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Single Quantum Emitters in Gallium Nitride

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Single Quantum Emitters in Gallium Nitride

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Abstract

Gallium nitride (GaN) quantum emitters have rapidly emerged as a promising platform for room-temperature single-photon generation, benefiting from high emission rates, robust optical properties, and compatibility with industrial GaN epitaxy and device fabrication. Over the past decade, these emitters have demonstrated bright, linearly polarized emission, strong antibunching without tight spectral filtering, and in some cases microwave and magnetically addressable spin transitions, highlighting their potential for quantum communication, sensing, and integrated photonics. In this Perspective, we consolidate recent progress in understanding the formation, control, and photophysical behaviour of GaN quantum emitters, including advances in controlled epitaxy, activation techniques, and external-field tuning. We further discuss outstanding questions surrounding their microscopic origin and spectral variability, and identify key challenges related to spectral stability, spin coherence, and device integration. Finally, we outline the most promising research directions and technological pathways that could enable scalable, low-cost, room-temperature quantum light sources based on GaN.

1 Introduction

In recent years, quantum emitters (QEs) in III-nitride wide-bandgap materials have attracted significant interest as platforms for room-temperature single-photon sources[1, 2, 3]. QEs in hexagonal boron nitride (hBN)[4], aluminium nitride (AlN)[5, 6], and GaN[7, 8] all exhibit room-temperature quantum emission under optical excitation, with brightness exceeding that of color centers in diamond and silicon carbide. Here, we focus on experimental studies of single quantum emitters in GaN.

GaN benefits from mature and highly scalable fabrication processes[9], driven by its widespread adoption in commercial solid-state lighting[10, 11] and in high-power and high-frequency electronic devices[12, 13, 14]. The availability of large-area substrates is driven by commercial demand and the associated economies of scale. Figure 1a shows a GaN-on-sapphire wafer with a diameter of 100 mm. GaN-on-silicon substrates are also commercially available at diameters of up to 300 mm[15]. Extensive research on the microstructure, doping and defects in GaN has been reviewed in the context of industrial applications, for which we direct the reader elsewhere[16, 17, 18].

Over the past decade, QEs in bulk GaN have been reported with emission spanning from the visible[19] to telecommunications wavelengths[8]. Under optical excitation in a confocal microscope, these emitters exhibit photon statistics consistent with single electronic transitions, even at room temperature. Notably, photon antibunching is observed under continuous-wave excitation without the need for spectral filtering, and the emission is linearly polarized. GaN-on-sapphire QEs typically exhibit a substantially higher Debye–Waller factor (approximately 50 percent [20]), with a pronounced zero-phonon line (ZPL), compared with less than 1 percent in

most AlN QEs [21, 6, 5]). In addition, microwave control of optically addressable spin states has been demonstrated at room temperature[22, 23], opening a route to practical quantum sensing applications. When cooled to cryogenic temperatures, near–transform-limited linewidths can be achieved under resonant excitation[24] with a dephasing mechanism attributed to optical phonons in an elastic Raman process[25]. Further studies of the spectral characteristics reveal temperature dependence of the dephasing in these QEs[26] as well as determinations of their microsecond spectral diffusion characteristic time[27]. At the present time, the microscopic origin of these QEs remains unresolved, if indeed they all arise from similar crystal defects. Ab initio studies which use density functional theory to attempt to identify the physical origin have been performed by Yuan *et al.*[28]. Calculated ZPL wavelengths of the $N_{Ga}V_N{}^0$ centre agree strongly with experimental results in literature. Further evidence in support for the $N_{Ga}V_N{}^0$ centre arises from the dipole orientation study of Geng *et al.*[29] where the optical dipoles of many QEs are found to align to the crystallographic axis of the sample. In future, it may be possible to uniquely attribute them to certain complexes through spectroscopy, optically detected magnetic resonance, and density functional theory, as has been achieved in other materials [30, 31].

In this perspective, we give an overview of what is known about the creation, control and photophysical properties of these QEs. We then briefly discuss future research directions and potential applications in quantum technologies that may benefit from a room-temperature quantum light source amenable to mass-manufacture.

2 Methods of creating GaN Quantum Emitters

Figure 1 shows the diversity of GaN epilayers within which we have observed QEs. Figure 1a shows a commercially available 100 mm GaN on sapphire template from Kyma Technologies, a technology developed to support mass-production of GaN-devices for electronics and photonics applications. Figure 1b shows the structure of wurtzite GaN which is the stable polytype most used in applications. Nitride semiconductors are often formed by heteroepitaxial growth on sapphire, silicon or silicon carbide using metal-organic chemical vapour epitaxy (MOVPE) or molecular beam epitaxy (MBE), which results in a high-density of crystal faults, dislocations, unintentional dopant incorporation and band-bending at the non-lattice-matched interface. Free-standing GaN can be grown by halide vapour phase epitaxy (HVPE). To our knowledge, QEs have not been identified in MBE grown wurtzite GaN. Room temperature, experimental data from a series of samples containing QEs we have studied is presented in Figure 1c-q. The free-standing samples shown in Figure 1c,h,m is a HVPE, nominally undoped, single-crystal GaN substrate with a (0001) C-plane orientation[32] sourced from MSE supplies. The unintentionally doped (UID) sample shown in Figure 1d,i,n is a commercially supplied sample from Kyma Technologies with an epilayer grown by MOVPE and a thickness of 1 µm. The Fe doped GaN on sapphire sample shown in Figure. 1e,j,o was grown by the University of Cambridge by MOVPE, with an epilayer thickness of 1 µm. The m-plane sample shown in Figure 1f,k,p was grown by MOVPE and sourced from Seren Photonics. The details of the GaN on silicon sample presented in Figure. 1g,l,q is given in Eggleton *et al.*[33].

