC can be improved by carefully controlling the properties of the host crystal [139]. Important aspects are the control of dopant density for charge state stability, a pristine crystalline structure to avoid strain inhomogeneity and undesired charge traps, and isotopic control to increase spin coherence as well as to reduce inhomogeneous broadening of the optical and spin transitions in some defects. Additionally, most if not all defects will benefit from charge depletion, which can be achieved in diode structures. A further necessity is the development of high-yield processes for the creation of thin, ultrasmooth membranes with uniform, µm-scale thickness for FP microcavities and even thinner structures for PC cavities. While proof-of-principle demonstrations of such processes have also been performed, the yield or crystal quality of these SiC membranes have not yet reached a sufficient level for large-scale deployment.

This development is necessary for all types of *opti*cal enhancement structures [107], apart from very few exceptions such as bullseye ring resonators, which can conceivably be implemented on bulk crystals but are not suitable for the spin-dependent reflection scheme discussed above. While defects which are spectrally and electronically stable might be utilized as emitters with Purcell or even only collection enhancement, the type of spin-photon interaction described above will be advantageous for most systems as it greatly reduces defect ionization and light-induced spectral diffusion. We underline here that defects with longer wavelength transitions benefit from lower losses and a higher tolerance to imperfections in the photonic enhancement structures: As an example, the loss due to interface roughness in FP cavities decreases with  $\sigma \propto 1/\lambda^2$ , leading to a corresponding increase of the enhancement. Only very few examples of photonic enhancement have been reported on for SiC defects so far, making the development of these structures an important task for the scientific community.

All *candidate defect centres* will require high-fidelity spin initialization, manipulation, and readout, and will need to reach the desired coherence times. Addi-



FIG. 8. Roadmap for deployment of high-performance quantum links based on SiC photonics in the next decade. Bar ends indicate when technological developments (materials, integration) are expected to have reached a level suitable for large-scale deployment. Similarly, bar ends for benchmarks indicate when a performance level sufficient for deployment on metropolitan-scale links is achieved. Defect identification, characterization, and development is expected to lead to continued improvements throughout this evolution.

tionally, high-yield creation of defects at predetermined positions in the crystal is highly desirable for the subsequent integration into photonic enhancement structures. In order to reduce the complexity of the multiplexing architecture, it is furthermore desirable to tune all defects at one repeater site to the same optical frequency so as to achieve indistinguishability. For most defects, this requirement implies tuning by strain or electrostatic means. Together with the requirement for fast individual spin control, this necessity implies a high degree of integration with multiple wire structures on the SiC surface, for which stringent limits on the power dissipation and conductive thermal load are given by the cooling power of the cryogenic environment. This, in turn, hints at the necessity for resonantly enhanced and/or superconducting spin control structures.

Many of the postulated requirements imply the use of *cryogenic infrastructure* for all candidate defects, though only vanadium is known to need temperatures < 1 K for sufficiently long spin relaxation lifetime, while impressive coherence times have been achieved with other defect systems at around 4 K.

Finally, *wavelength conversion* will be necessary for all known defects in SiC, apart from the NV centre in 3C SiC [42] and most neutral vanadium defects, which have transitions in the telecom O band. The development of compact, scalable, and efficient converters will thus be required for most candidate defects. Successful proof-of principle demonstrations have been achieved, but engineering a solution that is deployable at scale remains an outstanding task.

### 2. Applications

Photonic quantum links with memory units are broadly seen as having four distinct applications, which pose slightly different requirements:

**Repeaters for quantum key distribution** that are integrated in a global network additionally require an efficient interface to space-based quantum communication systems, which currently operate at visible wavelengths or in the telecom C-band.

Photonically connected qubits or qudits within spin-based quantum computers can be envisioned without wavelength conversion or frequency multiplexing. Fault-tolerant architectures, however, place even greater demands on yield, scalability, coherence, and fidelity of the SPI's. Additionally, they can benefit more strongly from nuclear spin ancillae than simple communication protocols. Quantum computing architectures based on small quantum processing units connected by a photonic channel [140], all integrated on a single SiC chip including elements such as waveguides, Bragg filters, electrically-controlled optical modulators for routing, etc., can be envisioned. Further applications will be entanglement distribution for other *networked quantum computers* and entanglement distribution for *networked quantum sensors*. For these, interfacing between the qubits or quantum sensors and the SPI needs to be developed.

