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Nuclear Instruments and Methods in Physics Research A 557 (2006) 124–130
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Photocathodes for the energy recovery linacs

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Available online 22 November 2005

Abstract

This paper presents an overview of existing and emerging technologies on electron sources that can service various energy recovering linacs under consideration. Photocathodes that can deliver average currents from 1 mA to 1 A, the pros and cons associated with these cathodes are addressed. Status of emerging technologies such as secondary emitters, cesiated dispenser cathodes, field and photon assisted field emitters and super lattice photocathodes are also reviewed.

PACS: 07.77.K; 41.60.Cr; 41.75.H; 85.60.H

Keywords: Energy recovery; Recirculating linacs; Free electron lasers; Photocathodes; Relativistic and non-relativistic electron beams

1. Introduction

In the past few years, there has been considerable interest in using an energy recovery linac (ERL) for future light sources and high-energy nuclear physics. The electron beam requirements of the ERLs under consideration span a wide range in parameters such as current, current density, frequency, operating temperatures, accelerating gradients etc. The design of the injector, whether it is normal conducting or superconducting, DC or RF, average current, temporal profile of the electron bunch all play a key role in the choice of the photocathode. In this paper, we attempt to provide an overview of the available cathode materials, the pros and cons associated with each and the electron beam parameters they can provide.

2. Metal photocathodes

Metal photocathodes have been used routinely in normal conducting injectors operating at room temperature [1,2]. The prompt time response of these cathodes renders them suitable for applications where very short electron bunches and/or complicated temporal profile are required. Their relative insensitivity to contamination makes their preparation, handling and usage very simple, in addition to reducing the vacuum requirements and increasing their operational lifetime. Mg and copper photocathodes have been used for years before requiring replacement. The high work function associated with the metal photocathode is an advantage as well as a deterrent. The high work function allows them to be operated in the presence of very high accelerating gradients with very little dark current [3]. However, in order to overcome this high work function, the photon energy must also be high, requiring the use of UV laser for driving these cathodes. Consequently, the QE of the metal photocathodes are very low efficiency.

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doi:10.1016/j.nima.2005.10.112

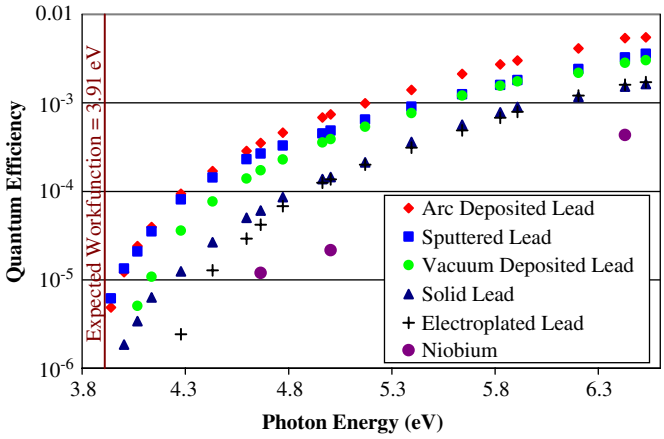

Fig. 1. Dependence of QE on photon energy for different lead samples.

Mg cathodes have delivered routinely QE of 5×10^{-4} [1,4] at 266 nm after laser cleaning. Fig. 1 shows recent measurements of a number of lead deposited on Nb where QE exceeding 0.2% has been obtained for wavelengths shorter than 213 nm. With the availability of commercial laser systems delivering a few watts at these wavelengths, these are suitable candidates for ERLs operating at high accelerating gradients, requiring short electron bunches of ~1 mA average current. Mg can be used in normal conducting injectors while lead coated Nb in superconducting injector without significant degradation of RF performance [5].