QEs form in GaN epitaxy with random position so the sample must be scanned to identify the sparse diffraction-limited emitters: under ambient conditions single emitters have distinct zero-photon lines (ZPL), intensity saturation behaviour and non-classical photon statistics. We observe QEs at the surface of the HVPE grown, free-standing GaN sample[34] as shown in Figure 1h, and have also shown that femto-second laser ablation can create regular arrays of bright spots with spectra and photon statistics consistent with the creation or activation of small numbers of QEs in the presence of background emission [32]. Further optimisation of this laser ablation method is required to reach the single emitter level. The MOVPE-grown UID and Fe doped samples on sapphire contain QEs with comparable densities, indicating that the doping of the GaN itself does not play a major role in the creation of this family of QEs. The m-plane GaN sample features different microstructural characteristics as SiO_2 micro-pucks are used to engineer a semi-polar, m-plane surface. QEs are still present in this material with similar properties albeit at lower densities. The growth of QEs on silicon substrates has numerous benefits for integration and scalability of this light source resulting in the sample shown in Figure 1l. In each sample, we highlight a single diffraction limited quantum emitter with a white circle, and show its emission spectrum in plots m-q. Typically, emitters in GaN are observed with a wide range of zero phonon line wavelength covering the visible and near-IR spectral regions.

