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[a]*St. Petersburg State Polytechnic University, Russia*
[b]*Institute of Nuclear Physics, Mainz University, Mainz, Germany*
[c]*Stanford Linear Accelerator Center, Stanford, CA, USA*
[d]*A.F. Ioffe Physicotechnical Institute RAS, Russia*
[e]*Department of Electronic and Electrical Engineering, University of Sheffield, UK*

## Abstract

Resonance enhancement of the quantum efficiency of new polarized electron photocathodes based on a short-period strained superlattice structures is reported. The superlattice is a part of an integrated Fabry-Perot optical cavity. We demonstrate that the Fabry-Perot resonator enhances the quantum efficiency by the order of magnitude in the wavelength region of the main polarization maximum. The high structural quality implied by these results points to the very promising application of these photocathodes for spin-polarized electron sources.

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**Abstract.** Resonance enhancement of the quantum efficiency of new polarized electron photocathodes based on a short-period strained superlattice structures is reported. The superlattice is a part of an integrated Fabry-Perot optical cavity. We demonstrate that the Fabry-Perot resonator enhances the quantum efficiency by the order of magnitude in the wavelength region of the main polarization maximum. The high structural quality implied by these results points to the very promising application of these photocathodes for spin-polarized electron sources.

**Keywords:** Quantum efficiency, Fabry-Perot resonator, Superlattice.
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## INTRODUCTION

Strained superlattices (SL) are known to be the most effective photoemitters of spin-polarized electron beams which are required for high-energy experiments [1]. In these structures, the heavy hole and light hole minibands are spitted due to the effects of both quantum confinement and strain-induced splitting. The enlarged valence band splitting results in a high initial electron polarization in the conduction band under excitation by circularly polarized light. The progress in design and fabrication of strained SL in the past years results in the development of electronic sources with maximal electronic polarization higher 90% [2-4]. However even in the best photocathode samples, quantum efficiency (QE) does not exceed 0.8%. The high electronic polarization (P) is achieved at the expense of QE. Indeed, the maximal spin orientation of photoelectrons take place at the photoabsorption threshold where the photoabsorption coefficient is rather small. Strained SL can not be made too thick due to the possible strain relaxation resulting in structural defects, smaller residual strain and lower polarization. Thus the thickness of the working layer is smaller by an order of magnitude than the photoabsorption length and most of the light intensity is lost in the photocathode substrate. To overcome this problem the photocathode structure with Distributed Bragg Reflector (DBR) at the back side of the photocathode has been proposed [5-8]. In such structures DBR reflects the incoming circularly polarized light back to the surface where approximately 0.3 of the intensity is reflected into cathode again and so on. In fact the photocathode working layer is placed in a Fabry-Perot optical resonance cavity.

In the present work we report the study of two photocathode structures that integrate a working layer to a Fabry-Perot optical cavity. The working layer of the first structure is based on the strain compensated InAlGaAs-GaAsP SL [9], whereby the composition of the GaAsP barrier layers is chosen to have opposite (tensile) strain from that of the InAlGaAs quantum well layers. The second photocathode is based on the InAlGaAs-AlGaAs SL with strained quantum wells [4]. In this structure the deformation of the InAlGaAs quantum well (QW) layer together with different confinement energy of light and heavy holes localized in QW results in larger valence band energy splitting and consequently in high electronic polarization.