#### 3. Prioritization

These differences notwithstanding, the overall set of requirements allows to set priority levels for development of different aspects of the technology. We focus here on aspects which are specifically connected to SiC devices, thereby excluding wavelength conversion and cryogenic infrastructure, to which advances in SiC photonics cannot contribute directly. The highest priority should be given to materials development aspects. Most of these are additionally beneficial to the SiC industry and to emerging applications of classical SiC photonics, thereby providing the highest incentives overall. The next priority is the selection of the most suitable defect for deployment, as this determines the requirements for photonic enhancement and interoperability with telecom networks. As several defects currently under study present advantageous features, this decision can only be taken at a fairly late stage of technological development. Nonetheless, several performance parameters need to be ascertained precisely along this path, including the Debye-Waller factor, radiative efficiency, and transition branching ratios, the spin relaxation and coherence lifetimes, the operation temperature, as well as any limitations on the single-spin initialization, readout, and gate times and fidelities which could limit the SPI performance. This type of characterization can be expected to exclude several defects from applications in quantum photonics. However, as new candidate defects continue to emerge, this task will remain ongoing beyond the deployment of the first devices.

For SPI benchmarking, each defect with sufficient performance parameters needs to be incorporated in a photonic enhancement structure, replete with all control wiring and potentially with SiC diode structures. Aside from the enhancement factor, the main emphasis in this development must be placed on scalability, as vast numbers of SPI's will be required for all quantum technology applications. A large part of these technological aspects is common to all defects and should therefore be performed in parallel to the detailed characterization of spin centres.

Since different applications and protocols place differing requirements on the performance of the SPI, a global benchmark cannot be defined. Nonetheless, certain performance indicators are common to most settings. A possible baseline benchmark which encapsulates many of the stated requirements is the product of the spinphoton entanglement rate and the spin coherence lifetime at telecom wavelength and after fiber coupling. The next benchmark level is the product of rate and lifetime of spin-spin entanglement with two such units, which subsumes aspects such as indistinguishability and synchronization. Both of these benchmarks need to be defined with a threshold fidelity, or be scaled appropriately for a chosen protocol.

#### 4. Timeline

For these developments to take place within the next decade, a concerted effort by the SiC photonics community with strong industrial participation will be required. The payoff, however, will be large for all involved stakeholders, and will provide technological developments with beneficial effects far beyond the science and technology domains. While ambitious, the timeline for these developments can be achieved assuming continued growth in support from governments and continued advances in the burgeoning SiC industry.

#### V. SUMMARY

We have provided an overview of SiC photonics using spin centres for quantum links. These devices have applications in quantum computing, secure key distribution, and as entanglement links for distributed quantum computation and sensing. Using memory-assisted QKD as an example, we have investigated the key parameters which determine the performance of such links, using current state of the art parameters as a starting point.

In this study, we have undertaken a comprehensive analysis of the key parameters of SiC devices and their impact on the performance of quantum nodes in the context of memory-assisted measurement-deviceindependent-QKD. We opted for this particular QKD protocol implementation, because it provides an excellent platform for examining the performance of a single quantum memory by focusing on a single parameter – the secure key rate. Importantly, the implementation of this protocol with SiC devices includes all essential building blocks of large-scale repeater networks. Our investigation has revealed several crucial factors that influence the secure key rate over long communication distances, shedding light on both the potential and limitations of spin centers in SiC.

From there, the technological maturity of SiC fabrication, will allow for many devices on a single SiC wafer. One possibility is to harness wavelength multiplexing techniques [141], which is efficient up to several tens of users. Extending this network size in a scalable fashion is feasible with active optical switches [142]. This entails integrating many defects on a SiC chip, which are linked by a programmable optical switch module. For example, one could use this quantum network router as the access node in a star topology network. Pairs of user nodes are then connected to a single SiC defect at the access node, where an asynchronous BSM is performed. This operation is initiated on request by two users. They can either establish a cryptographic key or use the BSM as entangling operation, e.g., for quantum repeater networks.

Quantum repeater networks are the ultimate goal for long-distance quantum communication and the SiC platform is a strong candidate for serving this purpose. This vision can only be realized once a single quantum repeater node outperforms point-to-point quantum communication. Only then, quantum repeater networks with several quantum repeater nodes will prove beneficial in quantum communication and might be deployed in the field. This should also guide the experimental efforts in SiC-based SPI's. Therefore, the first milestone on the roadmap towards a large-scale quantum repeater network is the demonstration of the single-node [23] or two-node [17, 18] scenario.

While other authors are mainly concerned with beating the repeaterless bound [143] per channel use [23, 132], we go one step further in this white paper. We benchmark SiC devices with existing QKD technologies, which, for example, allow higher photon repetition rates in comparison to current specifications of SiC devices. This practical approach allows us to make statements about the operational capability of SiC-based quantum memories in real-world quantum networks. Another usecase is the deployment of SiC devices for end nodes in quantum networks. The quantum memories in end nodes delay the read-out of photonic quantum states or re-emit stored states after certain time intervals for various quantum information processing tasks. End nodes therefore have a different set of requirements compared to repeater nodes. As an example, the transfer to nuclear spins is a good option to increase the storage time of end nodes, even though in-depth comparison to other quantum memory platforms is necessary to evaluate the deployability of defects in SiC for this usecase.