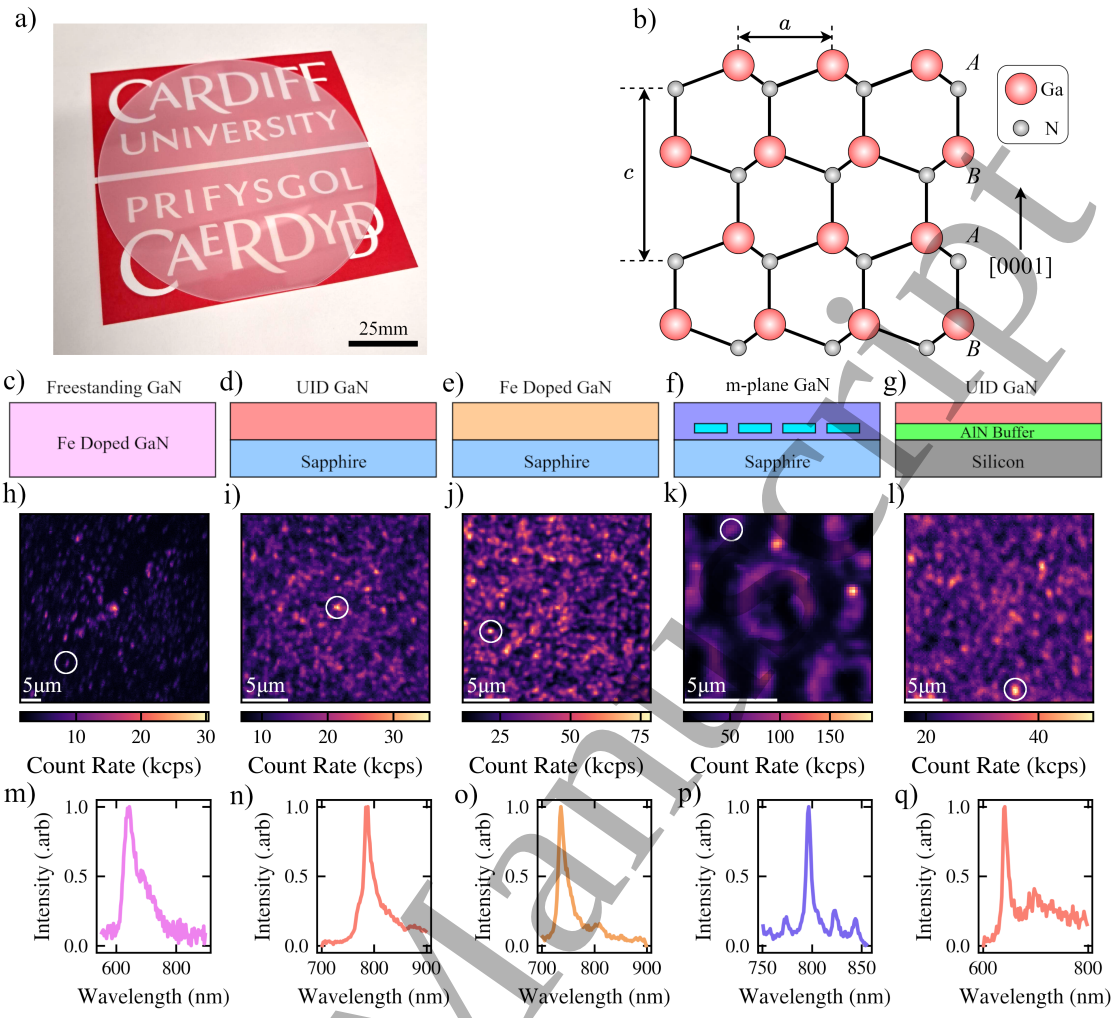

Figure 1. Optical properties of GaN QEs in different samples at room temperature. a) A 100 mm GaN on sapphire wafer from Kyma Technologies. b) Wurtzite crystal structure of GaN. c-g) Diagrams of the epilayer structure of different GaN samples. h-l) Series of room-temperature confocal scan maps of areas in samples c-g) with QEs identified by white circles. m-q) Room-temperature photoluminescence spectra of the QEs identified in the scan maps h-l).

Our studies have shown QEs in GaN on sapphire epitaxy form within the first few tens of nanometers of growth. Figures 2a-c show a series of samples grown by MOVPE on sapphire where point-like emitters are observed. These samples were terminated after the initial stages of growth on GaN on sapphire. Figure 2a shows a confocal scan map of a sample where approximately 20 nm of GaN is grown on sapphire at low-temperature (LT) and annealed in ammonia to form a nucleation layer (NL). The sample shown in Figure 2b follows on from this process with additional growth of GaN in a 3D island growth mode which occurs over 20 minutes approaching island coalescence. Finally, the sample shown in Figure 2c has 3 μm of overgrowth in a 2D growth mode with sub-nm surface roughness. QEs are observed in all of these samples confirming QE formation occurs at the low-temperature NL stage. Future device applications of these emitters may be hindered by their close proximity to the GaN-substrate interface, in a doped, high dislocation density region.

The ability to grow QEs in GaN at controlled depths has recently been reported by Eggleton *et al*[33]. The work was carried out on a silicon substrate to eliminate the layer of GaN-QEs that form in the initial NL. The sample structure hosting quantum emitters is shown in Figure 2g. A silane and ammonia treatment were used to create a sub-monolayer thick SiN_x layer on a GaN surface, upon which GaN islands were grown at a temperature of 540 C, mimicking the environment of GaN growth directly on sapphire and resulting in individually addressable quantum emitters shown in Figure 2h. These GaN emitters exhibit similar spectra to those grown directly on sapphire, with high DW factors in the red to near-IR spectral range and anti-bunched emission at room temperature. The ability to control the depth at which quantum emitters form is essential for future quantum photonic device integration. Furthermore, as this growth was performed on a silicon substrate it offers compatibility with established semiconductor processing techniques, but

should be compatible with growth on any substrate.

