# Solid-State Color Centers for Single-Photon Generation

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Single-photon sources are important for integrated photonics and quantum technologies, and can be used in quantum key distribution, quantum computing, and sensing. Color centers in the solid state are a promising candidate for the development of the next generation of single-photon sources integrated in quantum photonics devices. They are point defects in a crystal lattice that absorb and emit light at given wavelengths and can emit single photons with high efficiency.

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## 1. Introduction

Single-photon sources, i.e., physical systems offering the *on-demand* emission of individual photons with desired properties, are key ingredients for current and prospective applications in integrated photonics and quantum technologies [1]. In particular, the relevant properties that a single-photon source must have to enable the realization of these technologies generally include the photostable and on-demand delivery of fully polarized single indistinguishable photons. In addition, the ideal single-photon source is a scalable physical system operating at room temperature and characterized by a high emission count rate and quantum efficiency. The concept of single-photon sources originated in the late 20th century, with a significant subsequent body of work leading to their practical implementation. In the field of quantum communication, single-photon sources serve as building blocks for secure quantum key distribution (QKD) systems [2][3][4]. They also have the potential to play a pivotal role in quantum computing as optically addressable qubits for quantum information processing and sensing [5][6][7]. In the context of integrated photonics, these sources are also at the core of the development of quantum photonic circuits that integrate quantum components with existing optical technologies [8]. Although probabilistic sources based on approximating a quantum light emitter with attenuated lasers [9] or on nonlinear photon conversion processes [10][11] have gained immediate interest for high-level experiments in laboratory environments [12][13][14] and for selected commercial systems, the quest for deterministic sources exhibiting a truly on-demand behavior, with negligible multi-photon generation probability, has steadily led to the development of several alternative approaches, spanning cold atoms and ions [15], quantum dots [16][17], and isolated molecules [18]. Among the possible platforms, color centers in the solid state represent a viable candidate for the development of the next generation of single-photon sources integrated in quantum photonics devices. Color centers are point defects in a crystal lattice that absorb and emit light at given wavelengths, thus effectively acting as artificial atoms embedded in a solid-state material.

These unique quantum systems have immense potential as single-photon sources due to their ability to emit single photons with high efficiency, purity, and indistinguishability [19]. Furthermore, their occurrence as point defects at the solid state offers a viable path towards their native embedment in photonic circuits by micro- and nanofabrication of the host material. For several years, the interest in color centers has been limited to a few physical systems, among which, notably, is the nitrogen-vacancy center in diamond [20]. Due to sub-optimal emission properties for integrated photonics, scientific research has pursued specific applications such as the optically addressable spin properties for quantum sensing and computing. Since 2013, the landscape has changed abruptly with the subsequent identification of a wider set of color centers and the emergence of new, previously unexplored solid-state platforms for room-temperature-single-photon generation.

## 2. Single-Photon-Emitting Color Centers

Color centers are optically active defects that occur in the crystalline lattice structure of semiconductors and insulators. Both intrinsic, (i.e., related only to the occurrence of vacancies, interstitials, or their combination) and extrinsic (i.e., involving the presence of atomic impurities in the material) can result in optical transitions, depending on their specific electronic configuration. A color center presents an atom-like nature that is embedded in the solid-state matrix of the host material. The structure can be described by a finite number of energy levels introduced in the forbidden gap, among which electron transitions are allowed.

