

Cryogenic Enhancement of Electron Spin Polarization from a Strained GaAs/GaAsP Superlattice Photocathode

Matt Grau^{1,*}, Colin Kirk², Greg Blume¹, John Hill², Sushil Poudel², Alimohammed Kachwala³, Marcy Stutzman³, Joseph Michael Grames³, Sylvain Marsillac², and Matt Poelker³

¹*Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA*

²*Department of Electrical & Computer Engineering,
Old Dominion University, Norfolk, Virginia 23529, USA*

³*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*

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We report electron spin polarization of 95.0 ± 0.8 (stat) ± 2.4 (sys)% from a strained GaAs/GaAsP superlattice photocathode grown by metalorganic chemical vapor deposition (MOCVD) and cooled to dry-ice temperature (195 K). We achieved this polarization with 97.8% circularly polarized excitation light and a quantum efficiency of 0.7% at the peak polarization wavelength. This measurement exceeds the values of previously reported GaAs-based photocathode polarizations, which have clustered near 92% for two decades. We vary the temperature of the cathode and measure the polarization and quantum-efficiency spectra at 295 K, 273 K, 195 K, and 77 K. The polarization rises from 91.2(1)% at 295 K to its maximum at 195 K, while the spectral peak shifts from 775 nm to 739 nm (78 meV) over the full temperature range, tracking the widening band gap. The spectra probe two depolarization mechanisms: a thermalized transport channel that is suppressed on cooling, and energy-dependent hot-electron relaxation that persists and sets the low-temperature saturation. The polarization recovers after a full cooling and warmup cycle and is stable while the quantum efficiency decays, which disfavors surface energy filtering as the origin of the gain. These results indicate that modest cooling to 195 K, for which dry ice suffices, is a practical route to higher-polarization GaAs-based electron sources.

Introduction.—High polarization electron beams are central to parity-violating electron scattering [1–5], to measurements of nucleon spin structure [6] and elastic form factors by polarization transfer [7, 8], to polarized-positron production [9], and to future collider experiments, notably the Electron-Ion Collider (EIC) [10–13], where the statistical reach at fixed beam current scales quadratically in the beam polarization. GaAs-based photocathodes activated to negative electron affinity (NEA) are the standard for high-current high-polarization electron sources [14, 15]. Strained GaAs epilayers lift the degeneracy between heavy-hole (HH) and light-hole (LH) valence bands that limits bulk GaAs to 50% polarization [16, 17], and strained superlattices (SLs) combine strain with quantum confinement to push the emitted polarization toward unity [18–20]. The measured spin polarization from strained-layer and strained-superlattice cathodes has remained near 90–92% for two decades: $92 \pm 6\%$ [21], 91–92% [22, 23], and 92% with 1.6% quantum efficiency (QE) [24]. Over the same period, QE and operational lifetime have improved substantially [13, 25–29].

The gap between measured polarization and the theoretical limit comes from depolarization of the electrons during the excitation, transport, and emission processes. These mechanisms all depend strongly on temperature: thermally broadened LH leakage into the HH excitation window [20, 30], spin relaxation of thermalized electrons during transport to the NEA surface, dominated by exchange scattering from holes in heavily p-doped material [31–34], and spin relaxation during the hot-

electron cascade [35, 36]. For strained-superlattice photocathodes, changing temperature lets us probe these depolarization channels and distinguish polarization gain in the bulk or during transport from surface energy-filtering artifacts [37]. Cooling bulk GaAs to 77 K is known to recover its full 50% selection-rule value [33], but low-temperature photoemission studies have otherwise been confined to bulk GaAs or surface-physics contexts [15, 38], and to our knowledge no temperature-dependent measurement of the emitted-electron polarization of a strained-superlattice photocathode has been reported.

Here we use temperature to explore and suppress electron spin depolarization in an MOCVD-grown strained GaAs/GaAsP superlattice, measuring the spin-polarization spectra shown in Fig. 1 and QE spectra at nominal cathode temperatures of 295 K, 273 K, 195 K, and 77 K. The peak polarization rises from 91.2(1)% at room temperature to 95.0 ± 0.8 (stat) ± 2.4 (sys)% at 195 K, while the QE at the polarization peak remains near 1%. Correcting for the measured circular polarization of the excitation gives helicity-normalized polarizations of 97.1(0.8)% at 195 K and 94.3(1.3)% at 77 K; their respective laser-calibration uncertainties are 0.3 and 1.2 percentage points, in addition to Sherman-function uncertainties of 2.4 and 2.3 percentage points. Even the bare measured value exceeds the central values of the prior benchmark measurements, which cluster near 92% [21, 23, 24], and the largest delivered value is reached at dry-ice temperature. The temperature dependence of the peak wavelength tests the calculated band-structure