## DESIGN AND FABRICATION

The photocathode structure based on strain compensated SL is shown in Fig. 1a. Two samples of such type have been prepared with and without a DBR layer. The photocathodes were grown on a p-type (100) GaAs substrate by Metal Organic Vapor Phase Epitaxy (MOVPE) using trimethyl group III reagents and arsine. The photocathode consists of a DBR mirror containing 22 pairs of alternating $\lambda/4$ plates of $Al_{0.19}Ga_{0.81}As$ and AlAs. On the top of this mirror, a 500nm thick $Al_{0.35}Ga_{0.65}As$ buffer layer is grown that serves as the substrate for the strained SL. The superlattice contains 20 pairs of compressively-strained $(Al_{0.16}Ga_{0.84})_{0.82}In_{0.18}As$ quantum well layers and tensile-strained $GaAs_{0.83}P_{0.17}$ barrier layers. The layer compositions were designed to optimize the effect of strain magnitude and compensation on electron polarization. On top of the SL working layer, a 6-nm thick GaAs surface layer was deposited with Zn-doping concentration enlarged from $7\times10^{17}$ cm$^{-3}$ in the working layer to $1\times10^{19}$ cm$^{-3}$ to achieve negative electron affinity by the well known procedure of surface activation. The photocathode with strained QW has the similar structure (see Fig. 1b). The DBR layer was also grown by MOVPE while buffer layer and SL containing 12 periods were grown above DBR by Molecular Beam Epitaxy.

To optimize the photocathode structure the calculations of QE and P have been performed. The energy spectrum of SL and photoabsorption coefficient was calculated within 8-band Kane model [10], the distribution of the light intensity within the photocathode was simulated using transfer matrix method [11].

## RESULTS AND DISCUSSION

The polarization and quantum efficiency data obtained for photocathodes with strained QW are shown in Fig. 2 as a function of wavelength. The polarization spectra with and without the DBR layer are rather close. The structures show all the typical features of SL emission including high- polarization peak at the band edge absorption and a second peak at higher energies with a well-pronounced dip between them. However these samples have different quantum yield spectra. While the sample without a DBR exhibits a typical smooth QE(λ) behavior with a cutoff below the absorption edge, the quantum yield spectrum of the sample with a DBR has additional resonance features.

| As cap | | |
|---|---|---|
| GaAs | QW | 6nm |
| $(Al_{0.16}Ga_{0.84})_{0.82}In_{18}$ As | SL 20X | 4nm |
| $GaAs_{0.83}P_{0.17}$ | | 6nm |
| $Al_{0.35}Ga_{0.65}As$ | Buffer | 500nm |
| GaAs | | 20nm |
| AlAs | DBR 22X | 71nm |
| $Al_{0.19}Ga_{0.81}As$ | | 58nm |
| GaAs (100) – Substrate , Zn | | |

*a*

| As cap | | |
|---|---|---|
| GaAs | QW | 6nm |
| $Al_{0.19}In_{0.2}Ga_{0.61}As$ | SL 12X | 5.4nm |
| $Al_{0.4}Ga_{0.6}As$ | | 2.1nm |
| $Al_{0.35}Ga_{0.65}As$ | Buffer | 580nm |
| GaAs | | 20nm |
| AlAs | DBR 22X | 68nm |
| $Al_{0.19}Ga_{0.81}As$ | | 60nm |
| GaAs (100) – Substrate , Zn | | |

*b*

**FIGURE 1.** Composition of the photocathode with strain compensation (a) and strained QW (b).

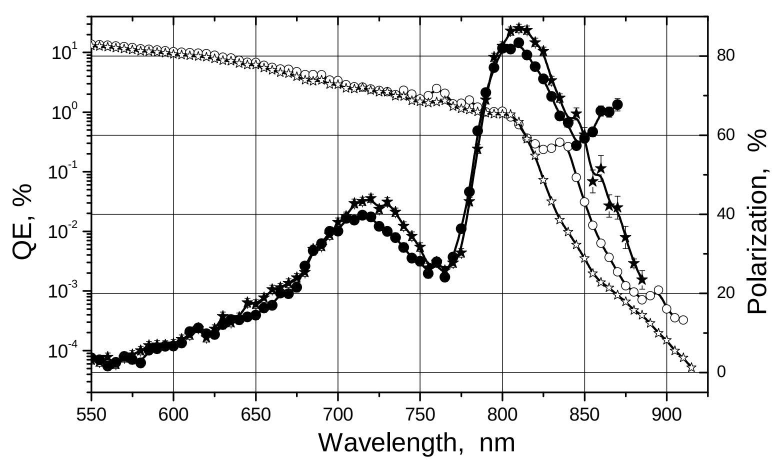


**FIGURE 2.** Polarization (solid symbols) and quantum efficiency (open symbols) spectra of the emitted photoelectrons from photocathodes with strained QW with (circles) and without (stars) DBR.