The electronic structure and related photon emission of a color center are typically discussed using a simplified model involving an excited state, a ground state, and generally a shelving state taking into account non-radiative transition paths, e.g., weakly allowed spin-flipping transitions from the excited state to the ground state [21] or resonant-energy-transfer processes involving neighboring lattice defects [22]. Therefore, the emission dynamics can be generally described using a two- or three-level system. The energy is delivered to the defect complex through the optical pumping of a laser pulse, while some color centers may also emit luminescence under electrical excitation [23]. The so-called Zero Phonon Line (ZPL) indicates the emission wavelength of the emitted photons when the radiative transition occurs between ground-state vibrational levels. Conversely, the embedment of a point defect in a crystal lattice naturally involves the occurrence of phonon-assisted transitions. In this case, less energetic photons are emitted, populating the region of the emission spectrum commonly indicated as the phonon sideband. The fraction of light emitted in the ZPL with respect to the overall emission of the color center defines the Debye–Waller factor, a reference parameter to classify the eligibility of the source for the implementation of quantum computation schemes with matter qubits and linear optics [24]. Additionally, the linewidth of the ZPL provides a piece of benchmark information on the indistinguishability of the emitted photons. Particularly, to discriminate the single-photon emission from thermal or coherent light, an analysis of the emission statistics is needed. A standard characterization technique is provided by the Hanbury-Brown and Twiss interferometer. This experimental method is implemented by feeding the light source onto a beam splitter separating the emission into two paths, each coupled to a single-photon-sensitive detector. Therefore, a time interferogram is obtained by acquiring a histogram of the differences between detection event pairs at the two detectors. In fact, under proper assumptions, the histogram of the time differences directly represents the so-called second-order autocorrelation function, $g^2(\tau)$, whose value at a zero-time delay is the main criterion used to measure the non-classicality of a source. Indeed, the emission collected from an ideal single-photon source will result in the lack of event pairs recorded at $\tau = 0$, producing an anti-bunching signature in the $g^2(\tau)$ histogram. The occurrence of nonclassical emission from an individual emitter is indeed verified when $g^2(0) < 0.5$. The $g^2(\tau)$ model for a three-level system is represented by a double-exponential function, in which the decay parameters are directly connected to the characteristic times associated with the de-excitation of the excited state and the shelving state [25]. As a result, the study of the second-order autocorrelation function is also a well-established procedure for evaluating the characteristic features of the transitions involved in the optical activity of the single emitter under study.

Moreover, since high-throughput information transmission and processing are needed in the practical implementation of quantum information processing devices such as QKD systems, the emission count rate is a key element for evaluating the suitability of the single-photon source for a given application. The emission intensity at saturation, meaning the maximum photon count rate when complete saturation of the emitter occurs, provides a reliable estimate of the source’s brightness and, together with the corresponding optical power required for excitation, represents a useful quantitative parameter for the assessment of single-photon sources’ performance.

## References


1. Eisaman, M.D.; Fan, J.; Migdall, A.; Polyakov, S.V. Invited Review Article: Single-photon sources and detectors. Rev. Sci. Instrum. 2011, 82, 071101.
2. Takemoto, K.; Nambu, Y.; Miyazawa, T.; Sakuma, Y.; Yamamoto, T.; Yorozu, S.; Arakawa, Y. Quantum key distribution over 120 km using ultrahigh purity single-photon source and superconducting single-photon detectors. Sci. Rep. 2015, 5, 14383.
3. Leifgen, M.; Schröder, T.; Gädeke, F.; Riemann, R.; Métillon, V.; Neu, E.; Hepp, C.; Arend, C.; Becher, C.; Lauritsen, K.; et al. Evaluation of nitrogen- and silicon-vacancy defect centres as single photon sources in quantum key distribution. New J. Phys. 2014, 16, 023021.
4. Schiavon, M.; Vallone, G.; Ticozzi, F.; Villoresi, P. Heralded single-photon sources for quantum-key-distribution applications. Phys. Rev. A 2016, 93, 012331.
5. Awschalom, D.D.; Hanson, R.; Wrachtrup, J.; Zhou, B.B. Quantum technologies with optically interfaced solid-state spins. Nat. Photonics 2018, 12, 516–527.

