

Essay: Semiconductor Sources of Large-Scale Photonic Entanglement for Science and Technology

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Over the past twenty-five years, intensive research on epitaxial semiconductor quantum dots (QDs) has transformed these systems from random quantum emitters embedded in a noisy solid-state environment into one of the most efficient platforms for generating not only single photons but also multiple entangled photons in highly pure quantum states. Today, QD-photon interfaces often outperform their natural-atom counterparts in both quantum-state purity and photon-generation rates while also offering a clear route toward scalable integration and industrial deployment. Building on these remarkable achievements, this Essay outlines a path toward a not-so-distant future in which large numbers of quantum-dot spins are entangled to generate quantum states of light with unprecedented numbers of entangled photons. Just as lasers evolved from laboratory curiosities into ubiquitous enabling technologies, semiconductor sources of large-scale photonic entanglement could become indispensable resources for both emerging quantum technologies and fundamental research.

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Forty years of epitaxial quantum dots—The year 2025 marked the 40th anniversary of the discovery of epitaxial semiconductor quantum dots (QDs) [1], randomly positioned, flat, lens-shaped semiconductor nanostructures capable of trapping electrons and holes in all directions of space [Fig. 1(a)]. Since then, QDs have inspired a remarkable scientific journey from the study of their optical and electronic properties to the realization of today's most advanced single-photon sources. Their true potential for quantum technologies became clear when they were shown to behave as artificial atoms [2–4], that is, two-level quantum systems capable of emitting single photons on demand [5,6]. A major challenge was then to efficiently extract these photons while preserving their quantum coherence. A key breakthrough came from the development of QD-photon interfaces exploiting the Purcell effect, which enhances and channels spontaneous emission into a well-defined optical mode [7,8]. Over the past two decades, advances in semiconductor nanofabrication and cavity quantum

electrodynamics have transformed these ideas into highly efficient integrated devices, with III-V quantum dots [see Fig. 1(a)] now generating photons with collection efficiencies exceeding 80% and indistinguishabilities routinely above 95% [9–15]. A major step forward came with techniques that enabled full control of the system by deterministically positioning a single QD in a microcavity [13,16] together with the development of multiple tuning knobs, including electric field and strain [12,17]. As a result, photons emitted by distant QD sources can now be made nearly as indistinguishable as photons emitted successively by a single source [18,19]. Such performances now rival, and in some respects surpass, those achieved with natural atoms and ions [20–22].

In parallel, the spin properties of single electrons and holes confined in QDs have been extensively investigated [23], and spin-photon entanglement has been demonstrated [24–27]. These achievements opened the door to adapting to QD protocols originally developed in atomic systems, where a long-lived quantum memory is successively entangled with emitted photons to generate multi-photon entangled states [28,29]. Experimental progress has advanced in parallel across atomic [30,31] and QD systems [32–38] and was very recently extended to QDs emitting in the telecom range [39,40]. Last but not least, the strong hyperfine interaction in III-V QDs, once regarded primarily as a source of decoherence, has increasingly emerged as a resource for controlling nuclear-spin ensembles, enabling electron-spin coherence on the hundred-microsecond

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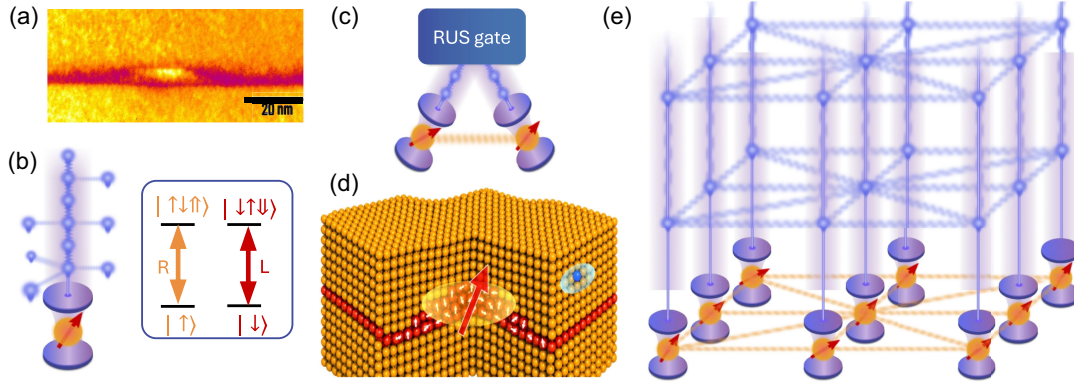


