

Enhancement of Indistinguishable-Photon Emission from a GaAs Quantum Dot via Charge-Noise Suppression

Priyabrata Mudi^{1,*}, Avijit Barua^{1,†}, Kartik Gaur¹, Steffen Wilksen², Alexander Steinhoff², Setthanat Wijitpatima¹, Sarthak Tripathi¹, Julian Ritzmann³, Andreas D. Wieck³, Sven Rodt¹,

Christopher Gies², Arne Ludwig³ and Stephan Reitzenstein^{1,‡}

¹*Institut für Physik und Astronomie, Technische Universität Berlin, Hardenbergstraße 36, D-10623 Berlin, Germany*

²*Institute for Physics, Carl von Ossietzky Universität Oldenburg, 26129 Oldenburg, Germany*

³*Experimental Physics VI, Faculty for Physics and Astronomy, Ruhr University Bochum, 44801 Bochum, Germany*



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The generation of indistinguishable single photons is a fundamental requirement for photonic quantum technologies. However, spectral fluctuations, often induced by charge noise in epitaxial quantum dots (QDs), lead to exciton dephasing, thereby limiting their practical usage in quantum applications. We present a straightforward approach to mitigate charge noise-induced decoherence in droplet-etched GaAs QDs embedded in an *n-i-p* diode structure and integrated deterministically into an electrically contacted circular Bragg grating resonator for emission enhancement. The quantum device allows for the stabilization of the charge environment by applying an external electrical field while producing a photon extraction efficiency of $(37 \pm 2)\%$. Hong-Ou-Mandel two-photon interference measurements reveal a strong dependence of the exciton dephasing time and interference visibility on the applied bias, in excellent agreement with our theoretical predictions. Notably, the reduction in visibility from a maximum, charge stabilized corrected value of 97% at the optimum bias point follows an inverse square dependence ($\propto 1/I^2$) with increasing diode current (I) in the forward direction. Under a quasi-resonant excitation scheme, we achieve a maximum exciton dephasing time (T_2^*) of approximately (6.8 ± 0.5) ns, reaching nearly the Fourier limit ($T_2 = 2T_1$) without the need for complex echo schemes like Ramsey or Carr-Purcell-Meiboom-Gill sequences. These findings are consistent with theoretical predictions from rate equation modeling and quantum optical analysis, as well as voltage-dependent linewidth measurements, demonstrating optimized electrical control of exciton dephasing.

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The foundation principle of photonic quantum information technology relies on the generation of indistinguishable single photons from quantum light sources [1–3]. Epitaxially grown In(Ga)As quantum dots (QDs) have shown excellent performance as on-demand single-photon emitters [4–8], but their use is limited by large fine-structure splitting (FSS) [9] and spin decoherence arising from nuclear spin noise [10,11]. In this context, GaAs QDs grown via droplet etching in an AlGaAs matrix offer a promising alternative [12]. Owing to their high structural symmetry, GaAs QDs exhibit significantly reduced FSS [13] and their emission in the 700–800 nm range enables

potential integration with atomic memory platforms [14–16]. Additionally, the absence of high-spin indium isotopes improves spin coherence [17]. These properties have enabled GaAs QDs to emit single photons with enhanced spin coherence [17], improved indistinguishability [18], and high entanglement fidelity [19]. Despite these advantages, GaAs QD emission is susceptible to charge-noise induced spectral fluctuations and random blinking between multiple states [14,20–22]. Although embedding QDs in an *n-i-p* diode can stabilize the charge environment, doping AlGaAs layers often introduces DX centers [23,24], which contribute to additional charge noise. Nevertheless, recent advancements have shown that reducing the Al composition in doped epitaxial layers suppresses DX center formation and enables blinking-free operation in the majority of QDs [25].

In this Letter, we investigate two exemplary droplet-etched GaAs QDs, QD1 and QD2, embedded in an *n-i-p* diode structure within an AlGaAs matrix [25–27]. Both QDs were deterministically integrated into an electrically contacted circular Bragg grating (eCBG) cavity [29]. Before integration, approximately 70% of such QDs exhibit stable, blinking-free emission on a millisecond timescale as

*Contact author: mudi@tu-berlin.de

†These authors contributed equally to this work.