These considerations allow to define a path towards deployment of SiC photonics for high-performance quantum links, which we outlined in IV. We project that, with a concerted effort of the scientific community and the SiC industry, it will be possible to achieve this goal within the end of the decade.

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# Appendix A: Parameter list for MA-MDI-QKD simulations

Here, we list all relevant parameters used for the simulations of the MA-MDI-QKD protocol using SiC devices. The values are derived from state-of-the-art experiments and off-the-shelf component specifications. The first part of Table I lists the spin-cavity parameters, while the second part of the table lists parameters used in the simulation.

Name	Symbol	Value	Comment/Description	
Amplitude decay time	$T_1$	30s	Amplitude decay time of the electron spin	
			$\eta_r(t) = \eta_{r0} \mathrm{e}^{-t/T_1}.$	
Coherence time	$T_2$	10ms-10s	Dephasing time of electron spin.	
Nuclear spin amplitude decay time	$T_{1N}$	30s	Amplitude decay time of the nuclear spin.	
Nuclear spin coherence time	$T_{2N}$	> 10s	Dephasing time of nuclear spin.	
Spin conversion time	$T_{\rm E-N}$	10 µs	Time needed for a conversion from electron spin	
			to nuclear spin.	
Spin readout time	$ au_{ m R}$	$400\mathrm{ns}$	Time required to measure the electron spin.	
$\pi$ -pulse time	$ au_{\pi}$	10-100 ns	$\pi$ -pulse duration.	
Initialization time	$ au_{ m init}$	$ au_{\mathrm{R}} +  au_{\pi}$	Initialization time for the electron spin.	
Reflectivity $ \uparrow\rangle$	$\eta_{\uparrow}$	1	Reflectivity of the cavity with the spin in the $\uparrow$	
			state, SMF included.	
Reflectivity $ \downarrow\rangle$	$\eta_{\downarrow}$	0	Reflectivity of the cavity with the spin in the $\downarrow$	
			state, SMF included.	
Linewidth	$\gamma$	100 MHz	Optical Fourier-limited linewidth (FWHM),	
			including cooperative broadening.	
Pulse duration	$\tau_{\rm p}$	11.2 ns	Optical pulse duration.	
Writing time	$ au_{\mathrm{W}}$	20-200 ns	$2(\tau_{\rm p}+\tau_{\pi})$ . Time difference between the time	
			that the beginning of the pulse arrives at the	
			QM and the time that a successful/unsuccessful	
			loading is declared.	
Reading time	$ au_{ m r}$	410-500 ns	400 ns + $\tau_{\pi}$ . Time difference between the time	
U U			that the retrieval process is applied until the	
			end of the pulse is out.	
Writing efficiency	$\eta_{\rm w}$	0.13	Probability to store a qubit and herald success	
	,		conditioned on having a single photon at the	
			QMs input.	
Reading efficiency	$\eta_{r0}$	1	1 Probability to retrieve a single photon out of the	
0 0	1. •		QM (right after loading $t=0$ ) conditioned on a	
			successful loading in the past.	
Single-photon detection efficiency	$\eta_{\rm SPD}$	0.85	Superconducting nanowire single photon	
			detector	
Temporal resolution	$t_{\rm SPD}$	$50 \mathrm{ps}$	Superconducting nanowire single photon	
•		*	detector, FWHM	
Dark count rate	$\gamma_{ m dc}$	100 Hz		
Background rate	$\gamma_{ m bg}$	$0~\mathrm{Hz}$	Photonic background rate per optical mode	
Channel length	L	$0-700 \mathrm{km}$	$L_{A(B)}$ is the channel length from Alice or Bob to	
			the respective memory. $L = L_{\rm A} + L_{\rm B}$ , where we	
			assume equal channel length $L_{\rm A} = L_{\rm B}$ .	
Fibre attenuation	$lpha_{ m Ob}$	0.3  dB/km	At the telecom O-band	
Setup misalignment probability	$e_{\rm A(B)}$	0	Probability of a qubit flip	
Error correction inefficiency	, Î	1.16	Efficiency of the error correction code	
Insertion loss fibre optical circulator	$\eta_{\rm oc}$	0.8 dB		
Insertion loss fibre optical switch	$\eta_{ m os}$	0.6  dB		
Optical rise/fall time optical switch	$t_{\rm os}$	8 ns		
Minimal pulse width optical switch	$\Delta t_{\rm os}$	90 ns		

TABLE I. Parameters	used in the MA-M	DI-OKD simulation	with SiC devices.
TIDDD I. I aramotors	about in one min in	Let grie simalation	with bio dovidob.