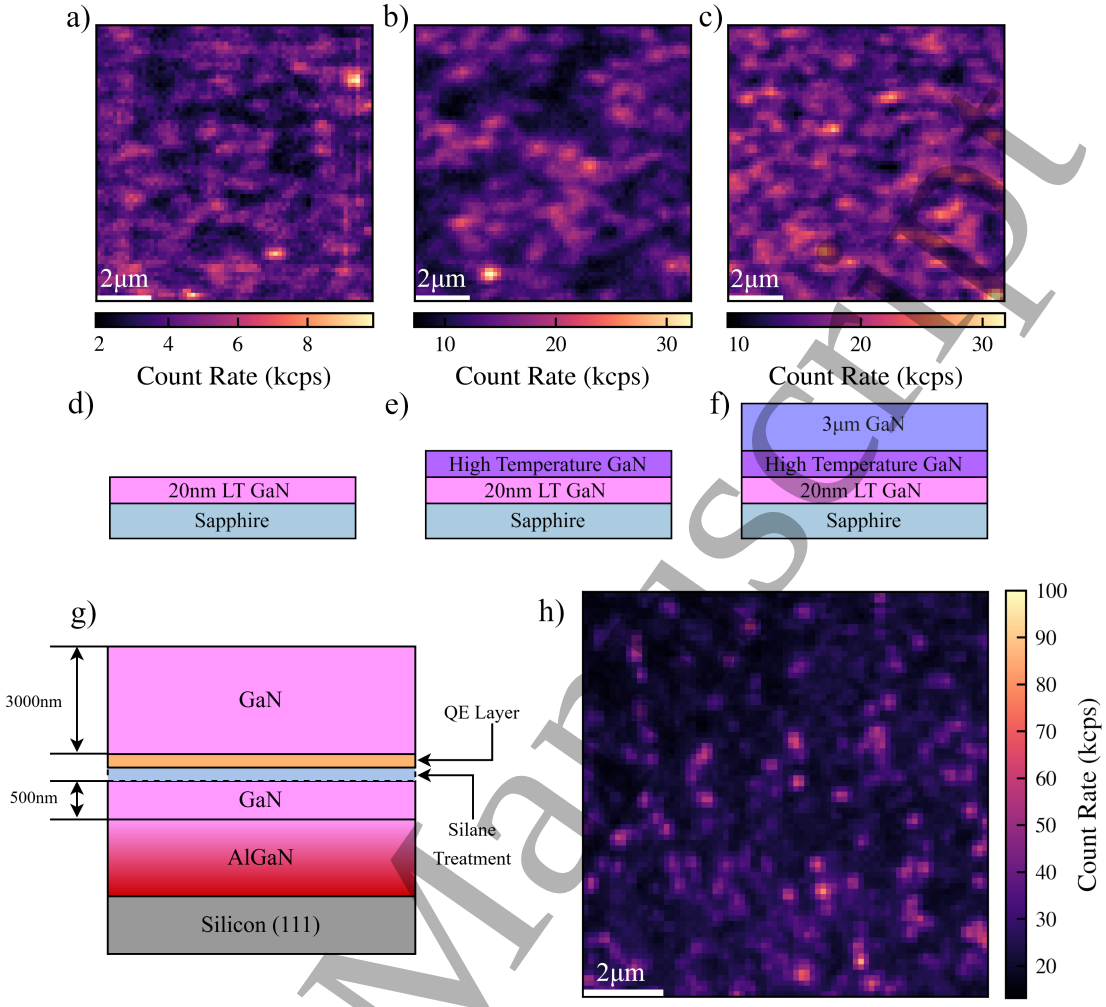

Figure 2. Bottom-up study of the growth of QEs in GaN on sapphire. Confocal scan maps of samples terminated at the growth stages of a) post low temperature nucleation layer annealing, b) high-temperature regrowth in 3D growth mode and c) continued regrowth in 2D mode. d-f) Diagrams of the samples in a-c) illustrating where the growth was terminated. g) Diagram of the epilayer structure of a GaN on silicon samples hosting QEs[33]. h) Confocal scan map of the samples shown in g) showing the presence of QEs.

On the topic of spatial control, several works have recently reported the deterministic creation of QEs in GaN via other methods. Nguyen *et al.* demonstrate limited site control of GaN QEs by engineering the crystal polarity of the sample[35]. By the introduction of an inversion layer during growth, the GaN polarity is switched from N to Ga-polar resulting in preferential QE formation in the Ga-polar regions and partial spatial control. QEs have been reported to form at preferential locations in samples grown on patterned sapphire substrates by Kim *et al.*[36]. GaN is grown on sapphire with conical features designed for optimising light extraction. QEs selectively form in the regions between cones with enhanced intensities. Ion implantation has been used to create QEs in various semiconductors, with high spatial determinism, including the III-nitrides[37, 38, 39, 40] but has recently been performed in GaN[41]. Tseng *et al.* employ dose engineering to produce single quantum emitters in samples of GaN on sapphire in deterministic 2D arrays. At higher doses, background emission in the GaN is suppressed after thermal annealing. The use of a gallium focussed ion beam in this work suggests a vacancy induced physical origin of the QEs. Although these methods allow for spatially deterministic QE formation, the wide diversity of photophysical properties remains a challenge.

3 Control of GaN QEs

3.1 Application of Electric Field

In many solid state systems post-fabrication tuning of emission energy is beneficial to match the emission to a cavity mode, and external source or to investigate the origin of the emitter.