‡Contact author: stephan.reitzenstein@physik.tu-berlin.de

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confirmed by the second-order autocorrelation measurements under continuous-wave (cw) excitation [25], with HOM visibilities reaching 93% without any temporal or spectral filtering [18]. To study the influence of diode current-introduced charge noise, QDs susceptible to blinking were preselected via cathodoluminescence (CL) mapping at 20 K and integrated using marker-based deterministic electron beam lithography [27,30]. Focusing on a noisy QD located near the wafer edge, we observe a pronounced voltage dependence of the Hong-Ou-Mandel (HOM) two-photon interference visibility, coherence time (T_2), and dephasing time (T_2^*).

This Letter advances beyond earlier studies of charge-controlled photon indistinguishability in GaAs QDs [31] in several important aspects. First, we demonstrate that even charge-noise sensitive QDs can be transformed into highly indistinguishable-photon sources, eliminating the need to preselect only intrinsically stable emitters. This generalizes the applicability of QDs for scalable quantum photonics by showing charge-noise suppression can be engineered rather than relied upon. Second, we integrate such QDs into eCBGs with a bottom DBR, achieving a record photon extraction efficiency of $(37 \pm 2)\%$ and a broad range spectral tuning while preserving efficient charge control, thereby combining scalability with performance. Third, by probing a single-exciton line with fine voltage tuning, we directly quantify how the observed visibility degrades at higher bias voltages due to increased diode current, supported by a quantum-optical model that incorporates current (I) induced charge noise. Finally, our results—97% visibility and $T_2^* = (6.8 \pm 0.5)$ ns—demonstrate that near Fourier limited coherence ($T_2 \approx 2T_1$) can be reached without implying complex optical pulse sequences. This is particularly significant for the optical interface of electrostatically defined AlGaAs/GaAs QDs, where a large dephasing time is essential for faithfully transferring the quantum state of a single photon (flying qubit) to the gate-defined QD (stationary qubit) without the loss of generality [32]. More broadly, the suppression of blinking is also relevant for other material system prone to blinking, such as CdTe/ZnS core-shell QDs [33] and the demonstrated bright emission with electrical-fine-tuning is directly compatible with hybrid quantum interfaces such as Rb-based atomic memories [15]. These advances, extend the scope of QD research well beyond Refs. [25] and [31] and underscore the potential of electrically controlled nanophotonic devices for scalable quantum technologies.

Following deterministic nanofabrication, the QD sample is characterized using a pulsed (80 MHz) Ti:Sapphire laser in ps mode under longitudinal optical (LO) phonon-assisted quasiresonant excitation at 759 nm. All measurements are performed at 4 K to suppress exciton-acoustic phonon coupling at elevated temperatures which would otherwise broaden the emission linewidth, introduce a substantial background and affect eCBG performance [34–38]. In this

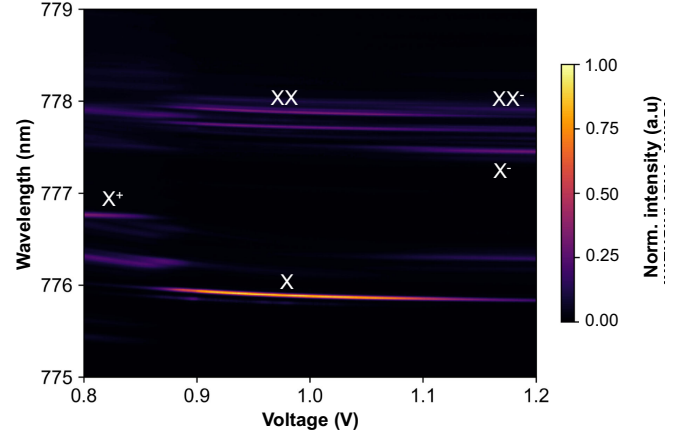


FIG. 1. μ -PL spectra of QD1 as a function of gate voltage under quasiresonant excitation, showing the emergence and suppression of distinct emission lines.

