Record-level Quantum Efficiency from a High Polarization Strained GaAs/GaAsP Superlattice Photocathode with Distributed Bragg Reflector

Wei Liu,^{1,2,3)} Yiqiao Chen,⁴⁾ Wentao Lu,⁴⁾ Aaron Moy,⁴⁾ Matt Poelker,³⁾ Marcy Stutzman,³⁾ and Shukui Zhang³⁾

¹*Institute of Modern physics, Chinese Academy of Sciences, 509 Nanchang Rd., Lanzhou, 730000, China*

²*University of Chinese Academy of Sciences, 19A Yuquan Rd., Beijing, 100049, China*

³*Thomas Jefferson National Accelerator facility, 12000 Jefferson Avenue, Newport News, Virginia, 23606, USA*

⁴*SVT Associates, Inc. 7620 Executive Dr., Eden Prairie, Minnesota, 55344, USA*

Photocathodes that provide high electron-spin polarization (ESP) and high quantum efficiency (QE) can significantly enhance the physics capabilities of electron accelerators. We report record-level QE from a high-polarization strained GaAs/GaAsP superlattice photocathode fabricated with a Distributed Bragg Reflector (DBR). The DBR photocathode technique enhances the absorption of incident laser light thereby enhancing QE, but as literature suggests, it is very challenging to optimize all of the parameters associated with the fabrication of complicated photocathode structures composed of many distinct layers. Past reports of DBR photocathodes describe high polarization but typically QE of only $\sim 1\%$, which is comparable to QE of high polarization photocathodes grown without a DBR structure. This work describes a strained GaAs/GaAsP superlattice DBR photocathode exhibiting high polarization of 84% and significantly enhanced QE of 6.4%.

Spin-polarized electron sources play a critical role in nuclear and high energy physics research, where the spin of the electron is used to study nuclear structure, the dynamics of strong interactions, electro-weak nuclear physics, including parity-violation, and physics beyond the Standard Model.¹ Inexpensive bulk GaAs provides very high quantum efficiency (QE) but electron-spin polarization (ESP) cannot exceed 50% due to the heavy-hole, light-hole degeneracy of the $^2p_{3/2}$ valence band state.² Photocathodes grown on a crystal structure with a different lattice constant can provide beam polarization exceeding 50% because of induced uniaxial strain that eliminates the degeneracy of the valence band.^{3,4} Throughout the 1990s, single-strained-layer GaAs/GaAsP photocathodes providing polarization 75%-80% and maximum QE $\sim 0.3\%$ ^{3,5,6} were used at electron accelerators worldwide⁷⁻¹³, but beam delivery using single-strained-layer photocathodes made apparent the delicate competing balance between maintaining the required degree of strain, and growing a layer thick enough to provide sufficient QE. In the

following decade, strained superlattice structures consisting of very thin quantum-well active layers and alternating lattice-mismatched barrier layers were developed.¹⁴ The superlattice structure maintained the required degree of strain to produce high polarization and also provided sufficient active layer thickness to obtain higher QE. The strained GaAs/GaAsP_{0.36} superlattice structure reported in ref. 15 provided QE of 1.2% with polarization of 86% and is available commercially¹⁶. Strained superlattice photocathodes fabricated at other facilities have also demonstrated very high polarization but no higher QE.¹⁷⁻²⁰

One of the proposed Electron Ion Collider (EIC) designs, eRHIC²¹, requires milliamperes of polarized electron beam representing a factor of ~ 250 beyond today's state-of-the-art. A photocathode with a QE of only 1% would require ~ 8 W of laser light (with RF structure) to generate the desired 50 mA average beam current and even more light when QE decays during operation due to ion-bombardment²². In the standard strained superlattice design, most of the incident laser light simply heats the photocathode instead of promoting electron ejection, which can degrade QE due to evaporation of the chemicals used to reduce the surface work function.²³ Methods to cool the photocathode during beam delivery are complicated because the photocathode floats at high voltage. Developing photocathodes with enhanced QE could simplify the photogun design, reduce the drive-laser power requirements and prolong the effective operating lifetime of the photogun.