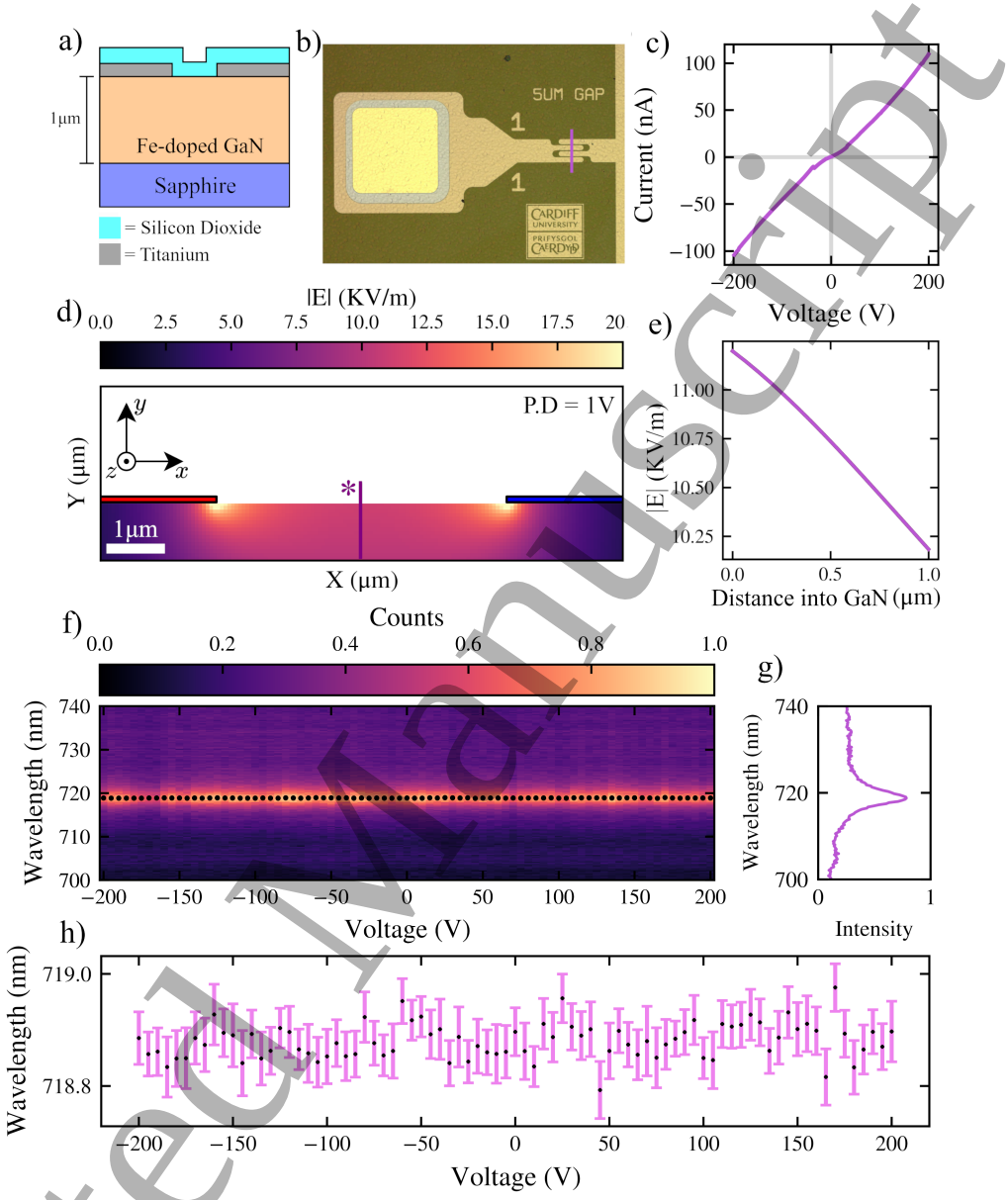

Figure 3. Application of electric fields to GaN QEs. a) Diagram sample structure. b) Optical image of the devices measured. c) Current-voltage characteristic of the device. d) Finite element simulation of the electric field amplitude between the electrodes. The simulation region is marked by a vertical line in b). e) Estimated electric field magnitude along the line marked by ∗ in d). f) Voltage dependent PL spectrum of a QE found between the electrode gap. g) Cumulative PL spectrum of the data in g). h) Fit values of the QE peak position from the data in f).

We have fabricated a device to apply in-plane electric fields using a 1 µm-thick Fe-doped GaN layer similar to Figure 1e. The Fe-doping compensates the unintentional doping introduced during epitaxy, suppressing electrical conduction. Figure 3a shows the device with 30 µm wide titanium 'finger' electrodes, separated by a 5 µm gap, encapsulated by a 200 nm silicon dioxide layer. Finite-element simulations were performed at a cross-section of the electrodes shown in Figure 3b to estimate the electric field inside the GaN. Neumann boundary conditions were used with dielectric constants of 9.7[42] and 3.9[43] for GaN and SiO_2 respectively. As shown in Figure 3d the field profile is symmetric about the midpoint between the electrodes which enforces a purely lateral electric field such that $\partial E/\partial x = 0$. At the midpoint, from the GaN surface to the base of the epilayer, the field intensity decreases by approximately 9.1 % as is shown in Figure 3e suggesting that at a bias of 200 V the applied field will be several MV/cm at the depth of the QEs.

However, room-temperature photoluminescence spectra, shown in Figure 3f and h, of a QE in the middle of the fingers show no detectable Stark shift, from -200 to 200 V. Even at a bias of 200 V only 100 nA leakage current flows illustrated in Figure 3c indicating an absence of dielectric breakdown. This remarkable result suggests that either these emitters are effectively shielded from the applied field through their proximity to the GaN/Sapphire interface or that they have zero dipole moment and exceptionally low polarisability. Going forward, it is hoped the study of QEs which are not located at the GaN/sapphire interface [33] will clarify this open question. Additionally, low-temperature measurements may suppress the thermal spectral diffusion allowing us to make more precise measurements of the Stark shift.

3.2 Annealing

Thermal annealing can play a crucial role in activating emitters after ion implantation in diamond [44, 45] and AlN[38, 37]. We have observed that annealing can alter the photophysical properties of QEs in GaN resulting in a continuous variation in emission wavelength. Figure 4 shows an exemplary GaN QE in undoped sample of GaN on sapphire, tracked following cycles of rapid thermal annealing for 30 min in nitrogen. QE tracking was accomplished by patterning the surface with titanium markers which are resistant to the heat from the RTA process. The data was fit using three overlapping Gaussians:

$$I(\lambda) = \sum_{i=1}^{3} A_i \exp\left(-\frac{(\lambda-\mu_i)^2}{2\sigma_i^2}\right) \quad (1)$$

where A, μ and σ are the amplitude, peak position and width of each peak. Figure 4 shows the fit results. After annealing at the highest temperature, a red shift in peak position from 706.8±0.1 nm to 724.2±0.1 nm is observed after tracking the spectrum of a single QE. The continuous and surprisingly large shift in wavelength, is substantially more than is seen for other defect complexes in wide-bandgap materials, possibly due to modification of the strain environment of the QE. Further work is required to determine whether the annealing has allowed the defects to become mobile, or whether it has changed the local strain or doping around the QE.