3. Cs_2Te photocathodes

Cs_2Te photocathodes with ~10% QE at 266 nm have been fabricated successfully for injector applications [6]. The QE of these cathodes under different operating conditions have been measured and shown in Fig. 2 [7]. This photocathode has high QE in the UV, has prompt response in the bunch lengths of interest. This cathode has been tested in normal conducting RF injector at high accelerating gradients, delivering charges in excess of 4 nC/pulse [8]. One of the major limitations of this material is, as in metal photocathode, its high work function and consequent UV photon requirement. Another limitation is its sensitivity to contaminants. As can be seen in Fig. 2, under normal operating conditions, the QE decays quickly from 12% to 3% in 50 h followed by slow decay over a few days. In addition, this sensitivity mandates the cathode be maintained at ultrahigh vacuum conditions from fabrication to usage, necessitating a load lock system for cathode transfer. Improvement in QE as well as life time has been seen when Cs and Te were co deposited onto the substrate [7]. With the availability of commercial laser systems delivering a few watts at UV wavelengths, this cathode will be suitable for ERLs requiring tens of mA average current. Cs_2Te has been tested in a superconducting RF injector [9]; however, the results are inconclusive since the cause of degradation of the RF performance is uncertain.

4. Cs:GaAs photocathodes

Cesiated GaAs cathodes have been used extensively in DC electron injectors and injectors for polarized electrons. The performance characteristics of the cathode depend on whether the electrons need to be polarized or not. Hence these two applications will be discussed separately.

4.1. Polarized electrons

In typical GaAs photocathodes used to generate polarized electron beams, a thin (~0.3 μm) GaAs is grown on a thick (2.5 μm) GaAsP. The lattice mismatch causes the degeneracy in the P3/2 top valence band to be lifted. When excited by circularly polarized resonant photons, the electrons emitted from any one of these levels would have preferred spin polarization. The QE can be enhanced by cesiating the cathode vacuum interface to produce NEA surface. Since the active layer is thinner than the absorption depth of the photon, these photocathodes typically have less QE compared to those used for nonpolarized electron beams. However, the advantage of the thinner layer is more prompt response of the electrons to the incident photons. Fig. 3 illustrates the QE and percentage of polarization of Cs:GaAs as a function of wavelength.

Fig. 4 shows the lifetime of the cathode. QE of 1% and charge of ~1 nC [10] and 80% polarization [11] have been obtained from these cathodes when irradiated with ~850 nm laser beam. The accelerating field in these measurements was 4 MV/m and the charge limit was inherent to the cathode rather than the space charge effect. The points in favor of using this cathode are: at present, cesiated, strained semiconductor material such as GaAs and InGaAsP [12,13] are the only candidates in the horizon for making polarized electrons. They operate in the near infrared where laser systems with a few watts of average power are commercially available. Since they operate near resonance, the energy distribution of the emitted electrons is very narrow, leading to low thermal emittance. However, issues related to sensitivity to contamination and related short life time, long trailing edge of the electron bunch as well as the maximum extractable charge need to be considered in the context of the application.

4.2. Non-polarized electrons

When polarized electrons are not needed, the thickness of the cathode can be increased to match the absorption depth of the photon energy, thereby increasing the QE. Cathodes with QE as high as 10% at 532 nm have been fabricated and cathodes with QE of 2–6% are routinely used in DC injectors. The small energy spread of the emitted electrons results in low thermal emittance from

QE = f (t)	QE1 %	τ1 (h)	QE2 %	τ2 (h)
Transport carrier	3.85	18.9	9.17	3311
DC gun	2.24	65.9	12.74	779.5
RF gun	9.2	14	3.4	315