A photocathode with a distributed Bragg reflector (DBR) was first proposed in 1993²⁴ and reported in following years^{25,26} as a means to enhance photocathode QE. The DBR serves to create a Fabry-Perot cavity formed by the front surface of photocathode and a DBR region existing beneath the superlattice active layer. Instead of a single pass in the standard design, laser light of a particular wavelength reflects repeatedly within the Fabry-Perot cavity which increases the beneficial absorption of the incident photons, and in principle, leads to enhanced QE. In our previous work²⁷, the enhanced QE of a strained GaAs/GaAsP superlattice photocathode with DBR was $\sim 1.2\%$ with polarization near 90%. Relatively low QE was attributed to weak resonant absorption of incident laser light and a mismatch between the wavelength of peak absorption and peak polarization. It was clear that the wavelength of peak reflectivity of the DBR was very sensitive to the refractive indices and thickness of each DBR layer constituent, and that the peak of resonant absorption was very sensitive to the thickness of the photocathode, especially the spacer layer between the DBR and the superlattice photocathode structures. Accurate control of the thickness of each layer and of the composition of each constituent chemical within the photocathode structure was challenging. In this study, a deeper appreciation for the global challenges of photocathode fabrication, together with improved modeling and fabrication techniques, allowed the fabrication of a strained GaAs/GaAsP superlattice photocathode with DBR (GaAsP/AlAsP) exhibiting significantly improved performance. The photocathode provided 84% polarization and QE of 6.4%, which is the highest QE of any reported "high polarization" photocathode. Moreover, peak polarization and QE were obtained at 776 nm, a wavelength compatible with CEBAF photogun drive lasers and readily available fiber-telecommunications hardware.

This DBR study benefited from past work that resulted in the fabrication of the strained GaAs/GaAsP superlattice photocathode described in ref. 15, which represents the basis for polarization and QE comparison. See

ref. 15 for a complete description of the design criteria and optimization of this photocathode structure. A schematic layout of the strained GaAs/GaAsP superlattice photocathodes with and without DBR structure is shown in Figure 1.

GaAs	5 nm	$p=5 \cdot 10^{19} \text{ cm}^{-3}$	GaAs	5 nm	$p=5 \cdot 10^{19} \text{ cm}^{-3}$
GaAs/GaAsP SL	(3.8/2.8 nm) $\times 14$	$p=5 \cdot 10^{17} \text{ cm}^{-3}$	GaAs/GaAsP SL	(3.8/2.8 nm) $\times 14$	$p=5 \cdot 10^{17} \text{ cm}^{-3}$
GaAsP _{0.35}	2750 nm	$p=5 \cdot 10^{18} \text{ cm}^{-3}$	GaAsP _{0.35}	750 nm	$p=5 \cdot 10^{18} \text{ cm}^{-3}$
			GaAsP _{0.35} /AlAsP _{0.4} DBR	(54/64 nm) $\times 12$	$p=5 \cdot 10^{18} \text{ cm}^{-3}$
			GaAsP _{0.35}	2000 nm	$p=5 \cdot 10^{18} \text{ cm}^{-3}$
Graded GaAsP _x ($x = 0 \sim 0.35$)	5000 nm	$p=5 \cdot 10^{18} \text{ cm}^{-3}$	Graded GaAsP _x ($x = 0 \sim 0.35$)	5000 nm	$p=5 \cdot 10^{18} \text{ cm}^{-3}$
GaAs buffer	200 nm	$p=2 \cdot 10^{18} \text{ cm}^{-3}$	GaAs buffer	200 nm	$p=2 \cdot 10^{18} \text{ cm}^{-3}$
p-GaAs substrate ($p > 10^{18} \text{ cm}^{-3}$)			p-GaAs substrate ($p > 10^{18} \text{ cm}^{-3}$)		

FIG. 1. Schematic structure of the photocathodes: without DBR (left) and with DBR (right).