device, the heavily doped n^+ back layer serves as both an electrical contact and as a gate electrode. While it also provides charge injection in the n - i - p diode structure, its primary role in the present Letter is to allow tuning of the QD emission energy via the applied vertical electric field. This functionality is analogous to the role of a gate in field-effect devices, where the applied gate voltage (V_G) modifies the electronic environment [25]. The microphotoluminescence (μ -PL) spectra of QD1, illustrated in Fig. 1, display distinct emission lines corresponding to various excitonic complexes and charge states, which appear and disappear as the gate voltage is varied. This phenomenon is attributed to changes in occupation probability of different charge state configurations [39]. The excitonic-biexcitonic (X - XX) charge plateau appears within the voltage range of 0.85 – 1.15 V, and the nature of the emission lines is identified through power- and polarization-resolved measurements. Importantly, the observed emission in this bias range is purely photoluminescence, with no contribution from electroluminescence. A typical FSS of 1–2 GHz is observed for both QD1 and QD2, consistent with values reported for other QDs in this sample [25] and in the literature for (001)-oriented wafers [13,40]. Notably, the electrical tuning of the present sample allows a wide control of the charge configuration ranging from X^{2+} to X^{8-} ; however, the present Letter focuses on neutral excitons (X^0), which are seen to be more susceptible to charge noise [31] and are particularly relevant for the generation of polarization-entangled photon pairs.

In order to investigate the effect of charge noise, second-order autocorrelation measurements were performed for various V_G , as illustrated in Fig. 2 (top panel). The coincidence histograms are recorded using a Hanbury Brown–Twiss (HBT) setup to inspect the photon statistics and to identify potential blinking. At $V_G = 0.88$ V, the coincidence peaks at shorter delays exhibit an increased number of coincidences, a potential signature of inherent