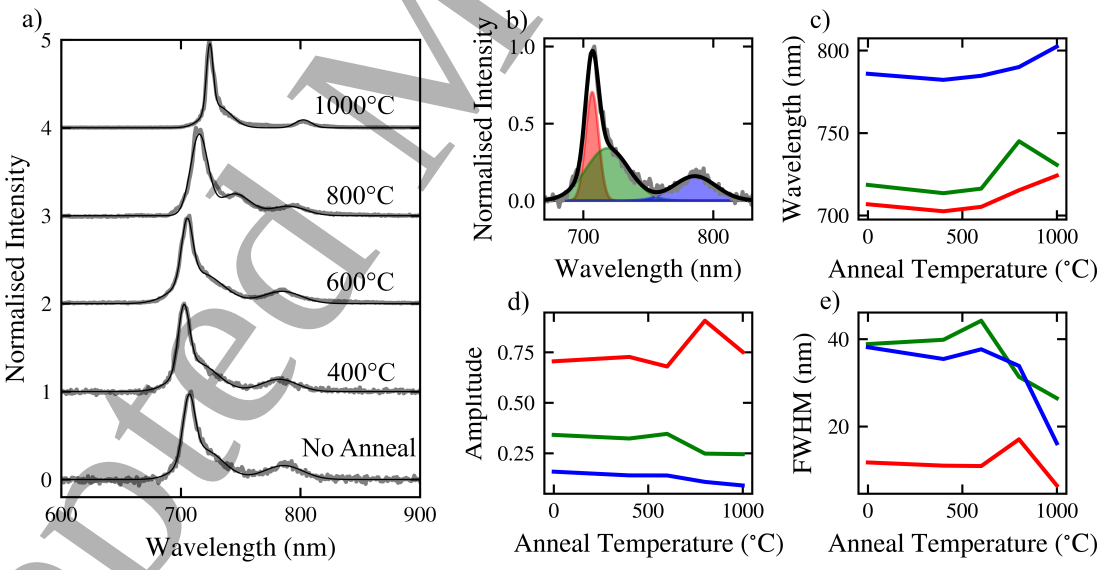

Figure 4. Anneal temperature dependent room-temperature photoluminescence spectrum of a single GaN QE. b) fitting a triple Gaussian to the spectrum of the emitter. The fitting parameters c) peak position, d) amplitude and e) FWHM of peaks 1, 2 and 3 as a function of anneal temperature. [46].

3.3 Temporal Dynamics

As with other room-temperature single-photon emitters, fluctuations in photoluminescence (PL) intensity and spectral position are observed over several orders of magnitude in time. These instabilities necessitate the application of multiple experimental approaches to quantify and elucidate their physical origin.

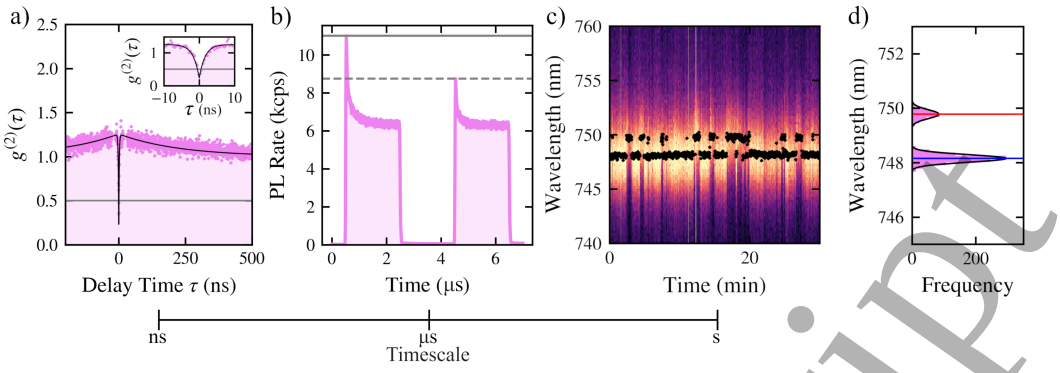

Figure 5. Dynamics of photon emission at different timescales in GaN QEs. a) Second order correlation measurement of a GaN QE showing typical 'bunching' of emission on a timescale of ≈100 ns[20]. b) Time-resolved PL of a GaN QE using double pulsed excitation showing time dependent intensity recovery over a timescale of microseconds.[32]. c) Time dependent spectrum of a GaN QE measured over 30 mins. Spectral hopping between 2 states can be seen. d) Histogram of peak fit positions in c).

A summary of the data is presented in Figure 5. Certain quantum emitters (QEs) in GaN exhibit time-dependent spectral instability on timescales ranging from nanoseconds to minutes. Photon correlation measurements performed under non-resonant excitation commonly exhibit photon bunching, as shown in Figure 5a. The characteristic timescale of this behaviour, typically tens to hundreds of nanoseconds, is attributed to population shelving into internal shelving states that emit outside the detection range of the apparatus. On intermediate timescales, the temporal response of the PL under excitation with square optical pulses provides further insight into the underlying dynamics. The decay of emission intensity during illumination reflects the pumping of the QE into an internal shelving state, whereas the partial recovery during the dark interval between pulses reveals the relaxation rate back into the ground state (Figure 5b). De-shelving processes have timescales of the order of microseconds. Figure 5c displays the time-resolved PL spectrum of a QE recorded over 30 min. The histogram of zero-phonon line (ZPL) positions in Figure 5d reveals two discrete distributions, indicating that the ZPL intermittently switches between two spectral positions under zero-field conditions while maintaining a constant emission intensity. It remains puzzling that such unstable single transitions (the overall emission remains anti-bunched) are not susceptible to the application of external electric field.