The DBR is composed of multiple layers of alternating high and low index of refraction. A natural choice for high index of refraction layer was GaAsP which provides a good lattice match to the graded buffer layer. Though a challenge for growth, we chose AlAs_{1-y}P_y for the low index of refraction layer for maximum refractive index contrast and minimum DBR thickness. The thickness of each layer follows the quarter wavelength condition:²⁴ $n_H(\lambda_{DBR})d_H = \frac{\lambda_{DBR}}{4} = n_L(\lambda_{DBR})d_L$. The bandwidth for which the DBR exhibits high reflectivity is given by the formula:

$$\Delta\lambda_{DBR} = \frac{4\lambda_{DBR}}{\pi} \sin^{-1} \left(\frac{n_H(\lambda_{DBR}) - n_L(\lambda_{DBR})}{n_H(\lambda_{DBR}) + n_L(\lambda_{DBR})} \right) \quad (1)$$

The Fabry-Perot cavity is formed by the vacuum/GaAs cap layer interface and the DBR. Proper thickness of a GaAsP spacer layer between GaAs/GaAsP superlattice and the DBR ensures the maximum absorption in superlattice active layer coincide with the central reflective wavelength of the DBR. To design the structure, the refractive index of these layers can be estimated using the simplified interband transition model as a function of photon energy²⁸:

$$n(E)^2 = A \left[f(X_0) + \frac{1}{2} \left(\frac{E_0}{E_0 + \Delta_0} \right)^{\frac{3}{2}} f(X_{so}) \right] + B \quad (2)$$

with $f(X) = X^{-2}(2 - \sqrt{1+X} - \sqrt{1-X})$, $X_0 = \frac{E}{E_0}$, and $X_{so} = \frac{E}{E_0 + \Delta_0}$. Here, A represents the strength parameter of the $E/(E_0 + \Delta_0)$ terms and B represents the nondispersive contribution arising from the higher-lying band gap terms ($E_1, E_1 + \Delta_1, E_2, \text{etc.}$) for each layer. The quantities E_0 and Δ_0 are the band-gap energy and spin-orbit splitting, respectively, given by Vegard's Law for $GaAs_{1-x}P_x$ ^{29,30}.

The desired wavelength of peak reflectivity was $\lambda_{DBR} \sim 780$ nm, compatible with CEBAF drive lasers. Setting the phosphorus fractions in the $\text{GaAs}_{1-x}\text{P}_x$ and $\text{AlAs}_{1-y}\text{P}_y$ layers to 0.35 and 0.4, respectively, provided refractive indices of $n_H(780\text{nm}) = 3.4506$ and $n_L(780\text{nm}) = 2.9443$. From these parameters, the design values for the thickness of the $\text{GaAsP}_{0.35}$ and $\text{AlAsP}_{0.4}$ layers were 56.5 nm and 66.5 nm, respectively. Actual layer thicknesses were very close to these design values, 54 nm and 64 nm, which set the wavelength of peak reflectivity to λ_{DBR} of 755 nm, and the reflectivity bandwidth $\Delta\lambda_{DBR} \sim 79$ nm. This implies the DBR can achieve a high reflectivity $> 90\%$ for wavelengths between 715 and 795 nm.

The transfer matrix method^{32,33} was used to calculate the reflection, transmission and absorption of incident light through the complete multilayer thin-film structure including the GaAs substrate. Calculated values of surface reflectivity (R), transmittance (T) into the GaAs substrate, absorption (A), and the absorption enhancement factor as a function of wavelength, are shown in Figure 2. There are two resonant absorption peaks within the optical cavity for the DBR photocathode at wavelengths 726 nm and 776 nm. Absorption by the substrate is not plotted as this process does not contribute to the polarized electron emission. The resonant peak at 776 nm is just 4 nm from the desired value 780 nm. At 776 nm, the absorption is 21.03%, surface reflectivity is 50.14%, and transmittance into GaAs substrate is 28.83% for the DBR photocathode, corresponding to maximum electron spin polarization. The full-width half-maximum of the Fabry-Perot resonance is about 10 nm at 776nm. The absorption enhancement factor is 7.4 at this wavelength.

To estimate the quantum efficiency of photocathode, one can solve the one-dimensional diffusion equations, based on Spicer's three-step model:^{34,35}

$$QE(\lambda) = \frac{P_L F_L A}{1 + \frac{1}{\alpha_\lambda L_L}} + \frac{P_\Gamma \exp[k(-\frac{1}{1.42} - \frac{\lambda}{1240})] A}{1 + \frac{1}{\alpha_\lambda L_\Gamma}} \left[F_\Gamma + \frac{F_L L_\Gamma}{\alpha_\lambda F_L (L_\Gamma + L_L) (1 + \frac{1}{\alpha_\lambda L_L})} \right] \quad (3)$$

where P_Γ and P_L are the surface electron escape probabilities for the Γ and L minima, respectively, which are independent of the incident photon energy, F_Γ is the remaining fraction of excited electrons, F_L is the fraction of electrons that is excited to energies greater than the L minima, A is the absorption of photocathode, L_Γ and L_L are the electron diffusion length for the Γ and L minima, respectively, α_λ is the absorption coefficient of the photocathode, and k is a coefficient ($k \geq 0$). The calculated QE for the DBR photocathode, together with the QE enhancement factor as a function of wavelength, are shown in Figure 2.