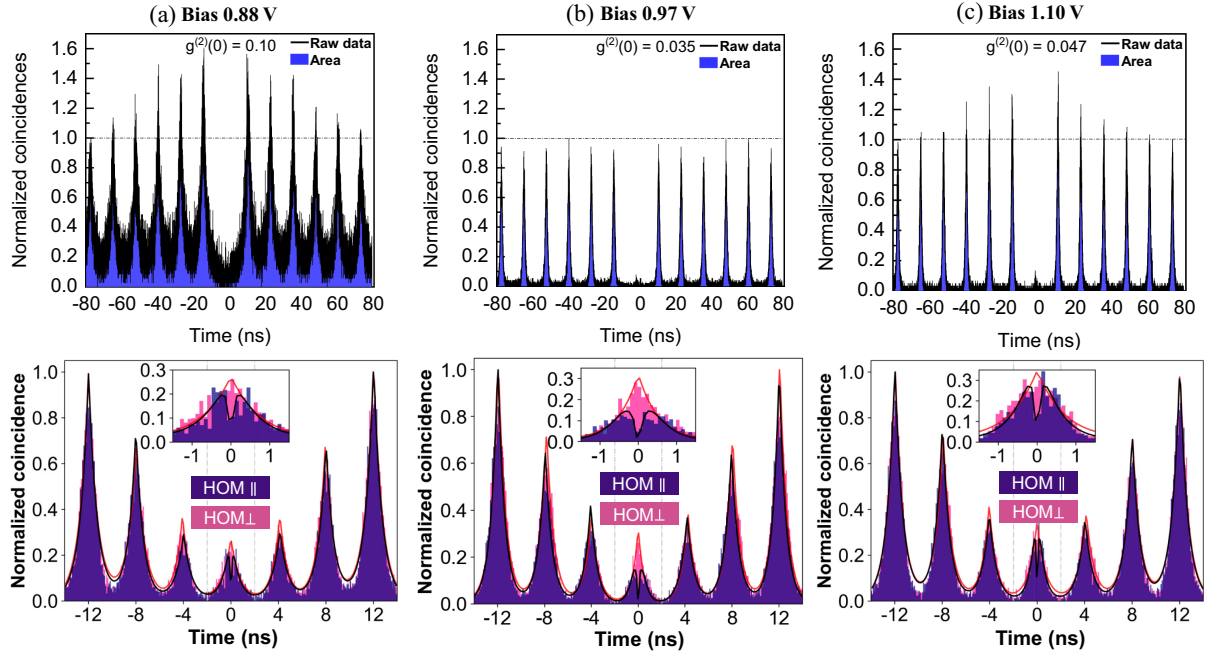


FIG. 2. Second-order autocorrelation measurements (top panel) and photon coincidence histograms from Hong-Ou-Mandel interference (bottom panel) of the QD1 X^0 line under quasi-resonant excitation at different bias voltages: (a) 0.88, (b) 0.97, and (c) 1.10 V.

charge fluctuation or QD blinking [41]. The behavior is due to fluctuation in the local charge environment, leading to transient trapping and detrapping of electrons and holes that perturb the QD emission [41]. At a slightly higher bias (0.97 V), however, the height of the coincidence peaks at both short and long delays becomes nearly identical, indicating effective suppression of charge noise and stabilization of QD emission. The absence of bunching confirms an optimal voltage range of 0.925 to 1.020 V where the charge environment remains stable, eliminating blinking effects. To further verify these results, similar measurements were performed under weak cw excitation (600 nW) that did not show blinking up to 400 ns (see Fig. S1 [27]). Nevertheless, at 1.05 V, bunching in the envelope function re-emerges, which is attributed to charge noise introduced by external currents.

To understand the underlying mechanisms responsible for the appearance of photon bunching at both lower and higher bias voltages, as well as the optimal intermediate V_G range where charge noise and bunching are effectively suppressed, HOM two-photon interference measurements were performed at varying V_G . These measurements reveal a strong bias dependence, as demonstrated in Fig. 2 (bottom panel). Notably, at the onset of the bias plateau for the QD1 X^0 line (0.85 V), the exciton lifetime is significantly prolonged (from 0.5 to 2.1 ns) due to band bending and a reduced overlap between the electron and hole wave functions [31]. This effect results in overlapped peaks in the HOM coincidence histogram. Consequently, HOM interference measurements are only conducted within the (0.88–1.10) V bias range, where the exciton

lifetime remains much lower than 4 ns (delay between two consecutive photons in the HOM experiments). Recently, Undeutsch *et al.* [31] reported a nonmonotonic variation of exciton lifetime affecting HOM visibility in XX-X cascade decays. However, their study was restricted to bias voltages below 1 V due to luminescence quenching caused by single-electron charging. In contrast, our integration of QDs into eCBGs ensures bright X^0 emission along with bias control, allowing measurements beyond the onset of significant forward current at 1 V. The HOM measurements show a distinctive volcano-shaped reduction in the central peak for co-polarized detection in both arms of the interferometer. This volcano shape originates from the imperfect excitation scheme [42], which introduces unintended time jitter between consecutive photon arrivals at the HOM interferometer beam splitter. It can be observed that at 0.88 V [Fig. 2(a) (bottom) inset] the central peak in the photon coincidence histogram exhibits nonzero events even at zero delay because of limited HOM visibility. However, at 0.97 V [Fig. 2(b) (bottom) inset], the number of events at zero delay is significantly reduced, signifying improved visibility, which aligns with the optimal bias range identified in the HBT measurements. At $V_G = 1.10$ V [Fig. 2(c) (bottom) inset], the number of zero-delay correlation events increases again, indicating a deterioration in HOM visibility. Such a bias dependence of visibility is not observed for XX [31] or X^- lines [29].