4 Potential applications

Research on GaN QEs has predominantly focused on room-temperature emission, where a pronounced phonon sideband and megahertz-scale broadening of the zero-phonon line (ZPL) occurs. Advantages such as quantized optical emission, high radiative intensity, and potential coupling to spin degrees of freedom make these emitters attractive candidates for quantum technologies. Here we briefly discuss potential avenues of future research.

4.1 A single-photon source for quantum communications

Single-photon sources are often regarded as key components for quantum-secure communication, as the no-cloning theorem and single-photon statistics intrinsically prevent photon-number-splitting attacks. However, developments in decoy-state and device-dependent quantum key distribution (QKD) protocols have enhanced the security of weak coherent pulse systems, narrowing the practical advantage of true single-photon emitters. Nonetheless, cryogenic quantum-dot sources have recently demonstrated improved performance over weak coherent pulse QKD in specific regimes [47, 48]. A bright, room-temperature single-photon source with strong multiphoton suppression could therefore offer compelling benefits for real-world deployment, particularly if it can be realised in a scalable and cost-effective semiconductor platform. Integrated prototypes based on GaN QEs have already been reported [49], achieving data transmission rates of 585.9 bps over 3.5 km. These results underscore the potential of III–nitride quantum emitters as practical, on-chip light sources for quantum communication networks.

4.2 Quantum sensing

Quantum sensing with QEs has been performed in SiC, hBN, diamond and many more with state of the art sensitivities[1] when detecting electric and magnetic fields, strain and temperature. It has recently been reported that two species of QE in GaN have microwave and optically addressable

spin-active transitions: [22] showed QEs at room temperature in the red and [23] found QEs in the telecoms O-band. These reports open up the possibility of definitively identifying the origin of the QEs as has been achieved in beautiful work on QEs in hexagonal-BN [50, 51]. In GaN, all isotopes of the constituent elements have non-zero nuclear spin so there is likely to be a complex interplay of the electronic spin states and multiple nuclear spins. Nevertheless, the surprisingly large contrast ($\Lambda \sim 30$ % [22]), intensity ($C \sim 0.5$ MHz) and modest $T_2^* \sim 100$ ns suggest single QEs could be useful as a room-temperature magnetic field sensor with DC-field sensitivity given by[52]:

$$\eta_{\mathrm{dc}} \sim \frac{\hbar}{g\mu_B} \frac{1}{\Lambda\sqrt{Ct_L}} \times \frac{1}{\sqrt{T_2^*}} \tag{2}$$

of $\sim 120\,\mathrm{pT\,Hz^{-0.5}}$ for a readout time $t_L = 0.8\,\mu$s. Although the spin coherence time is much below that achievable with single NV centers in state-of-the-art diamond [53], the lower-cost, wafer-scale availability, and manufacturability of GaN make it a promising spin system worthy of further investigation. A more useful comparison is to the field-sensitivity of nanodiamonds, where the chemical inertness and persistent optical activity even in close proximity to surfaces, mean GaN QEs could also be used for biosensing applications [54].

4.3 Photonic Devices

The development of solid-state quantum light sources over the past 25 years has been led by the semiconductor quantum dot community, which has established device architectures enabling electrical injection, charge-state control, wavelength tunability, enhanced photon extraction, and accelerated radiative lifetimes via the Purcell effect [55, 56]. Many of these advances could be transferred to the GaN materials platform, where mature doping, etching and nanofabrication techniques are already well developed for classical optoelectronic applications.

Figure 6 summarises several representative device concepts. Figure 6a illustrates a millimeter-scale zirconia solid immersion lens, which has previously achieved a fourfold enhancement in photon collection from GaN QEs over a broad spectral range over hundreds of square-micrometre area [20]. This straightforward post-fabrication approach mitigates refraction and total internal reflection losses at the GaN/air interface across the phonon-broadened emission band, with negligible change in radiative lifetime. Alternatively, nanofabrication of micron-scale photonic structures around QEs can enhance light extraction by a greater amount, but require sub-wavelength alignment of QE and cavity to deliver a high yield of devices. Bishop *et al.* [57] achieved sub-10 nm alignment precision using repeated localisation of QE position relative to metallic markers (coloured red), and subsequent photolithography to device 'nanostubs' (coloured blue). With this simple nanostub simulations predict a six-fold increase in intensity, even without appreciable Purcell effect, although the experimentally observed enhancement fell short of this value, probably as a result of uncontrolled QE orientation. More sophisticated cavity designs, such as the circular Bragg grating shown in Figure 6c can be optimised to enhance photon collection, or Purcell effect, or both, and are well suited to thin GaN films on Sapphire. To date, few reports have demonstrated the use of a circular Bragg grating cavity to enhance emission from a GaN QE [58, 59]. Meunier *et al.* [58] simulated a 10-fold acceleration of spontaneous emission, but concluded it would require more precise control of position than reported. Nevertheless, this is a promising route to realizing an efficient room temperature single-photon source.