Resonance peaks correspond to the increase of the electromagnetic field in the working layer when resonance conditions for the Fabry-Perot optical cavity are fulfilled. To check this statement we measured the reflectivity spectrum of the photocathode with DBR and show it in Fig. 3 as a function of wavelength together with the enhancement factor, the ratio of QE of the sample with and without DBR. The dip in the reflectivity spectrum at $\lambda$ = 836nm corresponding to the Fabry-Perot resonance almost coincides with the position of the peak enhancement of QE.

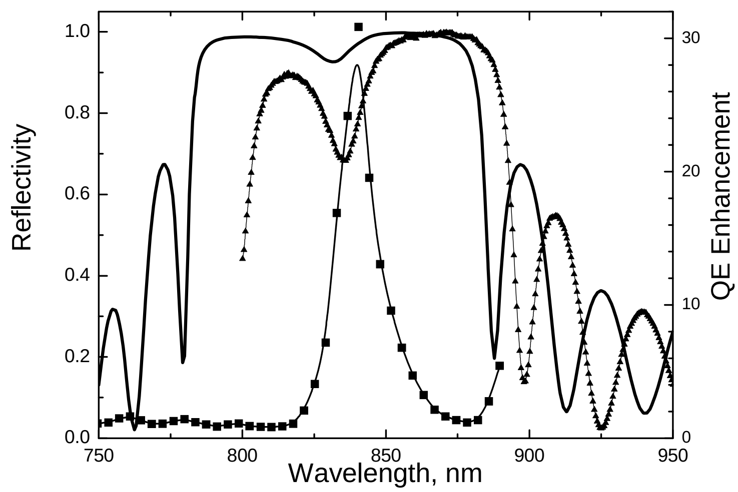


**Figure 3.** Reflectivity of photocathode with strained QW and DBR. Experimental spectrum is shown by triangles, calculated results by thick solid line. Solid squares show the enhancement factor of QE.

In Fig. 4 we show P and QE spectra of electron emission from photocathode with strain compensated SL. Circles show the results obtained for the sample with DBR, stars show spectra of sample without DBR and solid and dashed lines show the P and QE spectra calculated for the sample with DBR. Polarization spectra of both samples are almost identical while QE spectra are different. To illustrate the resonance enhancement of QE we plot in Fig. 5 the ratio of quantum efficiencies for these two samples together with the polarization curve for the DBR sample. The largest resonance peak of quantum yield enhancement at $\lambda$=870nm practically coincides with the main polarization maximum of electron emission. Thus the DBR layer in the present sample increases the quantum efficiency of polarized electron emission by factor 10.

It worth to emphasize, that the resonance enhancement of quantum yield is not accompanied by a decrease of electron polarization. This fact manifests the high structural quality of this photocathode. Since the resonance standing wave in a Fabry-Perot cavity is very sensitive to a phase shift near the resonance, even a small difference in the refraction indexes in in-plane directions as the result of a small anisotropy of the inplane lattice strain leads to a completely unpolarized wave in the working layer [6].

