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Highly-Polarized Electron Emission from Strain-Compensated Superlattices and Superlattices with High-Valence-Band Splitting*

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Results of experimental and theoretical studies of polarized electron emission from new short-period strain-compensated InAlGaAs-GaAsP superlattices and InAlGaAs-AlGaAs superlattices with a high-valence-band splitting are presented. The superlattice structures investigated are found to be very promising for spin-polarized electron sources.

1. Introduction

Strained layer heterostructure and short-period superlattice structures have been used to advantage in achieving highly spin-polarized electron photoemission [1]. The strain-induced splitting of the valence band at the band-gap minimum provides a high electron polarization in the conduction band under excitation by circularly polarized light. Smearing of the interband absorption edge and the hole scattering processes lead to polarization in the band-edge absorption of less than 100%, polarization losses being typically about 6%. This mechanism sets a limit on the maximum polarization of emitted electrons [2,3]. The initial polarization can be increased by choosing structures with a higher valence band splitting. The strained superlattice (SL) structures, in which the heavy- and light-hole bands, in addition to the strain splitting, are also split due to different light- and heavy-hole confinement energies in the SL quantum wells, are the best for this purpose. The necessary thickness of the stressed photocathode working layer, however, exceeds the critical thickness for strain relaxation resulting in structural defects, smaller residual strain and lower polarization. Critical thickness considerations limit the number of the SL periods in the working layer and thus the quantum efficiency of the structures. One of the possible

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solutions of this problem is to use a *strain-compensated* (or strain-balanced) superlattice structure.

In presently used superlattice structures, only the quantum well (QW) layer (or the barrier layer) has a lattice constant different from the lattice constant of the buffer layer. In the strain-compensated SL structure, the composition of the SL barrier layers is chosen to have opposite (tensile) strain from that of the QW layers. Thus, the average lattice constant mismatch of the SL structure relative to the buffer is close to zero for any number of layers. This means that a considerably larger overall thickness of the SL structure can be achieved with no degradation of the strain values.

Though strain compensated superlattice structures are very promising for use in polarized electron sources, their design is very complicated, and such structures are both difficult to grow and to optimize. Consequently research with conventionally strained superlattice structures continues. Taking into account the results obtained earlier with InAlGaAs/GaAs strained-barrier structures and the results of theoretical calculations of the optical orientation spectra, new strained InAlGaAs/AlGaAs superlattice structures were designed at St. Petersburg State Technical University (SPTU) to have highly-strained quantum wells. The advantage of the new structures compared to the GaAs/GaAsP superlattices structures that are claimed to give the highest polarization is the use of a standard GaAs substrate with no strained buffer layer, which should ensure a *high-valence-band splitting* and better structural quality [4].

2. Experimental

Two sets (1 and 2) of strain-compensated SL wafers[1] were investigated, two wafers (A and B) in each set. The cathodes from set 1 were very promising: peak polarization of 80% and quantum efficiency (QE) of about 0.3%. Since x-ray rocking curve measurements indicated the barrier and well widths may have been 46 Å vice the design value of 40 Å, the second set of superlattice wafers with barrier and well widths designed for 55 Å were grown. The new samples were designed to have a higher phosphorus fraction in the barrier layers (0.32 and 0.34 instead of 0.25) and slightly higher Al fraction in the QW layers (0.16 and 0.18 instead of 0.14) for samples 2A and 2B respectively. The design of these two samples is shown in Table 1.

[1] Grown by University of Sheffield (Sheffield, United Kingdom) using Metal-Organic Vapor Phase Epitaxy (MOVPE).

Table 1. The strain-compensated superlattice samples, set 2. For cathodes 2A and 2B, x,y,z=0.32,0.16,0.16 (14 periods) and 0.34,0.18,0.18 (12 periods) respectively.

Composition		**Thickness**	**Doping**
As cover			
GaAs QW		60 Å	$1{*}10^{19}$ cm^{-3} Be
$GaAs_{1-x}P_x$	SL	55 Å	$4{*}10^{17}$ cm^{-3} Be
$In_yAl_zGa_{1-y-z}As$		55 Å	
$Al_{0.3}Ga_{0.7}As$	Buffer	0.5 mm	$6{*}10^{18}$ cm^{-3} Be
p-GaAs substrate, Zn doped			

Two additional sets (3 and 4) of photocathode wafers–2 wafers (A and B) in each set–were grown[2] based on the strained AlInGaAs/AlGaAs superlattice structure. The high Al fraction in the AlGaAs barrier layers was designed to produce a high strain in the QW layers. The design of these samples is shown in Table 2. The main idea for these structures was to combine the valence band splitting due to strain with the splitting caused by quantum mechanic effects in the superlattice. Compared to AlInGaAs/GaAs superlattice cathodes with compensated barriers for electrons in the conducting band [5], these structures had a high-valence-band splitting between the heavy- and light-hole bands, but the barriers in the conducting band remained uncompensated.

Table 2. The strained AlInGaAs/AlGaAs superlattice samples, sets 3 and 4. For cathodes 3A and 3B, xyz=0.28,0.16,0.2 (15 periods) and 0.3,0.2,0.2 (14 periods) respectively. For cathodes 4A and 4B, xyz= 0.4,0.18,0.16 (12.5 periods) and 0.36,0.18,0.14 (10.5 periods).

Composition		**Thickness**	**Doping**
As cover			
GaAs QW		60 Å	$1{*}10^{19}$ cm^{-3} Be
$Al_xGa_{1-x}As$	SL	50 Å	$5{*}10^{18}$ cm^{-3} Be
$In_yAl_zGa_{1-y-z}As$		40 Å	
$Al_{0.4}Ga_{0.6}As$	Buffer	1.5 mm	$6{*}10^{18}$ cm^{-3} Be
p-GaAs substrate, Zn doped			

[2] Grown by the Ioffe Physical Technical Institute (St. Petersburg, Russia) using Molecular Beam Epitaxy (MBE).