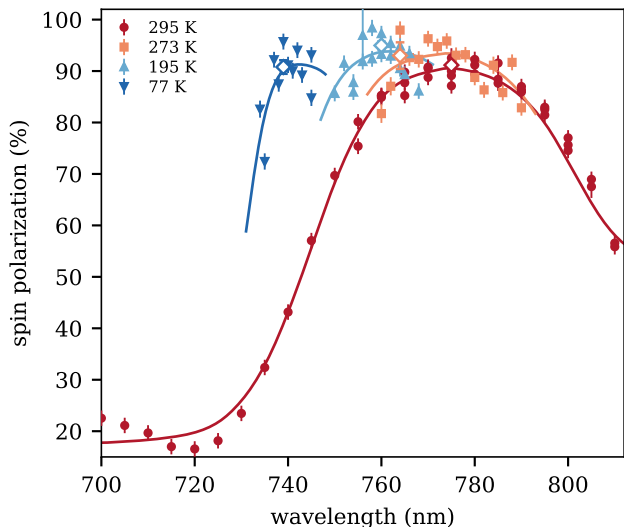


FIG. 1. Delivered beam polarization versus excitation wavelength at 295 K, 273 K, 195 K, and 77 K (filled points; error bars are the counting error and a 1.5-percentage-point scan-to-scan repeatability uncertainty, added in quadrature), with the empirical description of the spectra multiplied by the measured laser circular polarization (solid curves). The model uses the peak-shift-inferred cathode temperatures, the cold-saturation transport ceiling, thermal edge smearing, and the LO-occupation onset law described in the text. Open diamonds mark the quoted peak values, the error-weighted means of all production-spectrum measurements within 3 nm of each peak. A 2.49% relative Sherman-function uncertainty applies to all points; the separate laser-calibration uncertainty applies only to helicity-normalized quantities and is not shown.

shift, the temperature dependence of the peak polarization constrains an effective transport-depolarization contribution, and stability and reversibility measurements of the QE and polarization test for surface energy-filtering artifacts, in which an evolving activation layer raises the measured polarization without improving the source material [37].

Experiment.—The photocathode is a strained GaAs/GaAsP superlattice grown by MOCVD following Refs. [27, 28]. The superlattice comprises 30 pairs of 3.8 nm strained GaAs wells and 2.8 nm GaAs_{0.65}P_{0.35} barriers, Zn doped at a concentration of $5 \times 10^{17} \text{ cm}^{-3}$. All layer thicknesses are growth targets. The superlattice sits inside an optical cavity between a 5 nm GaAs surface layer carbon-doped at $5 \times 10^{19} \text{ cm}^{-3}$ and a distributed Bragg reflector (DBR) formed by 12 pairs of GaAs_{0.65}P_{0.35} and In_{0.30}Al_{0.70}P layers. A 338 nm GaAs_{0.65}P_{0.35} spacer separates the superlattice from the DBR. The p-GaAs substrate, metamorphic buffer, DBR, and spacer are Zn doped at $5 \times 10^{18} \text{ cm}^{-3}$. Reflectance measurements at normal incidence confirm the DBR stopband at the operating wavelengths. We initially

heat cleaned the sample at 550 °C for 1.5 h to remove surface oxides. Before each subsequent test we heated it at 350 °C to reset the NEA condition, then reactivated it with cesium and NF₃. Each activation required 6–10 Cs/NF₃ yo-yo cycles and ended when an additional cycle increased the photocurrent by less than 5%. During measurements, the chamber pressure was approximately 3×10^{-12} Torr to 1×10^{-11} Torr; during activation it rose as high as 1×10^{-9} Torr.

The sample holder is a hollow stainless-steel reservoir terminated by a thin molybdenum end plate. We mounted the GaAs photocathode against the end plate with indium foil and retained it with a tantalum cup, leaving a circular active area 12.9 mm in diameter. We filled the reservoir successively with ice water, dry ice, and liquid nitrogen [33]. Direct cathode thermometry was not available, so we report the nominal coolant temperatures of 273 K, 195 K, and 77 K. We measured the polarization and quantum efficiency spectra with excitation light from a broadly tunable supercontinuum light source (NKT Photonics SuperK) covering a wavelength range of 600 nm to 810 nm. We prepared circularly polarized light using a linear polarizer and a zero-order 780 nm quarter-wave plate, and reversed the helicity by inserting a half-wave plate during measurement to cancel instrumental asymmetries. We characterized the wavelength-dependent circular polarization of the excitation light at the cathode to be 89–100% over the polarization scans. We report two quantities: the electron spin polarization delivered to the polarimeter $P_{\text{beam}}(\lambda)$, measured with the actual circular polarization of the excitation, and the polarization corrected for the laser circular polarization, $P_{\text{corr}}(\lambda) = P_{\text{beam}}(\lambda)/C(\lambda)$, where C is the measured circular polarization of the light at the cathode. The measurement of $C(\lambda)$ used a rotating zero-order 780 nm half-wave plate and a fixed Glan polarizer, calibrated for the plate’s wavelength-dependent retardance (SM). The corrected value is the quantity we use to compare depolarization across temperatures and with prior work. We obtained the QE from the photocurrent and the incident power at each wavelength. We measured polarization with a retarding-field micro-Mott polarimeter [39, 40] operated at 20 kV with effective Sherman function $S_{\text{eff}} = 0.201(5)$, calibrated by comparison with the CEBAF 5 MeV Mott polarimeter [28, 40, 41]. The Supplemental Material (SM) [42] gives the full layer structure and details the polarimeter operation and calibration. We quote the statistical uncertainty of the helicity-pair asymmetry on each polarization point; where repeated measurements within the peak window scatter beyond counting statistics, we inflate the uncertainty by $\sqrt{\chi^2_{\nu}}$. We quote peak polarizations as the weighted mean of all measurements within 3 nm of the peak wavelength; the $\sqrt{\chi^2_{\nu}}$ inflation of the peak uncertainty reaches a factor of 11 at 77 K, where successive scans scatter by several percentage points. For helicity-normalized values we propagate the local uncer-