FIG. 1. Toward semiconductor sources of large-scale photonic entanglement. (a) Transmission electron microscope of a single InGaAs in GaAs quantum dot. The black line indicates the scale of 20 nm. The QD is represented in the next figures as an orange sphere. (b) A single spin in a QD coupled to an optical cavity constitutes a QD-photon interface used to generate single photons on demand and multiple photons entangled together and with the spin. The photonic state represented here is a caterpillar graph state. (c) Photon-mediated entanglement between QDs, where QDs emit photons that are entangled with their local spins, and a repeat-until-success protocol allows turning the probabilistic photon gate into a semideterministic QD-QD entanglement. (d) Representation of the solid-state noise sources affecting the quantum dot: phonons (lattice vibrations), hyperfine interactions between the electron or hole spin (large arrow) and the fluctuating nuclear spins (small white arrows), and a nearby charge trap (blue atom), inducing fluctuating electric fields. (e) A QD network in which multiple entangled QD spins enable the generation of various classes of high-dimensional, large-scale photonic entangled states. Color codes: orange represents the QD spin and blue the photons. Lines between photons and between QD spins and photons represent entanglement links.

timescale and mesoscopic optical quantum memories [41–47]. Compared with the photon emission time of hundreds of picoseconds, such coherence times could support the entanglement of thousands of photons.

Together, these results have established QDs as an excellent platform for the deterministic generation of entangled multiphoton states. Building on this progress, epitaxial quantum dots now offer a credible and scalable route toward *large-scale, high-dimensional photonic entanglement*, a resource expected to play a central role in future quantum technologies. Large-scale photonic entanglement is now widely recognized as an enabling resource for universal quantum computing and quantum networks, but it could also bring new paradigms and possibilities in quantum sensing and in fundamental science.

In this Essay, I will first discuss the scientific and technological challenges that still lie ahead on the road to quantum-dot sources of large-scale photonic entanglement. Far from being a distant ambition, this goal is now within reach, and the progress already made points toward a new generation of devices that combine the precision of atomic physics with the scalability of semiconductor technology. Indeed, beyond their intrinsic scientific interest, these efforts continuously push mesoscopic solid-state systems closer to the ideal behavior of isolated atoms. Yet the true promise of this platform stems from its semiconductor nature and its potential for large-scale fabrication. This combination could be transformative for quantum technologies but also bring entirely new approaches to sensing and to the exploration of fundamental quantum phenomena. I will then share my perspective on some of the technologies and scientific

directions that could be reshaped by the realization of such devices.

Toward semiconductor sources of large-scale photonic entanglement—In a single charged QD, the optical selection rules link the spin of a confined carrier to the polarization of an emitted photon [Fig. 1(b), right]. By repeatedly exciting the QD while performing coherent spin operations, one can generate linear chains of entangled photons, known as *linear cluster states* [29]. Additional spin control enables the generation of the so-called *caterpillar states* [Fig. 1(b), left], in which extra photons are entangled with each node of the linear cluster [37].

Extending these states to large-scale photonic entanglement with arbitrary topologies requires exploiting the modularity of QD-photon interfaces to entangle multiple QDs [48]. Remote QD-QD entanglement based on the quantum interference of highly indistinguishable photons entangled with local spins was demonstrated more than a decade ago [49,50]. However, this capability still needs to be combined with cavity-enhanced QD interfaces operating near unity efficiency. A particularly promising route is offered by repeat-until-success protocols developed in the context of quantum computing [Fig. 1(c)], which use the spin as a local quantum memory to preserve previously established correlations while overcoming failed entanglement attempts based on photon interference [51].