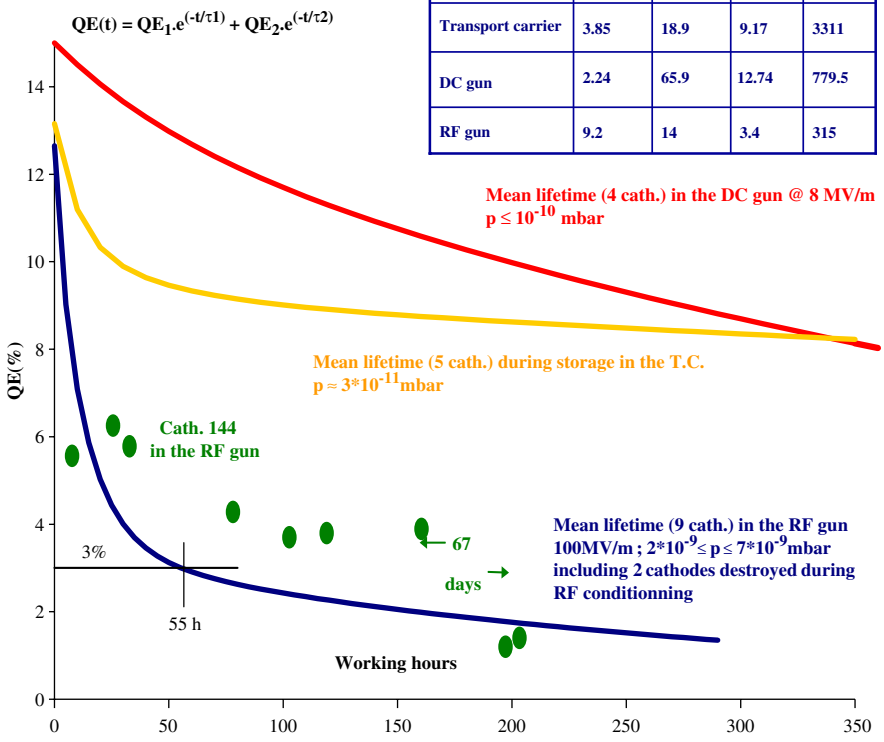

Fig. 2. Performance of Cs_2Te under different operating conditions.

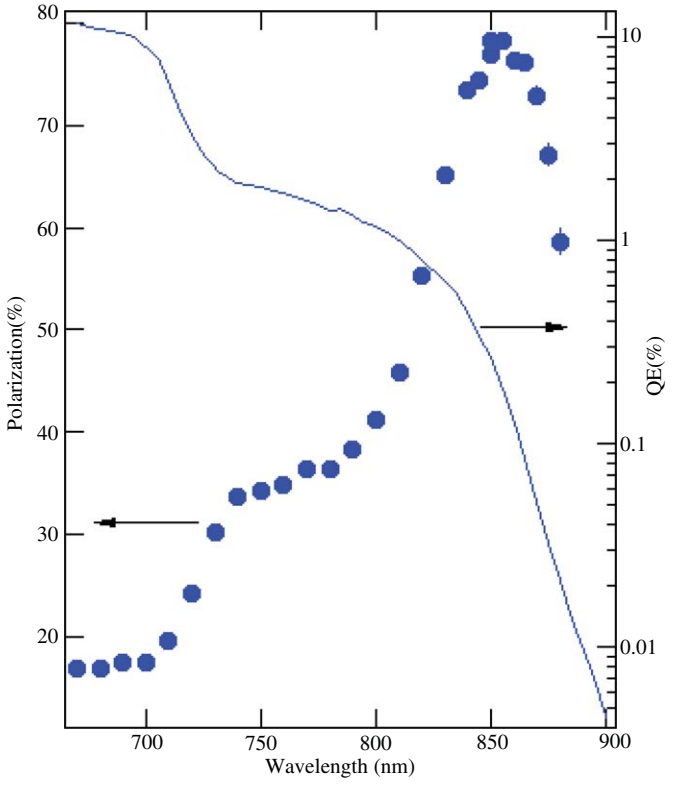

Fig. 3. QE and polarization of Cs:GaAS as a function of wavelength.