Fig. 2. Calculated values of absorption, reflectivity and transmittance of the DBR photocathode, as a function of wavelength. Also shown, calculated QE and the QE enhancement factor compared to the photocathode without the DBR.

All photocathodes were grown in a solid-source molecular beam epitaxy (SSMBE) system equipped with As and P crackers on a (100) p-type GaAs substrate, upon which a 200 nm Be-doped ($2 \times 10^{18} \text{ cm}^{-3}$) GaAs buffer layer was deposited. The 5- μm -thick Be-doped graded GaAsP_x layer was then grown with an increasing P composition from $x=0$ to 0.35, followed by a 2- μm -thick GaAs_{0.65}P_{0.35} layer, in order to produce a strain-relaxed GaAs_{0.65}P_{0.35} layer compatible with the superlattice active layer. The DBR structure consisting of 12-pair of GaAs_{0.65}P_{0.35} (54 nm)/AlAs_{0.6}P_{0.4} (64 nm) was subsequently grown on top of this layer. In order to create an effective Fabry-Perot resonant cavity for the desired wavelength near 780nm, a 750-nm-thick GaAs_{0.65}P_{0.35} layer was grown on top of DBR acting as a spacer. Both GaAs_{0.65}P_{0.35} and DBR layers were Be-doped at $5 \times 10^{18} \text{ cm}^{-3}$ to promote high electrical conductivity. The p-type ($5 \times 10^{17} \text{ cm}^{-3}$) GaAs (3.8 nm)/GaAs_{0.65}P_{0.35} (2.8 nm) superlattice layer was positioned between the GaAs_{0.65}P_{0.35} spacer and the 5-nm-thick GaAs cap layer doped at $p=5 \times 10^{19} \text{ cm}^{-3}$. The only difference between the DBR photocathode and the non-DBR photocathode was the 12-pairs of GaAs_{0.65}P_{0.35} (54 nm)/AlAs_{0.6}P_{0.4} (64 nm) layers.

The growth of GaAs_{0.65}P_{0.35}/AlAs_{0.6}P_{0.4} DBR structure was very challenging due to the large differences in growth temperatures and the V/III flux ratios for the GaAs_{0.65}P_{0.35} and AlAs_{0.6}P_{0.4} layers. The optimal growth temperatures for GaAs_{0.65}P_{0.35} and AlAs_{0.6}P_{0.4} were 660-700 °C and 700-750 °C, respectively, as determined by surface temperature measurement and reflective high energy electron diffraction (RHEED) images during MBE growth. Thicknesses and composition were verified using x-ray diffraction measurements and x-ray simulation models. It was very difficult to accurately control the growth rate of GaAs_{0.65}P_{0.35} at high temperatures, especially approaching 700 °C, because the re-evaporation rate of Ga atoms from the sample surface increases rapidly with increasing growth temperatures above 660 °C, resulting in inconsistent control of the layer thickness. Additionally, maintaining the As/P fraction in GaAs_{0.65}P_{0.35} layers is difficult when grown below 650 °C, as the As/P fraction is very sensitive at low growth temperatures.^{36, 37} For these reasons the thick graded composition GaAsP was grown at 660 °C. However, the material quality of AlAs_{0.6}P_{0.4} layer was poor when grown at this temperature. Therefore, the

growth temperature of GaAs_{0.65}P_{0.35}/AlAs_{0.6}P_{0.4} DBR had to be kept at 700 °C as measured by an SVT AccuTemp process monitor using a two-color infrared pyrometer. The large difference in V/III flux ratio during the growth between GaAs_{0.65}P_{0.35} and AlAs_{0.6}P_{0.4} added extra difficulty to achieving high quality DBR layers. The V/III ratio for GaAs_{0.65}P_{0.35} is around 50, whereas the ratio is only around 3 for AlAs_{0.6}P_{0.4}. Numerous growth-calibration and material-characterization runs were required to develop suitable substrate temperature and source-switching recipes to enable the fabrication of high quality GaAs_{0.65}P_{0.35}/AlAs_{0.6}P_{0.4} DBR and strained-superlattice structures grown by SSMBE.