With these ingredients in place, a wide variety of photonic states can, in principle, be generated by tailoring the sequence of remote-QD entanglement operations, spin manipulations, photon emission events, and fast photon routing, ideally carried out dynamically and at high speed to maximize flexibility [48].

Generating large-scale photonic entanglement will require suppressing the many sources of decoherence arising from the solid-state environment of a QD [Fig. 1(d)] to an unprecedented degree. *Phonon-induced decoherence*, including pure dephasing and phonon-assisted emission [52,53], can be strongly reduced by Purcell-enhancing the zero-phonon line in narrow-band cavities [53–57] and by suppressing phonon-sideband emission through tailored photonic environments [58]. Another promising strategy is to engineer the phonon density of states using acoustic phonon crystals to inhibit phonon-mediated processes such as spin flips [59–63]. *Electrical and magnetic noise* [64–68], arising from impurities, dopants, surface traps, and fabrication processes, can be mitigated through optimized device architectures, improved material purity, and advanced surface-processing techniques.

A second major challenge is bringing the QD to its *excited with near unity probability*. This will require advanced excitation protocols [69–71], including methods that exploit the specific properties of solid-state emitters such as phonon-assisted [72–75], swing-up [76–78], dichromatic [79–81], and two-photon excitation schemes [82]. At the system level, *photon losses* must also be reduced to unprecedented levels in *integrated photonic circuits* [83,84] required to perform photon-mediated remote spin entanglement. This will entail using architectures that remain robust against fabrication imperfections [85,86], a challenge that will directly benefit from advances driven by photonic quantum computing [87].

Entangling dozens of QD spins to generate large photonic entangled states remains a formidable technological challenge. It will require precise, individual control over each QD across the full range of available tuning parameters—including electric, magnetic, and strain fields—as well as efficient coupling of their emitted photons into single-mode fibers and, ultimately, reconfigurable integrated photonic circuits. These efforts build on the long-standing strengths of the semiconductor quantum-dot community, which has already made significant progress toward deployable quantum photonic technologies through the development of fiber-pigtailed single-photon sources [88,89] and the heterogeneous integration of sources, waveguides, and detectors on a common platform [90]. The pursuit of large-scale photonic entanglement-based technologies could catalyze highly multidisciplinary collaborations, bringing together atomic and solid-state physics, integrated photonics, and advanced ultrafast low-noise electronics.

Beyond enabling large-scale photonic entanglement, these efforts to quiet the solid-state environment will also deepen our understanding of condensed-matter systems at the single-quantum level and test the limits of quantum control in mesoscopic semiconductor systems. Can quantum measurements be harnessed to achieve ultimate control over complex solid-state systems, as exemplified by the quantum Zeno effect, where the evolution of a quantum

system is inhibited by sufficiently frequent measurements [91]? Can we tailor the fundamental properties of condensed matter systems, such as the Landé factor, effective mass, or optical dipole moments of excitations? Can the collective vibrations of a crystal be controlled through its interaction with a single quantum emitter? More broadly, to what extent—and up to what scale—can a quantum spin ensemble be coherently controlled?

Applications in quantum technologies—Large-scale photonic entanglement has long been recognized as a key resource for both quantum computing and quantum networks since the advent of measurement-based approaches. The central idea is remarkably powerful: rather than relying on entangling gates—which are notoriously difficult to implement for noninteracting particles such as photons—one begins with a large, highly entangled photonic state and then performs only single-qubit operations and measurements. In this framework, the complexity of quantum computation is *shifted* to the daunting task of generating large entangled photonic states [92,93]. Similarly, all-optical quantum networks based on large-scale photonic entanglement have emerged to reduce the requirements for quantum memories [94]. Remarkably, what once seemed like an unrealistic experimental requirement is now becoming a tangible scientific objective.

Hybrid photonic quantum computing—The large-scale spin-photon entanglement networks shown in Fig. 1(e) open the door to a disruptive computing paradigm that captures the best of both matter-based and photonic computers, which we refer to as a *hybrid photonic quantum computer*.