tainty of $C(\lambda)$ as a separate laser-calibration component. We also add a 2.49% relative Sherman-function uncertainty, common to all polarization points. We exclude both correlated calibration components from the spectral-fit weights and include them when comparing absolute peak polarizations with published benchmarks.

A high measured polarization can also be a surface artifact. As the activation layer degrades, the surface can shift from negative to positive electron affinity, which filters the emitted electrons in energy and raises the measured polarization of bulk GaAs without any change in the material itself [37]. Two controls address this concern. First, the polarization is reversible. After the full cooling sequence and warmup, we recovered the room-temperature peak polarization within uncertainty (+1.1(2.1) percentage points relative to the pre-cooling value); three same-day 775 nm checks span 89.1–92.5%, with the largest difference of +3.4(2.4) percentage points (counting plus repeatability uncertainty). Second, the polarization does not track activation decay. At 77 K the QE at the operating wavelength decreased by 43% over the measurement day, while the polarization measurements showed no systematic increase. A repeat dry-ice cooldown late in the campaign, after substantial QE decay, gave a *lower* helicity-normalized peak polarization (90.1(1.1)%), the opposite of the energy-filtering signature. These observations strongly disfavor activation degradation or energy filtering as the origin of the high-polarization state; they do not imply that the activation layer is unchanged, but they show that the polarization gain is not correlated with activation aging.

Polarization spectra.—At 295 K the spectrum has the form characteristic of high-quality strained SLs [19, 21, 24], with a delivered peak polarization of 91.2(1)% at 775 nm, or 91.6(1)% when corrected for the 99.5% circular polarization at that wavelength. Cooling the sample produces three correlated changes. The delivered peak polarization rises to 93.0(2.6)% at 273 K and 95.0(0.8)% at 195 K, corresponding to helicity-normalized values of 94.7(2.6)% and 97.1(0.8)% with $C = 98.1\%$ and 97.8% circular polarization at the respective peaks. At 77 K the delivered peak of 90.8(1.3)% is lower largely because the laser circular polarization at the 739 nm peak drops to 96.3%; the helicity-normalized value, 94.3(1.3)%, has a lower central value but remains consistent with the 195 K result within the combined statistical and laser-calibration uncertainties (a difference of 1.4 standard deviations). The data therefore do not resolve a further polarization increase below 195 K. The quoted peaks use all production-spectrum measurements within 3 nm of each peak, and their uncertainties include the observed point-to-point scatter. The highest individual scan points at 273 K, 195 K, and 77 K reach helicity-normalized values statistically consistent with complete spin polarization. The absence of a resolved further increase is consistent with the dominant temperature-dependent depo-

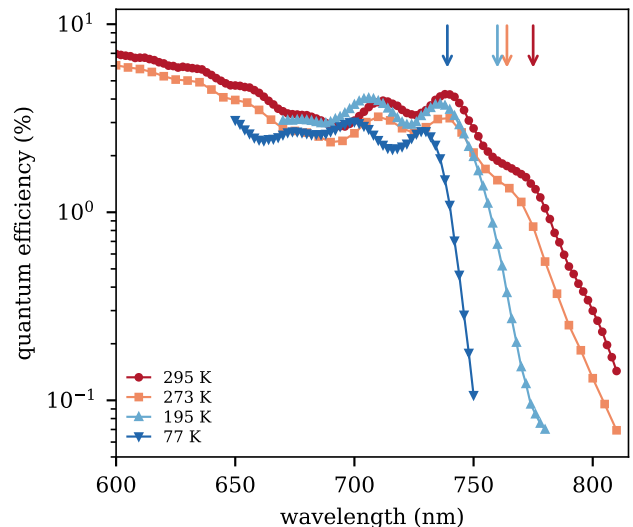


FIG. 2. Quantum efficiency versus excitation wavelength at each temperature, from the scans taken closest in time to the polarization runs. Arrows mark the operating (polarization-peak) wavelengths.

polarization channel being strongly suppressed already at dry-ice temperature. The peak polarization wavelength shifts from 775 nm at 295 K to 739 nm at 77 K, a shift of 78 meV, close to the 83 meV Varshni band-gap shift expected at fixed confinement offset for the nominal coolant temperatures [30, 43] [Fig. 3(a)]. Since we do not measure the emitting-surface temperature directly, this comparison is a consistency check on band-edge shift rather than an independent thermometric calibration. The spectral peak also narrows on cooling. At 77 K the scans cover 734 nm to 745 nm, and we infer the peak width there from the phenomenological description of the narrowing (see below).