Photocathode samples were evaluated using a low-voltage retarding-field Mott polarmeter³⁸. Samples were attached to sample holders and installed within the vacuum chamber which was baked at 250 °C for 36 hours, and allowed to cool to room temperature. Photocathodes were then heated to 480 °C to remove the As cap and cooled to room temperature under typical vacuum pressure $\sim 10^{-11}$ Torr. A negative electron affinity condition was obtained using the standard yo-yo activation procedure with cesium and NF₃.³⁹ A broadly tunable super-continuum laser (NKT Photonics, SuperK) provided milli-Watts of output power over the wavelength range from 400 to 800 nm. Optical waveplates (quarter and halfwave) were used to generate left and right circularly polarized light required to obtain spin polarized electrons.

Measured values of QE and polarization as a function of wavelength, for photocathodes with and without DBR, are shown in Figure 3a. For the non-DBR photocathode, results are consistent with past work¹⁵ indicating peak polarization of 90% and QE of 0.89% at a wavelength ~ 780 nm. In stark contrast, the QE of the DBR photocathode shows the telltale prominent oscillatory behavior indicative of resonant absorption. Measured reflectivity and QE enhancement (i.e., the ratio of QE values of photocathodes with and without DBR) are shown in Figure 3b. The two dips in the reflectivity spectrum are clearly correlated with wavelength locations of QE maxima. At the wavelength of interest, 776 nm, the QE was 6.4% and polarization $\sim 84\%$. The measured QE enhancement of ~ 7.2 is very close to the predicted value of ~ 7.4 . It should be noted that QE enhancement is a somewhat arbitrary metric dependent on when measurements were made following photocathode activation and subject to non-trivial variations in QE associated with vacuum conditions that influence photocathode lifetime.

Fig. 3. (a) The QE and electron-spin polarization (ESP) for the strained GaAs/GaAsP superlattice photocathodes with and without DBR as a function of the wavelength; (b) Reflectivity and QE enhancement factor of DBR photocathode as a function of the wavelength. The dash line indicates the resonant position.

These results are compared to results from other photocathodes listed in Table 1, showing QE, polarization and photocathode Figure of Merit (P^2QE). The Figure of Merit of our photocathode is a factor of four higher than the last highest value. In conclusion, a QE of 6.4% is the highest reported value of any “high polarization” photocathode. Precise control of the thickness of each layer and the composition of each constituent led to these improved results. Further optimization should lead to even higher QE, and polarization values approaching the best values from superlattice photocathodes without DBR structures.

Table 1. Figure of merit for polarized electron sources.

Cathode	Ref.	P (%)	QE (%)	Figure of Merit (P^2QE)
GaAs/GaAsP _{0.36} (no DBR)	SLAC/SVT ¹⁵	86	1.2	0.89
GaAs/GaAsP _{0.38} (no DBR)	Nagoya ²⁰	92	1.6	1.35
Al _{0.19} In _{0.2} GaAs/Al _{0.4} GaAs (with DBR)	St. Petersburg ¹⁸	92	0.85	0.72
GaAs/GaAsP _{0.35} (with DBR)	JLab/SVT	84	6.4	4.52

Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes. SVT Associates was funded by the U. S. DOE’s Office of Nuclear

Physics SBIR program DE-SC0009516. W. Liu is currently conducting research at Jefferson Lab toward a PhD degree.