Many matter-qubit platforms will eventually face practical limits when scaling beyond hundreds or thousands of qubits, making robust interfaces between stationary qubits and photons indispensable [95–97], an enduring challenge for most matter-based qubit systems. Photonic quantum computing, by contrast, offers unique advantages. Photons are naturally resilient to decoherence, can be manipulated at extremely high clock rates, and support long-range connectivity. The main challenge here is the probabilistic nature of photon-photon gates. The *one-way quantum computing framework* opened a path forward by leveraging large three-dimensional photonic graph states [98] and mapping logical circuits onto sequences of single-qubit operations and measurements [92]. *Fusion-based photonic quantum computing* takes this idea further by fusing small graph states into large fault-tolerant resource states while tolerating the probabilistic nature of photonic entangling operations [99]. Recent studies have shown that QD spin-photon interfaces capable of generating caterpillar states with typically 12–20 photons [Fig. 1(b)] could reduce by 5 orders of magnitude the number of components required to produce each resource state compared to approaches based on heralded single-photon sources and gates [100–102].

We can think even further with the recently proposed fully hybrid architectures that combine stationary QD spin

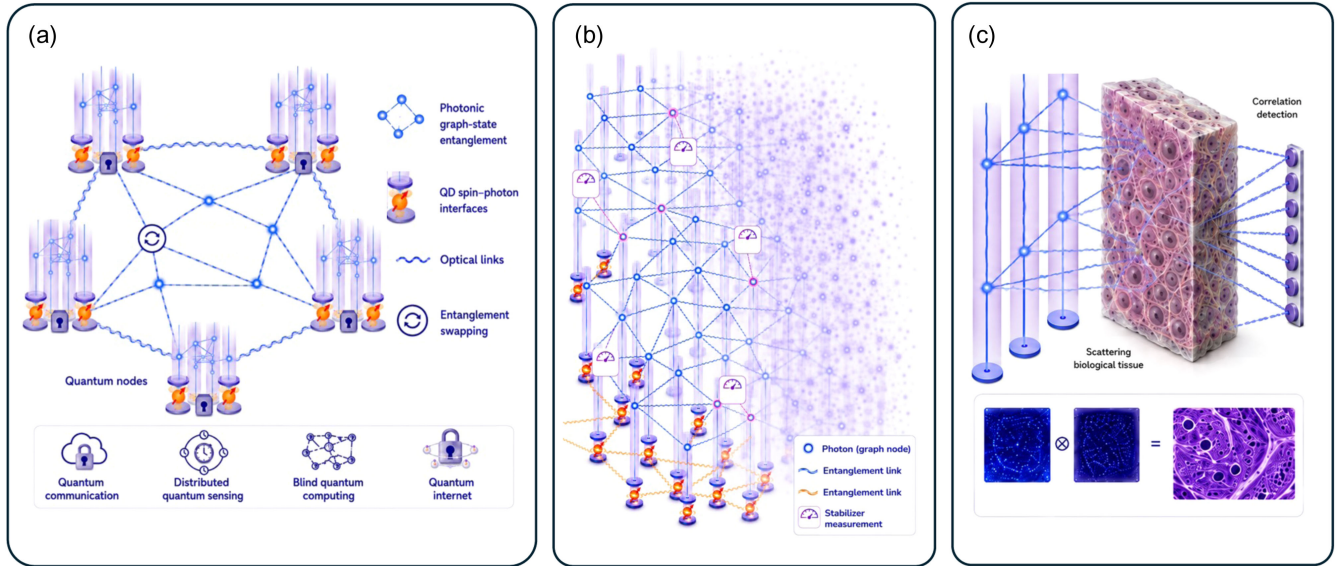


FIG. 2. Schematic illustrations of quantum technologies and fundamental research that could benefit from large-scale photonic entanglement. The figures, generated with the help of artificial intelligence, are illustrations: they do not constitute support for any practical proposal but are simplified representations. (a) Illustration of all photonic quantum networks. (b) Testing the limit between quantum and classical mechanisms using large hybrid matter-photonic qubit networks. (c) New paradigms in quantum sensing exploiting many-entangled photon quantum correlation; example in application to biology.

qubits and flying photonic qubits to enable scalable fault-tolerant quantum computing [103,104]. They rely on near-ideal spin-photon interfaces in which spin-photon entanglement is generated with high fidelity, photons are highly indistinguishable, and spin coherence remains sufficiently long-lived. With these interfaces, quantum information can be transferred and processed seamlessly between matter and photonic qubits, providing exceptional connectivity and flexibility. By drawing on the strength of both qubit modalities, these hybrid approaches offer new pathways for resource optimization and error-correction strategies while easing some of the stringent requirements imposed by purely matter-based or purely photonic-based approaches.