The maximum helicity-normalized polarization of $97.1 \pm 0.8(\text{stat}) \pm 0.3(\text{laser}) \pm 2.4(\text{Sherman})\%$ is, to our knowledge, the highest central value reported from a GaAs-based photocathode, exceeding the previous benchmarks, $92 \pm 6\%$ [21] and 92% [23, 24], by more than five percentage points, and even the delivered beam polarization, 95.0(0.8)%, exceeds these values. The SM tabulates a comparison with published strained-layer and superlattice results.

Quantum efficiency.— We define the nominal operating wavelength at each temperature as the polarization-peak wavelength. The QE spectra (Fig. 2) shift with the band edge. At the fixed room-temperature operating wavelength of 775 nm, the QE drops by a factor of 1.6 at 273 K and by more than an order of magnitude at 195 K as the absorption edge moves through it [33]. At the operating wavelength of each temperature, the QE is 1.4%, 1.4%, 0.7%, and 1.3% at 295 K, 273 K, 195 K, and 77 K. Polarization and QE enter the source perfor-

mance differently. The polarization of a beam is fixed at the point of photoemission, whereas the intensity at $\sim 1\%$ QE can be raised with illumination power, within laser and cathode heat-load and lifetime limits. Cooling therefore improves the quantity that is fixed at the source, while the measured QE of $\sim 1\%$ remains adequate for typical operation. For experiments limited instead by laser power or by the surface charge limit at high bunch charge [44, 45], the composite metric P^2 QE at the operating wavelength remains within a factor of two of its room-temperature value across the range (0.6–1.2%).

Model.—We model the spectra in two stages, with the adjustable spectral shape constrained by the room-temperature data. The model extends to lower temperatures through the known temperature dependence of the band gaps, plus one fitted transport factor per temperature. The first stage is a band-structure calculation with no adjustable parameters. We diagonalize a four-band Luttinger-Kohn Hamiltonian with Bir-Pikus strain for the superlattice valence minibands and a nonparabolic conduction miniband, using the nominal layer structure and literature material constants, and apply the σ^+ dipole selection rules [20, 43]. This calculation fixes the heavy-hole miniband edge 133 meV above the bulk GaAs gap, the HH-LH splitting $\delta = 105$ meV (with 97 meV arising from strain and the rest from confinement), and the decay of the excitation polarization above the edge through $k_{\parallel}$ valence-band mixing [20]. The Varshni gap laws set the temperature shift of every edge [30, 43]. Because the material parameters derive largely from low-temperature measurements, these quantities provide a reliable temperature-dependent baseline over the measured range. Next we assemble the transitions into a spectrum,

$$P(\hbar\omega, T) = \frac{1}{1 + \tau/\tau_s} \frac{\sum_i P_i s_i a_i g_i(\hbar\omega) + P_{\text{bg}} a_{\text{bg}}}{\sum_i a_i g_i(\hbar\omega) + a_{\text{bg}}}, \quad (1)$$

Each term carries one physical ingredient. Transition i has absorption weight a_i , including a two-dimensional Coulomb enhancement, and σ^+ polarization P_i , both taken from the band-structure calculation. The line shape g_i is a Gaussian of width Γ centered on the calculated transition energy E_i shifted by a fitted rigid offset ΔE_0 , with Γ and ΔE_0 common to all transitions. The factor $s_i = \exp[-(\Delta E_{c,i}/E_{\kappa})^4]$ is the spin survival of the hot-electron cascade, where $\Delta E_{c,i}$ is the conduction excess energy of transition i and E_{κ} is the excess energy beyond which the cascade erases the spin memory; the quartic form is the phonon-cascade integral of the D'yakonov-Perel' rate [35, 36, 46]. The term a_{bg} , carrying polarization P_{bg} , is an effective weakly polarized contribution whose microscopic origin is not fixed here (SM). The prefactor $1/(1 + \tau/\tau_s)$ describes spin relaxation of thermalized electrons during transport, with τ the emission time and $1/\tau_s$ the spin-relaxation rate [31, 33]. We fit the room-temperature spectrum and the three lower-

temperature peak polarizations with six shared spectral parameters and τ/τ_s at each temperature: the edge shift ΔE_0 , which absorbs the band-offset and layer-thickness uncertainty, the width Γ , the cascade scale E_{κ} , the excitation strength, and the background amplitude and polarization. The room-temperature spectrum fixes the spectral shape, and each lower temperature contributes only its measured peak polarization, which determines its τ/τ_s (SM).