Figure 3(a) shows the raw HOM visibility of the QD1 X^0 transition in the bias voltage range (0.88–1.10) V. The bias dependence of the maximum visibility (V), coherence time (T_2), and dephasing time (T_2^*) presented in Figs. 3(b)–3(d)

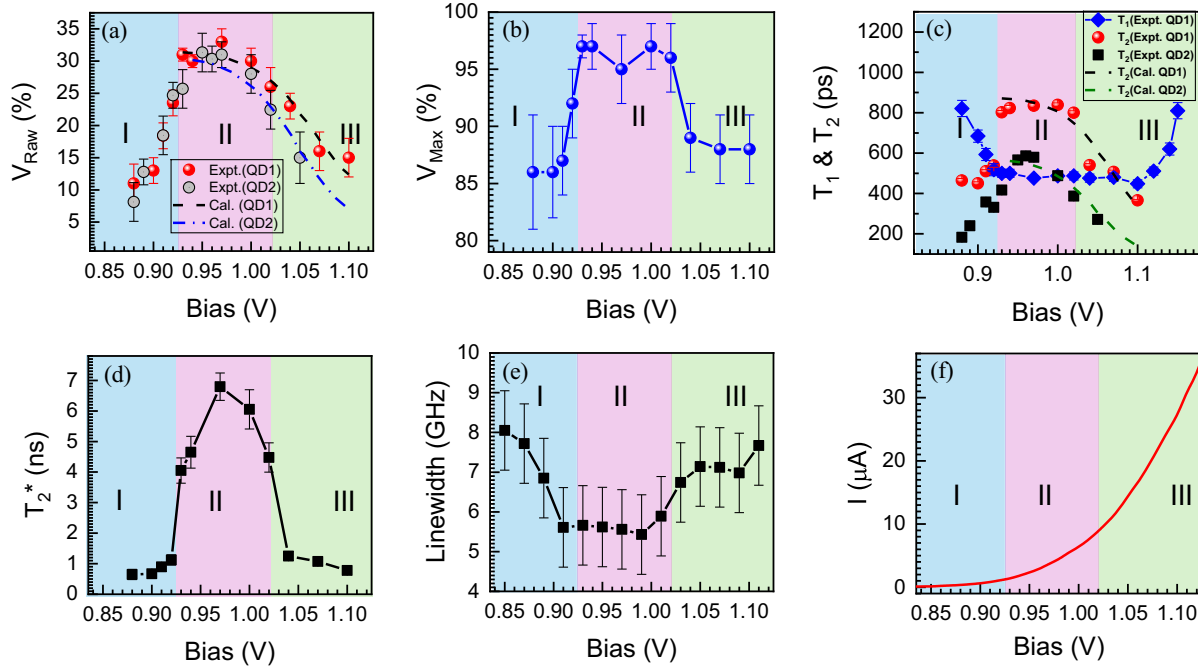


FIG. 3. Bias-dependent properties of the QD X^0 line under quasiresonant excitation: (a) Raw HOM visibility measured (symbols) and theoretically modeled (dashed line) for QD1 and QD2, (b) maximum HOM visibility of QD1, (c) exciton lifetime (T_1) of QD1 and estimated coherence time (T_2) along with theoretical calculations (dashed line)—for QD1 and QD2, (d) pure dephasing time (T_2^*) of QD1; and (e) emission linewidth of QD1, all plotted as a function of applied bias voltage. (f) Current-voltage (I - V) characteristics of the n - i - p diode.

are obtained from the co-polarized HOM coincidence histogram by fitting the central peak [$C_{\text{HOM},\parallel}(\tau)$] [27,43–45] at each bias voltage. The results obtained indicate that the QD system can be categorized into three distinct regions depending on the applied bias: (i) region I (0.850–0.925 V), (ii) region II (0.925–1.020 V), and (iii) region III (1.02–1.10 V). A brief description of each region is summarized in Table I.