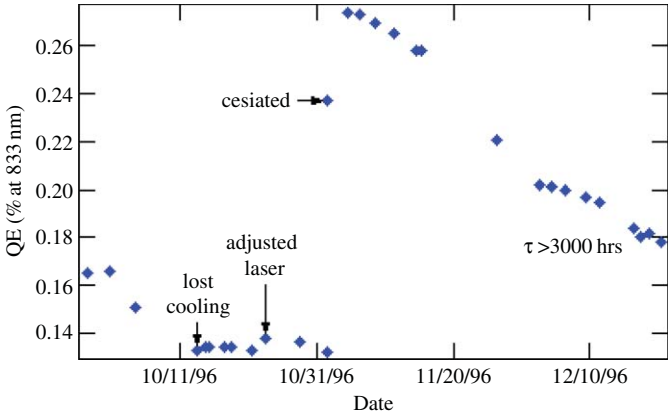

Fig. 4. Lifetime of GaAs photocathode with and without cesiation.

these cathodes. Although these cathodes are sensitive to contamination and ion back bombardment in these injectors, by maintaining better than 10–11 Torr vacuum near the cathode and by recesiating the cathode, the lifetime of the wafers have been extended significantly. The maximum deliverable charge between recesiation has also been increased to 500C [14].

When this cathode is irradiated by short laser pulses, the long transport distance of the electrons inside the cathode result in electron bunches with asymmetric temporal shape

with longer trailing edge. Generation of electron beams with bunch lengths <20 ps and temporal pulse shaping are difficult under these conditions. Neither of the GaAs cathodes has been tested in the RF injectors. Performance these cathodes in the high accelerating fields encountered in the RF injectors is yet to be determined. In addition, the conductivity of these semiconductors could be affected significantly at cryogenic temperatures. Hence, their operation in SRF injectors also need to investigated. The maximum charge of 500C extracted between recesiation implies that for average currents of 100 mA, the cathode needs to be recesiated nearly every hour. With the present technology, this cathode material is suitable for applications requiring average currents of <100 mA and pulse durations >20 ps.

5. K_2CsSb photocathode

Cesium potassium antimonide cathodes have been used extensively in photomultiplier applications. This material on a stainless steel substrate has been tested in a high average current, normal conducting injector operating at 433 MHz. As shown in Fig. 5, QE $>10\%$ at 532 nm has been routinely obtained. This injector has delivered >5 nC per pulse, and 25 mA at 25% duty factor [15]. It has been shown both the QE and the uniformity of emission can be increased by using 350 nm instead of 532 nm. Controlled exposure of this cathode to oxygen or water vapor also improves the electron yield. QE of K_2CsSb cathode, evaporated on metal substrate has been tested to be nearly constant to $-80\,^{\circ}C$ [16]. The response time of K_2CsSb is expected to be prompt based on its use as the cathode material in fast streak cameras (Fig. 6).

Lifetime of this cathode is also affected significantly by the presence of contaminants. The lifetime of $>10{,}000$ h in the UHV fabrication chamber had dropped to 20 h in the HV environment in the normal conducting RF injector [15]. However, no inherent charge limitation has been observed so far. With the existing laser technology, this cathode can be used in applications where short electron bunches with average currents of 1 A are required.

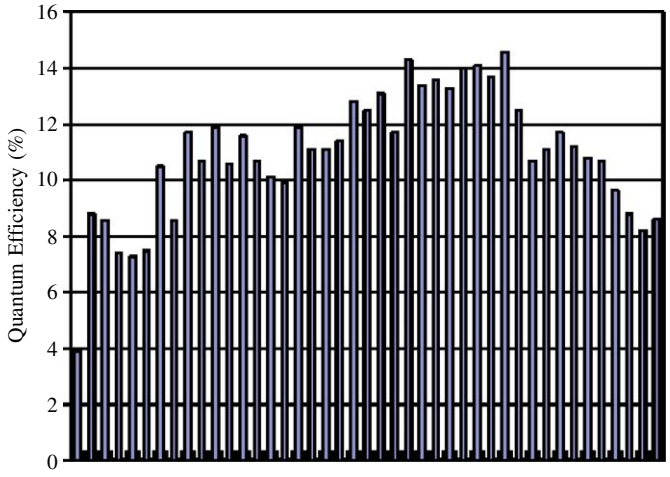

Fig. 5. QE of different K_2CsSb samples prepared for 433 MHz injector.