The use of DBR allows us to considerably reduce the heating of the cathode and,

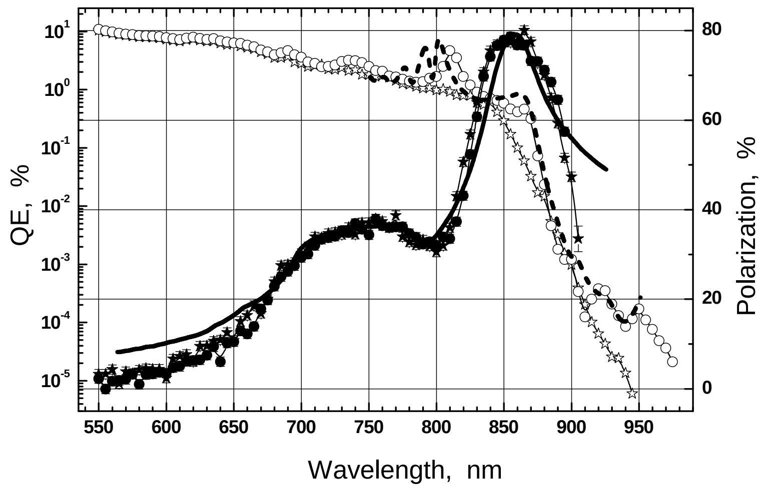


**FIGURE 4.** Polarization (solid symbols) and quantum efficiency (open symbols) spectra of the emitted photoelectrons from photocathodes with strain compensated SL with (circles) and without (stars) DBR. Thin solid lines connect each set of data points. Thick solid and dashed lines show the P and QE spectra, respectively, calculated for the sample with DBR.

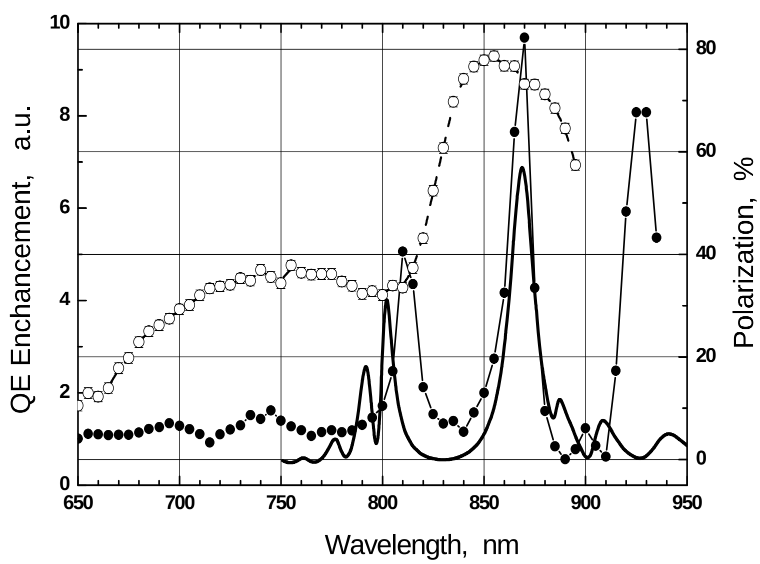


**Figure 5.** Resonance enhancement of quantum efficiency (solid circles) and polarization of electron emission (open circles) from strain compensated SL with DBR. Thick solid line shows the calculation results for the enhancement factor.

hence, increase the maximal obtained electron current. In the ordinary photocathode only the small part $\alpha d << 1$ of incoming light intensity is absorbed in the working layer and used to generate photoelectrons. Here $\alpha$ is the photoabsorption coefficient, $d$

is the width of the working layer, e.g. for photocathode with strained QW $\alpha d \leq 0.2$ in the region of main polarization maximum. The most part of the laser intensity is absorbed in the substrate resulting in heating of the structure. Since the reflectivity of the DBR is close to one unit all absorbed laser power in the sample with DBR goes for photogeneration. Thus the photocathode with DBR will produce by $1/(\alpha d)$ more electrons with the same heat loading as the cathode without DBR.

## CONCLUSION

We have developed a novel type photocathode based on strained semiconductor superlattices integrated into a Fabry-Perot optical cavity of high structural quality. We demonstrate a tenfold enhancement of quantum efficiency at the polarization maximum due to the multiple resonance reflection from DBR layer.

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