Region I lies near the lower-bias edge of the X^0 charge plateau, where fluctuations in the local charge environment enable to co-tunneling processes [46], manifested as blinking in both photoluminescence and autocorrelation measurements [47,48]. This charge-noise induced instability is reflected in the linewidth measurements shown in Fig. 3(e), where the linewidth is largest at the lowest voltage and systematically decreases as the bias voltage increases. A similar linewidth broadening trend has been previously reported for noisy QDs [25]. Both the HOM visibility and coherence time exhibit reduced values ($\approx 12\%$ and 450 ps, respectively) in this region, consistent with the impact of charge-noise induced blinking on the HOM visibility [49]. Notably, the longer lifetime in this region also contributes to the degradation of HOM visibility, as decoherence mechanisms are more likely to act before photon emission occurs. To further investigate the blinking phenomenon, we expanded a rate equation model introduced in Refs. [27,50] that predicts the behavior of the

second-order autocorrelation function under cw excitation. The model yields the blinking on-off ratio parameter (β), which follows a similar trend as HOM visibility [27], confirming that the charge environment remains unstable in region I, where pronounced blinking persists.

As the bias voltage approaches region II, the charge environment becomes more stabilized, effectively minimizing the charge-noise and spectral fluctuations. This stabilization is critical for the QD's quantum optical properties, as it suppresses charge-noise-induced decoherence mechanisms. Notably, diode current in this region is considerably small, and its change does not initiate any additional charge noise. As a consequence of the improved charge stability and suppressed blinking [27], the linewidth in this region reaches its lowest value and is almost independent of the bias voltage. The HOM raw visibility, maximum visibility and coherence time also reach their optimal values of approximately $(33 \pm 3)\%$, $(97 \pm 2)\%$, and (835 ± 12) ps, respectively. The maximum HOM visibility at zero delay ($\approx 97\%$) is comparable to the value of best-performing low noise GaAs QDs free from blinking effect under strictly resonant excitation [18]. This enhanced visibility suggests that the charge noise in a nonideal GaAs QD, which typically deteriorates the photon indistinguishability, is effectively suppressed within the voltage range of region II. The high coherence time measured in this region further supports this interpretation, indicating

TABLE I. Summary of three bias regions.

Region	V_{raw}	T_2/T_1	Dominating mechanism
I	0.11 ± 0.03	0.6 ± 0.1	Large T_1 and co-tunneling processes
II	0.33 ± 0.03	1.8 ± 0.1	Charge-noise suppression
III	0.15 ± 0.03	0.8 ± 0.1	Current induced charge noise

that the system is near its fundamental quantum coherence limit under electrical charge control. The coherence-to-lifetime ratio, T_2/T_1 reaches values as high as 1.8 ± 0.1 , which is remarkably close to the Fourier limit of $T_2 = 2T_1$. This also signifies a strong reduction in pure dephasing as the estimated pure dephasing time reaches as high as (6.8 ± 0.5) ns without the need for any complicated pulse sequence techniques [17], demonstrating the potential for achieving long-lived quantum coherence under relatively simple experimental conditions beneficial for real-world applications.

At higher bias voltages (region III), the QD1 emission intensity remains relatively stable, indicating that it is still well within the charge plateau and far away from X^0 to X^- transition edge. However, a significant increase in the diode current is observed in this region [Fig. 3(f)], introducing additional charge noise from externally injected electrons and holes in the active region leading to a higher blinking [27]. Consistently, the emission linewidth broadens and the HOM visibility, coherence time and dephasing time progressively deteriorate with increasing bias.

To validate the observed suppression of charge noise, the same set of measurements was performed on QD2. Similar to QD1, QD2 was integrated into a eCBG and is susceptible to charge-noise induced spectral fluctuations in its environment. As shown in Fig. 3(a), the raw HOM visibility of the QD2 X^0 transition exhibits a similar dependence on V_G . The extracted coherence time T_2 exhibits [Fig. 3(c)] the same dependence on V_G as observed for QD1, indicating a similar underlying mechanism governing charge-noise suppression in both QD1 and QD2.