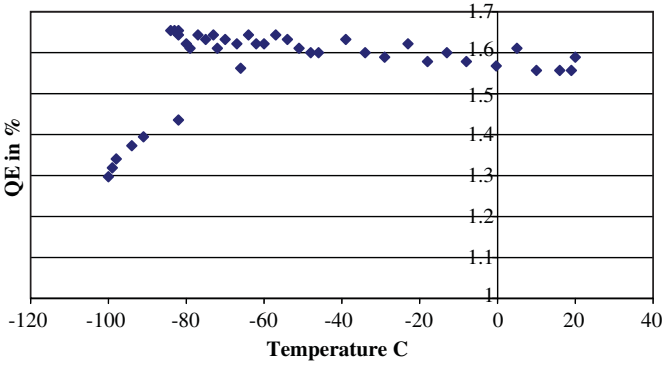

Fig. 6. QE of K_2CsSb as a function of temperature.

6. Improving the lifetime

As can be seen from the previous sections, all the high QE photocathodes suffer from short lifetime, either due to sensitivity to contaminants, ion bombardment or both. Several approaches in the fabrication process, post processing and in handling, are being currently investigated.

6.1. Fabrication process

Sen et al. [17] have observed that the cesium level that optimizes the QE is not necessarily the same level that optimizes the lifetime. By overcesiating the surface during fabrication, the lifetime has been extended from 2 h to over 3 days in a 10^{-10} vacuum system. This improvement is attributed to the slow migration of Cs from the non-irradiated, Cs rich sites to the Cs depleted emission sites.

Both the lifetime and the QE of Cs_2Te have been improved by co-deposition of Cs and Te instead of sequential evaporation. In co-deposition, a stoichiometrically stable compound formed prior to deposition while sequential deposition relies on Cs migration to Te to form the stable compound, making it more sensitive to Cs depletion and contamination.

6.2. Protective cover

Evaporation of CsBr on Cs_2Te has been shown to improve the lifetime of this cathode.

A new technique has been proposed [18] that uses a thin diamond layer between the cathode and the injector isolating them from each other, preventing the contamination of both. In addition, diamond has been shown to be a very good secondary emitter that is capable of increasing the current from the cathode more than 100 fold. Fig. 7 shows the gain of transmitted secondary electrons, measured for a number of primary currents and primary electron energies as a function of the bias across a natural diamond sample. Fig. 8 shows the gain at 81 K. As can be

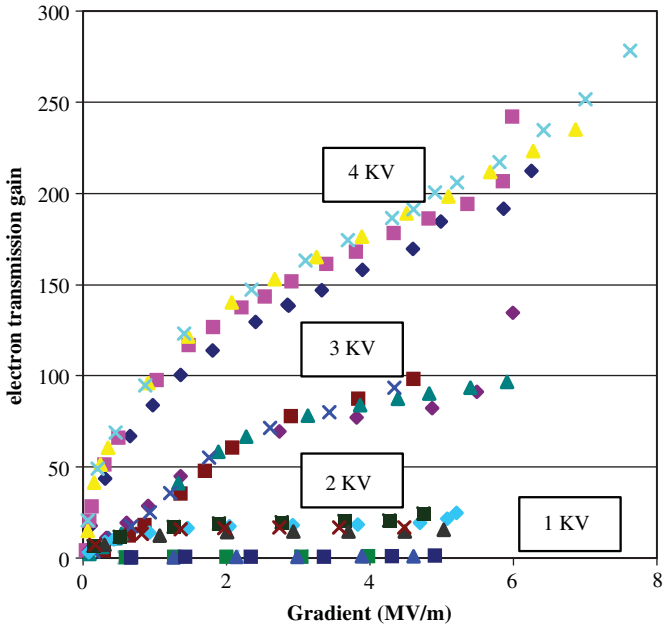

Fig. 7. Secondary electron yield for natural diamond, in transmission mode for different electron energies, and primary currents (◆—100 nA, ■—50 nA, ▲—20 nA and ×—10 nA) at room temperature. The electron energies are marked near each set of curves.