Two variants of spin-photon optical quantum computing architectures have already identified thresholds on photon generation and spin coherence that now appear increasingly realistic given the current level of control over QD photons and spins [105,106]. Although still in their infancy, these fully hybrid architectures are poised to inspire new ideas that exploit the remarkable modularity and connectivity of hybrid photonic hardware.

Scalable quantum networks—The near-ideal QD-photon platform developed over the past two decades combines the manufacturing power of semiconductor technology with the flexibility of multiple wavelength operation, pushing the vision of quantum communications and the quantum Internet well beyond the original idea [107]. Large photonic cluster states are key enabling resources for secure long-distance communications, blind and distributed quantum computing, and distributed quantum sensing [Fig. 2(a)].

Until now, the lack of highly efficient true single-photon sources has strongly shaped quantum key distribution architectures, which have relied primarily on Gaussian states of light such as attenuated lasers or squeezed states. The rapid progress in highly efficient QD-based single- and entangled-photon sources, including sources at telecom wavelengths [39,108] and at wavelengths compatible with atomic quantum memories [109,110], now makes it timely to revisit multipartite and long-distance quantum key distribution architectures. These sources could extend transmission distances, boost secret-key rates, and facilitate device-independent quantum communication protocols [111–113].

Large-scale photonic entanglement has long been recognized as a cornerstone for measurement-based quantum networks. In particular, large photonic entangled states constitute the central resource for all-photonic quantum repeaters, which can distribute entanglement over long distances while reducing the need for long-lived matter quantum memories [94,114–119]. More broadly, multipartite photonic entanglement enables loss-tolerant entanglement distribution, quantum-network architectures with reduced hardware overhead, and greater resilience to imperfect network components. The hybrid QD-photon platform could add key capabilities, with the local spin qubits serving both as deterministic entanglers and as local memories for synchronization.

Beyond communication, large-scale photonic entanglement will enable *heterogeneous distributed quantum computing*, in which spatially separated quantum processors from different modalities cooperate through measurement-based protocols and shared entanglement resources

[120–122]. It also underpins blind quantum computing protocols, allowing a client to delegate a quantum computation to a remote quantum server while preserving the privacy of both the input and the algorithm [123,124]. Finally, networked photonic entanglement can improve the performance of geographically separated quantum sensors beyond classical limits, opening exciting opportunities for distributed quantum metrology and sensing [125–127].

Enabling new fundamental science: New possibilities for imaging and sensing—Large-scale photonic entanglement can open new paths for quantum sensing, metrology, and imaging, pushing beyond the standard quantum limit even in the presence of dephasing [128]. It can deliver enhanced resolution with minimal illumination, compatible with fragile samples, or facilitate information transmission through disordered or turbulent media [129–131]. In bioimaging, entangled photon pairs have already enabled several proof-of-principle advances: time-energy entanglement and spatially entangled photons that persist through thick biological tissues [132] or scattering media [133] as well as quantum-assisted adaptive optics that correct aberrations in microscopy [134]. Recent experiments have also demonstrated quantum microscopy of cells at the Heisenberg limit [135] and background-resilient quantitative phase microscopy with spatially entangled photons [136].

Yet the central challenge remains: how can these advances be transformed into a clear practical advantage over continually improving classical protocols? Large-scale sources of photonic entanglement could mark a quantitatively new regime, where many-photon correlations drive sensitivity beyond classical limits and unlock capabilities that are not accessible today. The same question is emerging in gravitational-wave astronomy. Today’s observatories already rely on nonclassical states of light to suppress quantum noise [137,138], but they remain restricted to Gaussian quantum light states. Could large-scale photonic entanglement ultimately enable a new generation of gravitational-wave detectors based on truly non-Gaussian quantum light?