Dobrzanski *et al.* [51] have studied the relationship between diode current (I) and low-frequency $1/f$ -type charge noise (S) in QDs embedded within n - i - p structure, demonstrating that for current values $\leq 10^{-4}$ A, as in our case, charge noise follows the relation $S \propto I^2$ [27]. To model the current dependence of the indistinguishability, we first calculated the two-time correlation function $C(t, \tau) = \langle \hat{\sigma}^+(t + \tau) \hat{\sigma}^-(t) \rangle$, where $\hat{\sigma}^+$ ($\hat{\sigma}^-$) is the raising (lowering) operator of the QD transition. In addition to the two levels involved in the optical transition ($|g\rangle$ and $|e\rangle$), a pump state $|p\rangle$ is included to account for timing jitter introduced by quasiresonant excitation. The correlation function is obtained by using the adjoint master equation formalism [52] and the quantum regression theorem [53], yielding [27],

$$C(t, \tau) = \begin{cases} \frac{\gamma_p}{\gamma_{\text{rad}} - \gamma_p} (e^{-\gamma_p t} - e^{-\gamma_{\text{rad}} t}) e^{-\frac{1}{2}(\gamma_{\text{rad}} + \gamma_{\text{deph}})\tau} & , \gamma_p \neq \gamma_{\text{rad}} \\ \gamma_{\text{rad}} t e^{-\gamma_{\text{rad}} t} e^{-\frac{1}{2}(\gamma_{\text{rad}} + \gamma_{\text{deph}})\tau} & , \gamma_p = \gamma_{\text{rad}} \end{cases} \quad (1)$$

Here, γ_p denotes the relaxation rate from the pump state to the radiative state, γ_{rad} is the radiative decay rate. The pure dephasing rate is given by $\gamma_{\text{deph}} = \alpha I^2 + \gamma_{\text{pure}}^{(0)}$ with the proportionality constant α and a small bias-independent offset $\gamma_{\text{pure}}^{(0)}$. With these parameters, the two-photon indistinguishability can be calculated from the correlation function via [54,55]

$$V_{\text{raw}} = \frac{\int_0^\infty dt \int_0^\infty d\tau |C(t, \tau)|^2}{\int_0^\infty dt \int_0^\infty d\tau C(t + \tau, 0) C(t, 0)}. \quad (2)$$

Using α , γ_p , and $\gamma_{\text{pure}}^{(0)}$ as fitting parameters, the model accurately reproduces the measured values of HOM visibility in regions II and III [see Fig. 3(a)]. Applying the same parameters, the measured coherence time T_2 also is well described by $T_2 = 2/(\alpha I^2 + \gamma_{\text{deph}}^{(0)} + \gamma_{\text{rad}})$ [see Fig. 3(c)]. Notably, this quantum optical model is only valid in regions II and III, where diode current exhibits a clear voltage dependence. In contrast, region I is dominated by charge state blinking, which introduces linewidth broadening through a distinct mechanism. Extending the model to region I would require microscopic modeling to obtain bias-dependent blinking rates of this specific QD, which lies beyond the scope of this Letter. Overall, the model captures both the observed degradation in HOM visibility and coherence time with increasing voltage in region III. Additionally, the linewidth exhibits a systematic increase with bias in region III, further confirming the presence of charge noise. Note that the mechanism of linewidth broadening in region III is different from that in region I, as the bias is not yet high enough to reach the other end of the charge plateau. The aforementioned effect is also responsible for the reappearance of bunching in the envelope function of HBT measurements.

In summary, the present Letter furnishes an approach to suppress charge-noise-induced decoherence in droplet-etched GaAs QDs embedded within an n - i - p diode structure and integrated into an eCBG nanocavity for electrical control and emission enhancement. By applying an external electric field, the charge environment is stabilized while achieving high photon extraction efficiency of $(37 \pm 2)\%$. HBT and HOM measurements reveal a strong bias dependence of the single-photon purity, exciton dephasing time, and indistinguishability. At an optimal bias voltage, the coherence time reaches 1.8 times the lifetime, approaching the Fourier limit ($T_2 = 2T_1$), and the pure dephasing time T_2^* extends up to (6.8 ± 0.5) ns, all under simple quasi-resonant excitation. These findings

demonstrate that by maximizing the trade-off between charge stability and diode current, they provide a workable method to reduce charge noise in GaAs QDs, highlighting its promise for scalable photonic quantum technology.

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Data availability—The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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