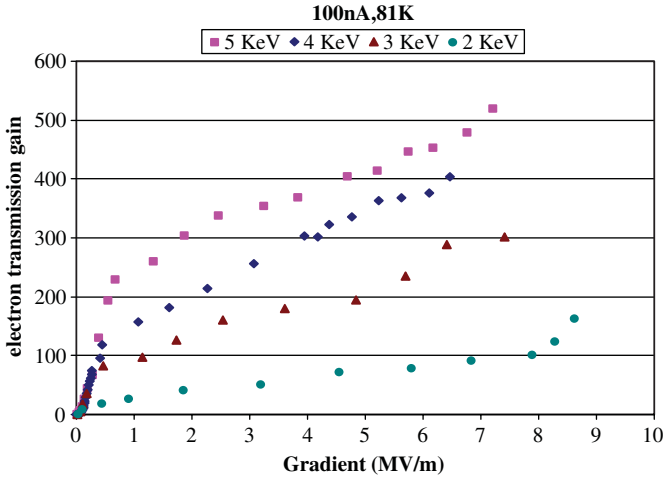

Fig. 8. Secondary electron yield for natural diamond, in transmission mode for 100 nA current with electron energies from 5 to 2 keV, at 81 K.

seen from Fig. 8, the secondary electron yield does not depend significantly on the temperature. With such large gains, the demand on the cathode and the laser system relax considerably. The high thermal conductivity and low electrical conductivity inherent to diamond as well as it's superior mechanical properties make this approach very appealing for high current applications [19]. Still significant amount of work is needed to fully understand the performance of diamond and realize its usefulness in this application.

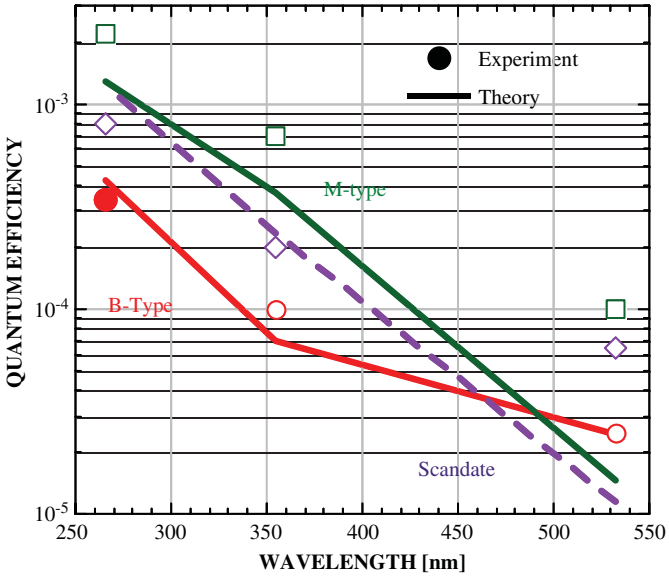

Fig. 9. QE of M, B type and scandate cathodes.

7. Emerging technologies

7.1. Dispenser cathodes

B and M type dispenser cathodes as well as scandate cathodes have been shown [20] to have QE exceeding that of metal photocathodes. Fig. 9 shows the measured electron yield of these cathodes. In situ heating of these cathodes replenishes the active medium, extending its lifetime. Performance of these cathodes in an injector environment has not yet been tested. The QE and lifetime measurements so far indicate that it could be an alternative to Cs_2Te cathode.