We take the three changes of the spectra upon cooling in turn: the shift of the peak wavelength, the rise of the peak polarization, and the narrowing of the peak. With the room-temperature edge shift fixed, the peak wavelength contains no further fitted temperature dependence, and the predicted peaks lie within 6 nm of the measured values over the full 36 nm shift [Fig. 3(a)]. If the effective background is temperature independent, the fit attributes the polarization gain to suppression of the transport factor, which falls from $\tau/\tau_s = 0.049(12)$ at 295 K to values consistent with zero at and below 273 K [Fig. 3(b)]. The modeled gain of 4.4 percentage points is close to the measured 5.5; within this parameterization, the absence of a resolved further increase below 195 K follows because the residual deficit at the peak (background, band mixing, and cascade depolarization) is held temperature independent. Three mechanisms govern conduction-electron spin relaxation in p-type III-V semiconductors [47–49]: D'yakonov-Perel' (DP) precession about the momentum-dependent effective field of the inversion-asymmetric lattice [46], Bir-Aronov-Pikus (BAP) electron-hole exchange scattering [31, 32], and a small Elliott-Yafet contribution at our acceptor density of $5 \times 10^{17} \text{ cm}^{-3}$ [35]. DP dominates at room temperature and BAP becomes the larger thermalized channel on cooling. The transport factor we extract, however, falls to a value consistent with zero already at 273 K, a change far larger than any thermalized bulk rate produces over a 22 K interval, and may reflect temperature dependence of the emission time, energy relaxation, additional transport channels, or the low-polarization contribution represented by a_{bg} [34]. We describe the peak narrowing below room temperature phenomenologically. A simplified two-edge description of the spectra (SM) locates the narrowing in the blue-side depolarization onset, which falls from 92(8) meV above the heavy-hole edge at 295 K, close to the fixed HH-LH splitting, to 48(8) meV at the 77 K coolant setting. The onset can be parameterized as $\delta_{\text{eff}}(T) \simeq \hbar\omega_{\text{LO}}[1 + 4.2(5) \bar{n}_{\text{LO}}]$, where $\bar{n}_{\text{LO}}$ is the Bose occupation of the 36.7 meV LO phonon evaluated at the peak-shift-inferred cathode temperature. The onset approaches the single LO-phonon energy as the phonons freeze out. This correlation is consistent with LO-phonon freeze-out contributing to the narrowing, but the relation is purely empirical and does not establish a microscopic mechanism or a unique cause.

Conclusion.—Our temperature-dependent polariza-

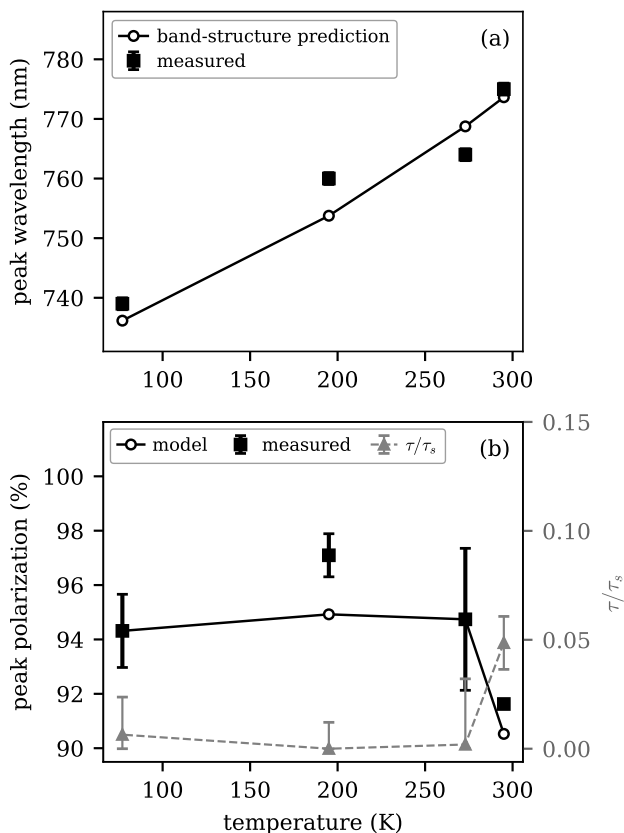


FIG. 3. (a) Measured polarization-peak wavelength versus temperature (squares) with the band-structure prediction (circles). (b) Measured helicity-normalized peak polarization (squares) with the model (circles) and the effective transport factor τ/τ_s extracted under the temperature-independent-background assumption (right axis, triangles). This factor is consistent with zero at and below 273 K.

tion and QE spectra of a strained GaAs/GaAsP superlattice photocathode distinguish an effective transport contribution from energy-dependent spin relaxation during the hot-electron cascade. The increase in polarization on cooling is consistent with suppressed transport depolarization, raising the delivered peak polarization from $91.2(1)\%$ at 295 K to $95.0 \pm 0.8(\text{stat}) \pm 2.4(\text{sys})\%$ at 195 K, corresponding to a helicity-normalized polarization of $97.1 \pm 0.8(\text{stat}) \pm 0.3(\text{laser}) \pm 2.4(\text{Sherman})\%$. Within the temperature-independent-background parameterization, the absence of a resolved further increase on cooling to 77 K is consistent with the surviving energy-dependent hot-electron contribution, and the QE remains near 1% at the polarization-optimized wavelength throughout. The peak wavelength follows the band-structure prediction within 6 nm at every temperature. Reversibility of the QE and polarization spectra, and a repeat cooldown in which activation decay lowered rather than raised the polarization, strongly disfavor surface-filtering artifacts. The peak narrowing can

be parameterized by the LO-phonon occupation, consistent with a possible role for LO-phonon freeze-out. The gain is consistent with suppression of bulk or transport depolarization, and the full gain is available at dry-ice temperature, compatible with dc high-voltage photogun operation. Combined with high-QE superlattice designs [25, 26, 28], cooled operation provides next-generation experiments [12, 13] with polarized electron sources at the highest central polarization yet reported for GaAs photocathodes.