- ¹ H. Montgomery, “Jefferson Lab: A Long Decade of Physics”, J. Phys.: Conf. Ser. 299 (2011) 011001
- ² D. T. Pierce, and F. Meier, “Photoemission of spin-polarized electrons from GaAs”, Phys. Rev. B 13, 5484 (1976)
- ³ 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 the strained GaAs layer” Phys. Lett. A 158, 345 (1991)
- ⁴ T. Maruyama, E. L. Garwin, R. Prepost, G. H. Zapalac, J. S. Smith, and J. D. Walker, “Observation of strain-enhanced electron-spin polarization in photoemission from InGaAs”, Phys. Rev. Lett. 66, 2376 (1991)
- ⁵ Bandwidth Semiconductor, LLC, 25 Sagamore Park Drive, Hudson, NH 03051, <http://www.bandwidthsemi.com>
- ⁶ T. Maruyama, E. L. Garwin, R. Prepost, and G. H. Zapalac, “Electron-spin polarization in photoemission from strained GaAs Grown on GaAs_{1-x}P_x”, Phys. Rev. B 46, 4261 (1992)
- ⁷ K. Aulenbacher, Ch. Nachtigall, H. G. Andresen, J. Bermuth, Th. Dombo, P. Drescher, H. Euteneuer, H. Fischer, D. v. Harrach, P. Hartmann, *et al.*, “The MAMI source of polarized electrons”, *Nucl. Instrum. Meth. A*, vol. 391, pp. 498-506, June 1997.
- ⁸ G. D. Cates, V. W. Hughes, R. Michaels, H. R. Schaefer, T. J. Gay, M. S. Lubell, R. Wilson, G.W. Dodson, K. A. Dow, S. B. Kowalski, *et al.*, “The Bates polarized electron source”, *Nucl. Instrum. Meth. A*, vol. 278, pp. 293-317, June 1989.
- ⁹ E. Tsentalovich, D. Barkhuff, J. Chen, G. Dodson, M. Farkhondeh, W. Franklin, E. Ihloff, F. Kaertner, C. Tschalaer, B. Yang, T. Zwart, “Development of a polarized electron source for the MIT-Bates Linear Accelerator Center, *Nucl. Instrum. Meth. A* 582, 413-428 (2007)
- ¹⁰ M. J. J. van den Putte, C. W. De Jager, S. G. Konstantinov, V. Ya. Korchagin, F. B. Kroes, E. P. vanLeeuwen, B. L. Milityn, N. H. Papadakis, S. G. Popov, G. V. Serdobintsev, *et al.*, “The polarized electron source at NIKHEF”, in AIP Conf. Proc., vol. 421, 1997, pp. 260-269.
- ¹¹ W. Hillert, M. Govin, and B. Neff, “The 50 keV inverted source of polarized electrons at ELSA”, in AIP Conf. Proc., vol. 570, 2000, pp. 961-964.
- ¹² 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*, vol. 10, pp. 023501-1–023501-21, February 2007.
- ¹³ R. Alley, H. Aoyagi, J. Clendenin, J. Frisch, C. Garden, E. Hoyt, R. Kirby, L. Klaisner, A. Kulikov, R. Miller, *et al.*, “The Stanford linear accelerator polarized electron source”, *Nucl. Instrum. Meth. A*, vol. 365, pp. 1-27, November 1995.