7.2. Group III nitride cathodes

Cesiated GaN cathodes have yielded QE of up to 50% in the reflection mode when irradiated with 312.6 nm radiation [21]. In addition, the Cs desorption measurements indicate that the Cs adhesion to GaN is superior to that of GaAs. InGaN cathodes have shown [22,23] high QE, as well as low energy spread for emitted electrons making this family of cathodes possible contenders for high current injectors. As in other cesiated cathodes, the presence of cesium makes these candidates also sensitive to contaminants.

7.3. Field and photo assisted field emitter arrays

Field emitter arrays of evaporated metal tips (Spindt tips) and carbon nanotubes (CNT) show promise as potential cold electron sources that can easily be modulated by the applied electric field. The Spindt type metal tips can emit at electric fields of 100 V/μm while the CNTs can emit at very low fields of 2–3 V/μm. Energy distribution

of the emitted electrons is <1 eV. CNT films of up to 9 mm lateral dimension can be manufactured using CVD techniques [24]. Presently, their performance is limited by the large variation in emitted current due to local statistical variations in Φ, E, electronic structure and transmission probability. However, with commercial applications such as flat panel display driving the technology, rapid progress is expected.

7.4. GaAs superlattice photocathode

A superlattice structure consists of semiconductors of well- and barrier-layer, thickness of which is less than 10 nm. By selecting appropriate semiconductor, band gap of a superlattice can be larger than that of bulk GaAs. Superlattice photocathodes has been developed as a polarized electron source with ~70% polarization [24]. Superlattice has the advantage of high QE and small initial emittance to realize a high-brightness electron source. The advantage can be explained using joint density of states (JDOS). JDOS around a band gap corresponds to QE spectrum depending on excitation energy [25]. Fig. 10 shows JDOS of a bulk GaAs and a superlattice derived by Kronig–Penny–Bastard model. JDOS of bulk GaAs is proportional to the square root of band-gap energy. Hence, we have only small QE when excitation photons energy is tuned to the band-gap energy for small initial emittance (point A), and emittance becomes large when excitation energy is tuned to higher energy for enlarging QE (point B). A superlattice, however, has larger JDOS around the band gap energy than that of bulk GaAs because of a steep edge of JDOS. In a superlattice photocathode, high QE and small emittance are available simultaneously by setting operation parameters at C as shown in Fig. 10. Plans to fabricate a superlattice photocathode at a DC-gun test bench [25], and compare the cathode properties, QE and emittance, with theoretical predictions are underway.

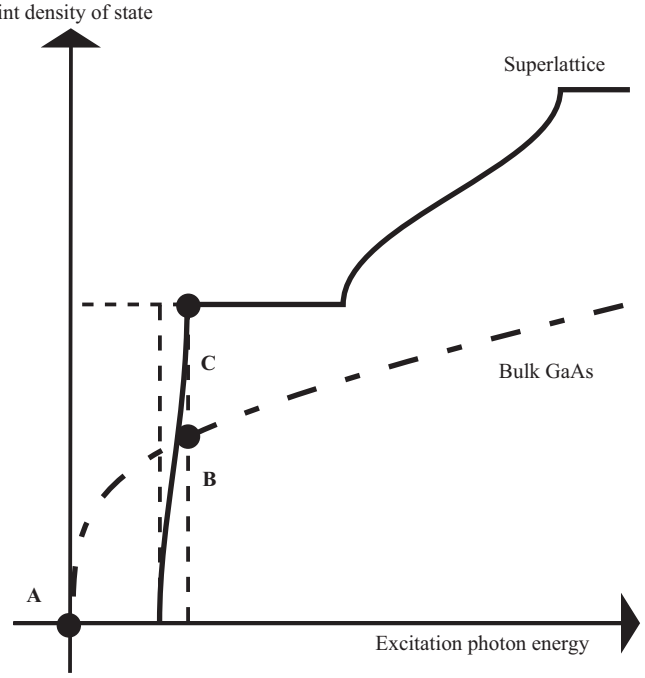

Fig. 10. Joint density of states of bulk GaAs and superlattice.