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* mgrau@odu.edu

- [1] K. Aulenbacher, C. Nachtigall, H. G. Andresen, J. Bermuth, T. Dombo, P. Drescher, H. Euteneuer, H. Fischer, D. v. Harrach, P. Hartmann, J. Hoffmann, P. Jennewein, K.-H. Kaiser, S. Köbis, H. J. Kreidel, J. Langbein, M. Petri, S. Plützer, E. Reichert, M. Schemies, H.-J. Schöpe, K.-H. Steffens, M. Steigerwald, H. Trautner, and T. Weis, The MAMI source of polarized electrons, *Nucl. Instrum. Methods Phys. Res., Sect. A* **391**, 498 (1997).
- [2] C. K. Sinclair, P. A. Adderley, B. M. Dunham, J. C. Hansknecht, P. Hartmann, M. Poelker, J. S. Price, P. M. Rutt, W. J. Schneider, and M. Steigerwald, Development of a high average current polarized electron source with long cathode operational lifetime, *Phys. Rev. ST Accel. Beams* **10**, 023501 (2007).
- [3] P. A. Adderley, J. Clark, J. Grames, J. Hansknecht, K. Surles-Law, D. Machie, M. Poelker, M. L. Stutzman, and R. Suleiman, Load-locked dc high voltage GaAs photogun with an inverted-geometry ceramic insulator, *Phys. Rev. ST Accel. Beams* **13**, 010101 (2010).
- [4] J. Grames, R. Suleiman, P. A. Adderley, J. Clark, J. Hansknecht, D. Machie, M. Poelker, and M. L. Stutzman, Charge and fluence lifetime measurements of a dc high voltage GaAs photogun at high average current, *Phys. Rev. ST Accel. Beams* **14**, 043501 (2011).
- [5] P. A. Adderley, D. Bullard, Y. C. Chao, C. H. Garcia, J. Grames, J. Hansknecht, A. Hoffer, R. Kazimi, J. Musson, C. Palatchi, K. Paschke, M. Poelker, G. Smith, M. L. Stutzman, R. Suleiman, and Y. Wang, An overview of how parity-violating electron scattering experiments are performed at CEBAF, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1046**, 167710 (2023).
- [6] S. E. Kuhn, J.-P. Chen, and E. Leader, Spin structure of the nucleon—status and recent results, *Prog. Part. Nucl. Phys.* **63**, 1 (2009).
- [7] M. K. Jones *et al.* (Jefferson Lab Hall A Collaboration), G_{E_p}/G_{M_p} ratio by polarization transfer in $\vec{e}p \rightarrow e\vec{p}$, *Phys. Rev. Lett.* **84**, 1398 (2000).
- [8] C. F. Perdrisat, V. Punjabi, and M. Vanderhaeghen, Nucleon electromagnetic form factors, *Prog. Part. Nucl. Phys.* **59**, 694 (2007).
- [9] D. Abbott *et al.* (PEPPo Collaboration), Production of