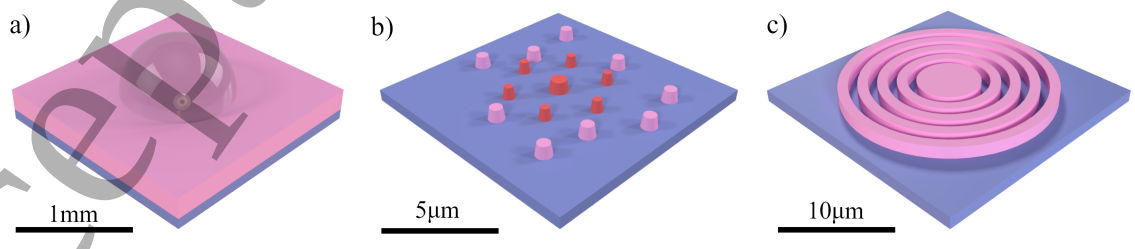

Figure 6. Structures to enhance photon collection. a) A zirconia solid immersion lens is well-matched in index to GaN at 600 nm, suppressing refraction at the semiconductor surface [20] b) micron-scale 'nanostub' pillars [57] c) graphic of a circular Bragg grating etched into a GaN-on-Sapphire film similar to that reported by [58].

5 Conclusion

Gallium nitride (GaN) quantum emitters are emerging as highly promising room-temperature single-photon sources, combining several compelling advantages: exceptionally bright emission,

relative to other room-temperature sources; the presence of magnetic- and microwave-addressable transitions; and compatibility with the mature epitaxy and nanofabrication technologies that underpin GaN's widespread use in electronic and optoelectronic devices. Their robust photon antibunching across the full emission spectrum indicates that only a small number of optical transitions contribute to the observed luminescence, with the dynamics governed by internal metastable states. Recent breakthroughs in the controlled growth of emitters at arbitrary depth [33], suggest a way to produce functional devices in the near future.

Looking ahead, a key priority is the integration of GaN quantum emitters into engineered nanophotonic environments to boost photon extraction and radiative emission rates. Many of the device concepts already proven in other solid-state emitter systems can be directly translated to GaN, creating bright, scalable and low-cost single-photon sources. Equally important is the ongoing effort to uncover the microscopic origin of these emitters. Coordinated experimental and theoretical studies—combining low-temperature spectroscopy, nano-structural analysis, and detailed investigation of electronic and spin properties will be essential for attributing emitters at diverse emission wavelengths, and with a variety of spin behaviours, to particular complexes. It seems probable these emitters are not the result of simple two-site emitters, for example consisting of an impurity atom adjacent to a vacancy, because the density of emitters is many orders of magnitude below the known density of common impurities in GaN.

Overcoming the current limitations facing these QEs is a clear focus for future research projects. Ion implantation has been proven to produce deterministic arrays of single QEs however the ability to produce QEs with the same spectra, intensity and lifetimes remains challenging. Although we have shown a technique to grow QEs at deterministic depths, the exact origin of the QE is unknown. To realise a commercial and convenient source of single photons, an electrically pumped QE needs to be demonstrated which to our knowledge has not yet been achieved in GaN QEs. A further avenue for progress lies in improving emitter stability. Techniques to suppress spectral diffusion, intensity intermittency, and spin decoherence will be vital for advancing device performance. Developing chip-scale platforms capable of applying controlled electric, magnetic, strain, or microwave fields at the emitter site will provide powerful tools both for probing the underlying physics and enabling practical quantum technologies.

In summary, GaN quantum emitters stand out among room-temperature single-photon sources as strong candidates for delivering bright, cost-effective, and scalable quantum light generation. With a clear path toward identifying their microscopic structure, improving their stability, and integrating them with mature GaN device technologies, these emitters are well positioned to play a central role in the next generation of quantum photonic applications.

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The authors declare no competing financial interests.

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Author contributions
Joseph K. Cannon: Data curation (equal); Investigation (equal); Methodology (equal); Resources (equal); Writing – original draft (equal); Writing – review & editing (equal). **Katie M. Eggleton**: Data curation (equal); Methodology (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yanzhao Guo**: Data curation (equal); Methodology (equal); Writing – original draft (equal); Writing – review & editing (equal). **Chunyu Zhao**: Investigation (supporting); Resources (equal); Writing – review editing (equal). **Saptarsi Ghosh**: Methodology (equal); Resources (equal); Writing – review editing (equal). **Menno J. Kappers**: Methodology (equal); Resources (equal); Writing – review editing (equal). **Rachel A: Oliver**: Funding acquisition (equal); Methodology (equal); Project administration (equal); Resources (equal); Writing – review editing (equal) **John P. Hadden**: Funding acquisition (equal); Resources (equal); Software (equal); Supervision (equal); Writing – review editing (equal) **Anthony J. Bennett**: Conceptualization (equal); Funding acquisition (equal); Methodology (equal); Project administration (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

Data availability

The data that support the findings of this study are openly available at the following DOI: https://doi.org/10.17035/cardiff.31819855

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