8. Conclusions

The choice of the photocathode is dictated by the requirements on the average current and the available laser. Reliable cathode and laser systems exist for average currents of ~10 mA. With a small improvement in both the cathode and the laser system, this can be increased to ~100 mA. Although with existing photocathode and laser technologies, >0.5 A can be generated, their application in operational ERLs are severely hampered by the limited lifetime of the cathodes. Significant effort is needed to address the issues related to the degradation of the cathode performance and to improve the lifetime of these cathodes at least by an order of magnitude.

Acknowledgements

This manuscript has been authored by Brookhaven Science Associates, LLC under Contract no. DE-AC02-98CH10886 with the U.S. Department of Energy. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges a world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for the United States Government purposes.

References

[1] X.J. Wang, T. Srinivasan-Rao, K. Batchelor, I. Ben-Zvi, J. Fischer, Nucl. Instr. and Meth. A 356 (1995) 159.
[2] M.E. Conde, et al., Proc. PAC 03, 2032, Portland, OR, May 2003.
[3] T. Srinivasan-Rao, J. Smedley, J. Schill, K. Batchelor, J.P. Farrell, Pres. Eighth Workshop on Advanced Accelerator Concepts, 6–11 July 1998, Baltimore, MD.
[4] T. Srinivasan-Rao, J. Fischer, T. Tsang, J. Appl. Phys. 69 (1991) 3291.
[5] J. Sekutowicz, et al., Phys. Rev. ST Accel. Beam. 8 (2005) 010701.
[6] D. Nguyen, Workshop on Photo-injector for Energy Recovery Linac, 22, 23 January 2001, BNL Report No. 52624.
[7] G. Suberlucq, Proceedings of EPAC 2004, Lucerne, Switzerland, 2004, p. 64.
[8] S. Schreiber, et al., Proceedings of EPAC 2004, Lucerne, Switzerland, 2004, p. 348.
[9] D. Janssen, et al., Nucl. Instr. and Meth. A 507 (2003) 314.
[10] Schultz, et al., Nucl. Instr. and Meth. A 340 (1994) 127.
[11] J. Clendenin, Nucl. Instr. and Meth. A 340 (1994) 1.
[12] SLAC-R-432 1993, Proceedings of the Workshop on Photocathodes for Polarized Electron Sources for Accelerators, http://www.slac.stanford.edu/grp/ad/source/.
[13] Bates Report 1999, MIT, pp. 9, 10, http://filburt.lns.mit.edu/pilot/news/report1999/sec4.pdf.
[14] C.H. Garcia, et al., Pres. PAC 2005, 16–20 May 2005, Knoxville, TN, USA.
[15] D. Dowell, Nucl. Instr. and Meth. A 356 (1995) 167.
[16] A. Burrill, et al., Pres. PAC 2005, 16–20 May 2005, Knoxville, TN, USA.

[17] P. Sen, et al., J. Vac. Sci. Technol. B 16 (1998) 3380.
[18] T. Rao, et al., Proceedings of AAC Workshop, AIP Conference Proceedings 737, V. Yakimenko (Ed.), June 2004, Stony Brook, p. 178.
[19] X. Chang, et al., Pres. PAC 2005, 16–20 May 2005, Knoxville, TN, USA.
[20] K.L. Jensen, et al., Appl. Phys. Lett. 85 (2004) 5448.
[21] F. Machuca, et al., J. Vac. Sci. Technol. B 18 (2000) 3042.
[22] F. Machuca, et al., J. Vac. Sci. Technol. B 22 (2004) 3565.
[23] P. Groning, et al., Adv. Eng. Mater. 5 (2003) 541.
[24] T. Nakanishi, et al., AIP Conf. Proc. 421 (1998) 300.
[25] T. Nishitani, et al., J. Appl. Phys. 97 (2005) 094097.