6. Piergentili, P.; Amanti, F.; Andrini, G.; Armani, F.; Bellani, V.; Bonaiuto, V.; Cammarata, S.; Campostrini, M.; Cornia, S.; Dao, T.H.; et al. Quantum Information with Integrated Photonics. Appl. Sci. 2023, 14, 387.
7. Polino, E.; Valeri, M.; Spagnolo, N.; Sciarrino, F. Photonic quantum metrology. AVS Quantum Sci. 2020, 2, 024703.
8. Wang, J.; Sciarrino, F.; Laing, A.; Thompson, M.G. Integrated photonic quantum technologies. Nat. Photonics 2020, 14, 273–284.
9. Paraïso, T.K.; Woodward, R.I.; Marangon, D.G.; Lovic, V.; Yuan, Z.; Shields, A.J. Advanced Laser Technology for Quantum Communications (Tutorial Review). Adv. Quantum Technol. 2021, 4, 2100062.
10. Li, X.; Voss, P.L.; Sharping, J.E.; Kumar, P. Optical-Fiber Source of Polarization-Entangled Photons in the 1550 nm Telecom Band. Phys. Rev. Lett. 2005, 94, 053601.
11. Signorini, S.; Pavesi, L. On-chip heralded single photon sources. AVS Quantum Sci. 2020, 2, 041701.
12. Broome, M.A.; Fedrizzi, A.; Rahimi-Keshari, S.; Dove, J.; Aaronson, S.; Ralph, T.C.; White, A.G. Photonic Boson Sampling in a Tunable Circuit. Science 2013, 339, 794–798.
13. Adcock, J.C.; Vigliar, C.; Santagati, R.; Silverstone, J.W.; Thompson, M.G. Programmable four-photon graph states on a silicon chip. Nat. Commun. 2019, 10, 3528.
14. Hu, X.-M.; Guo, Y.; Liu, B.-H.; Li, C.-F.; Guo, G.-C. Progress in quantum teleportation. Nat. Rev. Phys. 2023, 5, 339–353.
15. Kuhn, A.; Hennrich, M.; Rempe, G. Deterministic Single-Photon Source for Distributed Quantum Networking. Phys. Rev. Lett. 2002, 89, 067901.
16. Norman, J.C.; Jung, D.; Wan, Y.; Bowers, J.E. Perspective: The future of quantum dot photonic integrated circuits. APL Photon. 2018, 3, 030901.
17. Arakawa, Y.; Holmes, M.J. Progress in quantum-dot single photon sources for quantum information technologies: A broad spectrum overview. Appl. Phys. Rev. 2020, 7, 021309.
18. Toninelli, C.; Gerhardt, I.; Clark, A.S.; Reserbat-Plantey, A.; Götzinger, S.; Ristanović, Z.; Colautti, M.; Lombardi, P.; Major, K.D.; Deperasińska, I.; et al. Single organic molecules for photonic quantum technologies. Nat. Mater. 2021, 20, 1615–1628.
19. Aharonovich, I.; Englund, D.; Toth, M. Solid-state single-photon emitters. Nat. Photonics 2016, 10, 631–641.
20. Schirhagl, R.; Chang, K.; Loretz, M.; Degen, C.L. Nitrogen-Vacancy Centers in Diamond: Nanoscale Sensors for Physics and Biology. Annu. Rev. Phys. Chem. 2014, 65, 83–105.

21. Doherty, M.W.; Manson, N.B.; Delaney, P.; Jelezko, F.; Wrachtrup, J.; Hollenberg, L.C. The nitrogen-vacancy colour centre in diamond. Phys. Rep. 2013, 528, 1–45.
22. Siyushev, P.; Jacques, V.; Aharonovich, I.; Kaiser, F.; Müller, T.; Lombez, L.; Atatüre, M.; Castelletto, S.; Prawer, S.; Jelezko, F.; et al. Low-temperature optical characterization of a near-infrared single-photon emitter in nanodiamonds. New J. Phys. 2009, 11, 113029.
23. Forneris, J.; Traina, P.; Gatto Monticone, D.; Amato, G.; Boarino, L.; Brida, G.; Degiovanni, I.P.; Enrico, E.; Moreva, E.; Grilj, V.; et al. Electrical stimulation of non-classical photon emission from diamond color centers by means of sub-superficial graphitic electrodes. Sci. Rep. 2015, 5, 15901.
24. Martínez, J.A.; Parker, R.A.; Chen, K.C.; Purser, C.M.; Li, L.; Michaels, C.P.; Stramma, A.M.; Debroux, R.; Harris, I.B.; Appel, M.H.; et al. Photonic Indistinguishability of the Tin-Vacancy Center in Nanostructured Diamond. Phys. Rev. Lett. 2022, 129, 173603.
25. Corte, E.; Andrini, G.; Nieto Hernández, E.; Pugliese, V.; Costa, Â.; Magchiels, G.; Moens, J.; Tunhuma, S.M.; Villarreal, R.; Pereira, L.M.C.; et al. Magnesium-Vacancy Optical Centers in Diamond. ACS Photonics 2023, 10, 101–110.