- ¹⁴ T. Omori, Y. Kurihara, Y. Takeuchi, M. Yoshioka, T. Nakanishi, S. Okumi, M. Tsubata, M. Tawada, K. Togawa, Y. Tanimoto, C. Takahashi, T. Baba, and M. Mizuta, “Highly polarized electron source using InGaAs-GaAs strained-layer superlattice”, *Jpn. J. Appl. Phys.* 33, 5676 (1994)
- ¹⁵ 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)
- ¹⁶ <http://www.svta.com/>
- ¹⁷ A. V. Subashiev, L. G. Gerchikov, Y. A. Mamaev, Y. P. Yashin, J. S. Roberts, D.-A. Luh, T. Maruyama, and J. E. Clendenin, “Strain-compensated AlInGaAs-GaAsP superlattices for highly polarized electron emission”, *Appl. Phys. Lett.* 86, 171911 (2005)
- ¹⁸ Yu. A. Mamaev, L. G. Gerchikov, Yu. 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)
- ¹⁹ 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)
- ²⁰ X. Jin, B. Ozdol, M. Yamamoto, A. Mano, N. Yamamoto, and Y. Takeda, “Effect of crystal quality on performance of spin-polarized photocathode”, *Appl. Phys. Lett.* 105, 203509 (2014)
- ²¹ E. C. Aschenauer, M. D. Baker, A. Bazilevsky, K. Boyle, S. Belomestnykh, I. Ben-Zvi, S. Brooks, C. Brutus, T. Burton, S. Fazio, et al., “eRHIC design study: An electron-ion collider at BNL”, arXiv: 1409. 1633
- ²² Wei Liu, Shukui Zhang, Marcy Stutzman, and Matt Poelker, “The effects of ion bombardment on bulk GaAs photocathodes with different surface-cleavage planes”, *Phys. Rev. Accel. Beam* 19, 103402 (2016)
- ²³ S. Zhang, S. V. Benson, and C. H-Garcia, “Observation and measurement of temperature rise and distribution on GaAs photo-cathode wafer with a 532 nm drive laser and a thermal imaging camera”, *Nucl. Instrum. Meth. A.* 631, 22 (2011)
- ²⁴ T. Saka, T. Kato, T. Nakanishi, M. Tsubata, K. Kishino, H. Horinaka, Y. Kamiya, S. Okumi, C. Takahashi, Y. Tanimoto, et al., “New-type photocathode for polarized electron source with Distributed Bragg Reflector”, *Jpn. J. Appl. Phys.* 32, 1837 (1993)
- ²⁵ J. C. Grobli, D. Oberli, and F. Meier, “Polarization resonances of optically spin-oriented photoelectrons emitted from strained semiconductor photocathodes”, *Phys. Rev. Lett.* 74, 2106 (1995)
- ²⁶ L. G. Gerchikov, K. Aulenbacher, J. E. Clendenin, V. V. Kuz'michev, Y. A. Mamaev, T. Maruyama, V. S. Mikhlin, J. S. Roberts, V. M. Ustinov, D. A. Vasilev, A. P. Vasiliev, Y. P. Yashin, and A. E. Zhukov, “Highly Effective Polarized Electron Sources Based on Strained Semiconductor Superlattice with Distributed Bragg Reflector”, *AIP Conf. Proc.* 980, 124 (2008)

- ²⁷ S. Zhang, M. L. Stutzman, M. Poelker, Y. Chen, and Aaron Moy, "Observation of significant quantum efficiency enhancement from a polarized photocathode with distributed bragg reflector", Proceedings of IPAC2015, Richmond, USA (2015)
- ²⁸ S. Adachi, "Properties of semiconductor alloys: group-IV, III-V and II-VI Semiconductors", (Wiley, 2009) P.238
- ²⁹ M. Levinshtein, S. Rumyantsev, M. Shur, "Handbook series on semiconductor parameters", (World Scientific, 1996)
- ³⁰ 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)
- ³¹ D. E. Aspnes, S. M. Kelso, R. A. Logan, and R. Bhat, "Optical properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ", J. Appl. Phys. 60, 754 (1986)
- ³² H. A. Macleod, "Thin-film optical filters", 4th edition, (CRC Press, 2010)
- ³³ P. Peumans, A. Yakimov, and S. R. Forrest, "Small molecular weight organic thin-film photodetectors and solar cells", J. Appl. Phys. 93, 3693 (2003)
- ³⁴ J. Zou, B. Chang, H. Chen, and L. Liu, "Variation of quantum-yield curves for GaAs photocathodes under illumination", J. Appl. Phys. 101, 033126 (2007)
- ³⁵ J. Zou, B. Chang, Z. Yang, Y. Zhang, and J. Qiao, "Evolution of surface potential barrier for negative-electron-affinity GaAs photocathodes", J. Appl. Phys. 105, 013714 (2009)
- ³⁶ B.W. Liang and C.W. Tu, "A kinetic model for As and P incorporation behaviors in GaAsP grown by gas-source molecular beam epitaxy" J. Appl. Phys. 74, 255 (1993)
- ³⁷ Stephanie Tomasulo, John Simon, Paul J. Simmonds, Jonathan Biagiotti, and Minjoo L. Lee, "Molecular beam epitaxy of metamorphic $\text{In}_y\text{Ga}_{1-y}\text{P}$ solar cells on mixed anion $\text{GaAs}_x\text{P}_{1-x}/\text{GaAs}$ graded buffers" J. Vac. Sci. Technol. B 29, 03C118 (2011)
- ³⁸ J.L. McCarter, M.L. Stutzman, K.W. Trantham, Timothy G. Anderson, A.M. Cook, and Timothy J. Gay, "A low-voltage retarding-field Mott polarimeter for photocathode characterization" Nucl. Instr. and Meth. A 618, 30 (2010)
- ³⁹ R. L. Bell, Negative electron affinity devices, (Clarendon, Oxford, England, 1973)