Enabling new fundamental science: Testing the limits of quantum mechanics—Current efforts to probe the quantum-to-classical transition largely focus on preparing quantum superpositions of increasingly massive objects, from large molecules and biological complexes to mesoscopic and macroscopic mechanical oscillators [139–141]. Large-scale photonic entanglement offers a compelling complementary route: rather than increasing the mass of the system, it expands the size and complexity of the quantum state itself, potentially across many particles and arbitrary topologies. Large-scale hybrid spin-photonic entangled states could, therefore, provide a powerful test bed for exploring how quantum correlations and multipartite nonlocality persist in increasingly complex systems [142] and for tracing the

emergence of classical behavior from quantum dynamics. Their hybrid nature also provides a versatile platform for isolating and controlling distinct decoherence mechanisms, including photon loss, pure dephasing, and long-term fluctuations, within a single entangled state.

As the number of entangled particles continues to grow, new approaches will be essential for efficiently characterizing and certifying multipartite entanglement [143,144]. In these settings, the combination of high-rate photonic generation with direct access to the underlying spin qubits may enable simpler, sharper, or more scalable entanglement witnesses. Beyond questions of nonlocality, large hybrid spin-photon systems could establish a new framework for studying the interplay between information, measurement, and thermodynamics in heterogeneous quantum systems. In particular, they may make it possible to investigate how which-path information is stored, distributed, and erased across multiple matter and photonic degrees of freedom and how these processes are connected to entanglement witnesses and quantum energetics [145–147].

Final remarks—Novel ideas and applications have repeatedly emerged once new quantum resources become experimentally accessible. Entangled photon pairs alone have transformed our understanding of quantum nonlocality and opened the door to entirely new approaches in communication, sensing, and computation. Not long ago, the deterministic entanglement of a handful of photons represented a major experimental milestone. In the coming decade, however, the ability to deterministically generate dozens—and eventually hundreds—of entangled photons may become routine.

The shift into this new regime is more than a quantitative leap. It will dramatically expand the landscape of quantum protocols that can be realistically explored and implemented. Large-scale photonic entanglement promises to provide the foundation for fault-tolerant photonic and hybrid quantum computing, all-photonic quantum repeaters, distributed quantum networks, secure communication protocols, delegated quantum computing, and network-enhanced sensing. Just as importantly, it will support the emergence of heterogeneous quantum networks. Because semiconductor quantum emitters are so diverse, sources of large-scale photonic entanglement shall progressively become available across a wide range of wavelengths, making it possible to interconnect disparate quantum systems.

While this Essay has focused primarily on semiconductor quantum dots, similar objectives are pursued with other solid-state emitters that are still at an earlier stage of development, including color centers in diamond [148], silicon [149], rare-earth ions [150], or defect-based emitters in two-dimensional materials [151]. Together, these platforms promise to broaden the scope of what quantum technologies can achieve in the years ahead.

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Credit: Collège de France / Patrick Imbert. Pascale Senellart is a CNRS research director at the Center for Nanoscience and Nanotechnology (CNRS/Université Paris-Saclay), is a professor at École Polytechnique, and was invited an professor at Collège de France for 2025-2026. She works at the interface of quantum optics, semiconductor physics, and nanotechnology, and is best known for her work on quantum light sources based on quantum dots in microcavities—bright, pure, single-photon and entangled-photon states that underpin photonic quantum technologies. She co-founded Quandela, where she serves as scientific advisor, building bridges between academic advances and industrial quantum photonics. Professor Senellart's contributions have been recognized with several awards, like the CNRS Silver Medal, the CNRS Innovation Medal, the Mergier-Bourdeix Award from the French Academy of Sciences, and the Jean Ricard Award from the French Physical Society. She is an elected fellow of Optica and an elected member of the French Academy of Sciences and of the French Academy of Technologies.

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