- highly polarized positrons using polarized electrons at MeV energies, *Phys. Rev. Lett.* **116**, 214801 (2016).
- [10] A. Accardi *et al.*, Electron-Ion Collider: The next QCD frontier, *Eur. Phys. J. A* **52**, 268 (2016).
 - [11] R. Abdul Khalek *et al.*, Science requirements and detector concepts for the electron-ion collider: EIC Yellow Report, *Nucl. Phys. A* **1026**, 122447 (2022).
 - [12] E. Wang, O. Rahman, J. Skaritka, W. Liu, J. Biswas, C. Degen, P. Inacker, R. Lambiase, and M. Paniccia, High voltage dc gun for high intensity polarized electron source, *Phys. Rev. Accel. Beams* **25**, 033401 (2022).
 - [13] V. N. Litvinenko, N. Bachhawat, J. C. Brutus, L. Cultrera, K. Decker, M. Gaowei, P. Inacker, Y. Jing, J. Ma, K. P. Mondal, G. Narayan, I. Pinayev, F. Severino, K. Shih, J. Skaritka, L. Smart, Y. Than, J. Walsh, E. Wang, G. Wang, and D. Weiss, Towards advanced polarized electron sources, *Nat. Phys.* **22**, 325 (2026).
 - [14] D. T. Pierce, F. Meier, and P. Zürcher, Direct observation of spin dependent electronic structure of GaAs using spin polarized photoemission, *Phys. Lett. A* **51**, 465 (1975).
 - [15] D. T. Pierce and F. Meier, Photoemission of spin-polarized electrons from GaAs, *Phys. Rev. B* **13**, 5484 (1976).
 - [16] T. Maruyama, E. L. Garwin, R. Prepost, G. H. Zappalac, J. S. Smith, and J. D. Walker, Observation of strain-enhanced electron-spin polarization in photoemission from InGaAs, *Phys. Rev. Lett.* **66**, 2376 (1991).
 - [17] T. Nakanishi, H. Aoyagi, H. Horinaka, Y. Kamiya, T. Kato, S. Nakamura, T. Saka, and M. Tsubata, Large enhancement of spin polarization observed by photoelectrons from a strained GaAs layer, *Phys. Lett. A* **158**, 345 (1991).
 - [18] T. Omori, Y. Kurihara, T. Nakanishi, H. Aoyagi, T. Baba, T. Furuya, K. Itoga, M. Mizuta, S. Nakamura, Y. Takeuchi, M. Tsubata, and M. Yoshioka, Large enhancement of polarization observed by extracted electrons from the AlGaAs-GaAs superlattice, *Phys. Rev. Lett.* **67**, 3294 (1991).
 - [19] T. Maruyama, D.-A. Luh, A. Brachmann, J. E. Clendenin, E. L. Garwin, S. Harvey, J. Jiang, R. E. Kirby, C. Y. Prescott, R. Prepost, and A. M. Moy, Systematic study of polarized electron emission from strained GaAs/GaAsP superlattice photocathodes, *Appl. Phys. Lett.* **85**, 2640 (2004).
 - [20] A. V. Subashiev, L. G. Gerchikov, and A. N. Ipatov, Optical spin orientation in strained superlattices, *J. Appl. Phys.* **96**, 1511 (2004).
 - [21] T. Nishitani, T. Nakanishi, M. Yamamoto, S. Okumi, F. Furuta, M. Miyamoto, M. Kuwahara, N. Yamamoto, K. Naniwa, O. Watanabe, Y. Takeda, H. Kobayakawa, Y. Takashima, H. Horinaka, T. Matsuyama, K. Togawa, T. Saka, M. Tawada, T. Omori, Y. Kurihara, M. Yoshioka, K. Kato, and T. Baba, Highly polarized electrons from GaAs-GaAsP and InGaAs-AlGaAs strained-layer superlattice photocathodes, *J. Appl. Phys.* **97**, 094907 (2005).
 - [22] L. G. Gerchikov, Y. A. Mamaev, A. V. Subashiev, Y. P. Yashin, D. A. Vasil'ev, V. V. Kuz'michev, A. E. Zhukov, E. S. Semenova, A. P. Vasil'ev, and V. M. Ustinov, Photoemission of polarized electrons from InAlGaAs/GaAs superlattices with minimum conduction band offsets, *Semiconductors* **40**, 1326 (2006).
 - [23] Y. A. Mamaev, L. G. Gerchikov, Y. P. Yashin, D. A. Vasiliev, V. V. Kuzmichev, V. M. Ustinov, A. E. Zhukov, V. S. Mikhlin, and A. P. Vasiliev, Optimized photocathode for spin-polarized electron sources, *Appl. Phys. Lett.* **93**, 081114 (2008).
 - [24] X. Jin, A. Mano, F. Ichihashi, N. Yamamoto, and Y. Takeda, High-performance spin-polarized photocathodes using a GaAs/GaAsP strain-compensated superlattice, *Appl. Phys. Express* **6**, 015801 (2013).
 - [25] W. Liu, Y. Chen, W. Lu, A. Moy, M. Poelker, M. Stutzman, and S. Zhang, Record-level quantum efficiency from a high polarization strained GaAs/GaAsP superlattice photocathode with distributed Bragg reflector, *Appl. Phys. Lett.* **109**, 252104 (2016).
 - [26] J. Biswas, L. Cultrera, W. Liu, E. Wang, J. Skaritka, K. Kisslinger, S. D. Hawkins, S. R. Lee, and J. F. Klem, Record quantum efficiency from strain compensated superlattice GaAs/GaAsP photocathode for spin polarized electron source, *AIP Adv.* **13**, 085106 (2023).
 - [27] B. Belfore, A. Masters, D. Poudel, G. Blume, S. Polly, E. Wang, S. M. Hubbard, M. Stutzman, J. M. Grames, M. Poelker, M. Grau, and S. Marsillac, High figure of merit spin polarized electron sources grown via MOCVD, *Appl. Phys. Lett.* **123**, 222102 (2023).
 - [28] A. Masters, G. Blume, S. Poudel, J. M. Grames, M. Poelker, M. Stutzman, S. Polly, S. M. Hubbard, S. Marsillac, and M. Grau, Impact of superlattice size on quantum efficiency and polarization in MOCVD-grown strained GaAs/GaAsP photocathodes, *Appl. Phys. Lett.* **128**, 083501 (2026).
 - [29] E. Wang, O. Rahman, J. Biswas, J. Skaritka, P. Inacker, W. Liu, R. Napoli, and M. Paniccia, High-intensity polarized electron gun featuring distributed Bragg reflector GaAs photocathode, *Appl. Phys. Lett.* **124**, 254101 (2024).
 - [30] Y. P. Varshni, Temperature dependence of the energy gap in semiconductors, *Physica* **34**, 149 (1967).
 - [31] G. Fishman and G. Lampel, Spin relaxation of photoelectrons in *p*-type gallium arsenide, *Phys. Rev. B* **16**, 820 (1977).
 - [32] K. Zerrouati, F. Fabre, G. Bacquet, J. Bandet, J. Frandon, G. Lampel, and D. Paget, Spin-lattice relaxation in *p*-type gallium arsenide single crystals, *Phys. Rev. B* **37**, 1334 (1988).
 - [33] W. Liu, M. Poelker, X. Peng, S. Zhang, and M. Stutzman, A comprehensive evaluation of factors that influence the spin polarization of electrons emitted from bulk GaAs photocathodes, *J. Appl. Phys.* **122**, 035703 (2017).
 - [34] S. Ohki, X. Jin, T. Ishikawa, T. Kamezaki, K. Yamada, S. Muto, and A. Tackeuchi, Prolonged spin relaxation time in Zn-doped GaAs/GaAsP strain-compensated superlattice, *Appl. Phys. Lett.* **111**, 022405 (2017).
 - [35] O. Chubenko, S. Karkare, D. A. Dimitrov, J. K. Bae, L. Cultrera, I. Bazarov, and A. Afanasev, Monte Carlo modeling of spin-polarized photoemission from *p*-doped bulk GaAs, *J. Appl. Phys.* **130**, 063101 (2021).
 - [36] J. R. Callahan, *Monte Carlo Modeling of Spin Polarized Photoemission from GaAs at Low Temperatures and Positive Electron Affinity Surfaces*, Master's thesis, Northern Illinois University, DeKalb, Illinois (2025), Graduate Research Theses & Dissertations, 8108.
 - [37] S. J. Levenson, M. B. Andorf, M. A. Reamon, B. Vareskic, A. Galdi, O. Chubenko, J. Callahan, J. M. Maxson, and I. V. Bazarov, Characterization of electron spin polarization from positive electron affinity GaAs photocathodes, *J. Appl. Phys.* **138**, 104901 (2025).

- [38] R. Allenspach, F. Meier, and D. Pescia, Spin polarized photoemission from GaAs and Ge: Temperature dependence of the threshold polarization, *Appl. Phys. Lett.* **44**, 1107 (1984).
- [39] T. J. Gay and F. B. Dunning, Mott electron polarimetry, *Rev. Sci. Instrum.* **63**, 1635 (1992).
- [40] J. L. McCarter, M. L. Stutzman, K. W. Trantham, T. G. Anderson, A. M. Cook, and T. J. Gay, A low-voltage retarding-field Mott polarimeter for photocathode characterization, *Nucl. Instrum. Methods Phys. Res., Sect. A* **618**, 30 (2010).
- [41] M. Steigerwald, MeV Mott polarimetry at Jefferson Lab, in *AIP Conf. Proc.*, Vol. 570 (2001) pp. 935–942.
- [42] See Supplemental Material at [URL will be inserted by publisher] for the full device structure, apparatus and calibration details, stability controls, model details, and a comparison with prior photocathodes.
- [43] I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, Band parameters for III–V compound semiconductors and their alloys, *J. Appl. Phys.* **89**, 5815 (2001).
- [44] K. Togawa, T. Nakanishi, T. Baba, F. Furuta, H. Horioka, T. Ida, Y. Kurihara, H. Matsumoto, T. Matsuyama, M. Mizuta, S. Okumi, T. Omori, C. Suzuki, Y. Takeuchi, K. Wada, K. Wada, and M. Yoshioka, Surface charge limit in NEA superlattice photocathodes of polarized electron source, *Nucl. Instrum. Methods Phys. Res., Sect. A* **414**, 431 (1998).
- [45] J. E. Clendenin, A. Brachmann, E. L. Garwin, S. Harvey, J. Jiang, R. E. Kirby, D.-A. Luh, T. Maruyama, R. Prepost, C. Y. Prescott, and J. L. Turner, Recent progress at SLAC extracting high charge from highly polarized photocathodes for future-collider applications, *Nucl. Instrum. Methods Phys. Res., Sect. A* **536**, 308 (2005).
- [46] M. I. D’yakonov and V. I. Perel’, Spin relaxation of conduction electrons in noncentrosymmetric semiconductors, *Sov. Phys. Solid State* **13**, 3023 (1972).
- [47] F. Meier and B. P. Zakharchenya, eds., *Optical Orientation*, Modern Problems in Condensed Matter Sciences, Vol. 8 (North-Holland, Amsterdam, 1984).
- [48] I. Žutić, J. Fabian, and S. Das Sarma, Spintronics: Fundamentals and applications, *Rev. Mod. Phys.* **76**, 323 (2004).
- [49] M. W. Wu, J. H. Jiang, and M. Q. Weng, Spin dynamics in semiconductors, *Phys. Rep.* **493**, 61 (2010).
- [50] B. Belfore, *Development of high quantum efficiency strained superlattice spin polarized photocathodes via metal organic chemical vapor deposition*, Ph.D. thesis, Old Dominion University (2022).
- [51] V. S. Rusetsky, V. A. Golyashov, S. V. Eremeev, D. A. Kustov, I. P. Rusinov, T. S. Shamirzaev, A. V. Mironov, A. Y. Demin, and O. E. Tereshchenko, New spin-polarized electron source based on alkali antimonide photocathode, *Phys. Rev. Lett.* **129**, 166802 (2022).
- [52] I. Vurgaftman, M. P. Lumb, and J. R. Meyer, *Bands and Photons in III-V Semiconductor Quantum Structures* (Oxford University Press, Oxford, 2021).