Polarization and quantum efficiency (QE) were first studied with the SLAC Cathode Test System (CTS) shown schematically in Fig. 1. The CTS is an ultra-high vacuum system pumped by a combination of ion and non-evaporable getter (NEG) pumps. The residual pressure in setup is about $1*10^{-11}$ Torr. The system is equipped with a load-lock chamber through which samples can be introduced without venting the system vacuum. Polarization measurements are accomplished by an electron transport column, an electrostatic 90^0 spin-rotator and a 20 keV Mott polarimeter. The photon helicity is controlled by a linear-polarizer/liquid-crystal retarder combination.

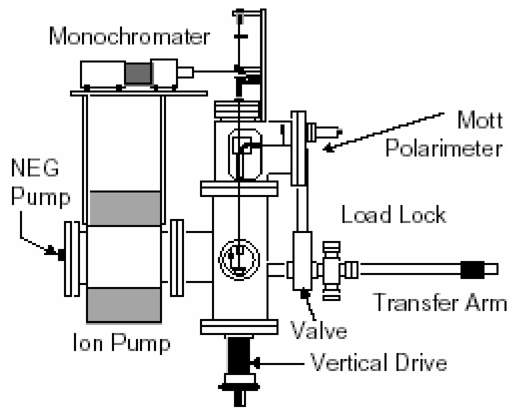

Fig. 1. Schematic diagram of the Cathode Test System showing the load lock.

Prior to installation in the system, a sample was degreased in a boiling solution of trichloroethane. After the protective oxide layer was removed in ammonium hydroxide, the sample was rinsed in distilled water and methanol. The cathode activation method used to obtain a negative electron affinity (NEA) surface consisted of heat cleaning at 600^0C for 1 hour; cool down for an hour, followed by application of cesium until the photo-yield peaked, and then cesium and nitrogen-trifluoride co-deposition until the photo-yield was again maximized. The heat-cleaning temperature was monitored via an infrared pyrometer. The cathode was activated while monitoring the photo-yield with a white light and a 670 nm diode laser. Once a red response was observed from the diode laser, the white light was turned off, and the diode laser was used to complete the activation. The absolute QE was measured using the diode laser at a photon wavelength of 670 nm. A tungsten lamp and a monochromator were used to measure the relative QE as a function of photon wavelength, and these measurements were then normalized to the diode laser measurement at 670 nm.

3. Results and discussion

Low-voltage polarization and QE measurements at room-temperature of the strain-compensated SL samples have been made at SLAC. The experimental data for set 2 are presented in Fig 2. Unfortunately, the resulting polarization values are disappointing: maximum polarization of 66% for the first sample and 75% for the second with QE at the polarization peaks about 0.4% for both cathodes. The measured wavelength for the polarization peaks for this pair of cathodes is close to 850 nm as it was for the previous samples, but the calculated polarization spectra [6] predict that the peaks should be at a slightly higher energy and in addition the peaks for the first set of cathodes should be shifted to higher energy than for the second. X-ray measurements have been made including rocking curve measurements along the 004 axis and surface mapping to clarify these results. Comparing x-ray measurements with simulations revealed a significant difference between the actual cathode composition and that designated by the design. According to x-ray data the cathodes had a significantly lower phosphorus fraction in the GaAsP layers, and the width of the SL layers was higher then designed.

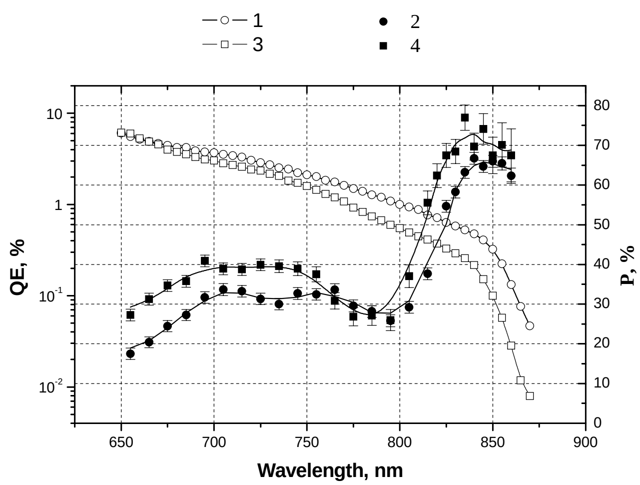

Figure 2. Polarization and quantum yield spectra of the emitted photoelectrons for set 2 of the strain-balanced superlattice cathodes: curves 1 and 2 – QE and P for cathode 2A ($In_{0.16}Al_{0.16}Ga_{0.68}As/GaAs_{0.68}P_{0.32}$); curves 3 and 4 – QE and P for cathode 2B ($In_{0.18}Al_{0.18}Ga_{0.64}As/GaAs_{0.66}P_{0.34}$).

The AlInGaAs/AlGaAs superlattice cathodes have been measured at SLAC also. The measured spectra are presented on Figs. 3 and 4. Low voltage measurements with the Cathode Test System for set 3 gave encouraging results: maximum polarization values were 80% and 75% for samples 3A and 3B with 0.28 and 0.3 Al fraction and the corresponding QE about 1% for both cathodes. An attempt to increase the valence-band splitting by increasing the Al fraction to

0.36 and 0.40 for samples 4A and 4B respectively led to a degradation of cathode performance; i.e., the maximum polarization values were 60% and 58% and the corresponding QE about 0.5%. Probably an Al fraction of 0.3 in the QW is optimum.

X-ray rocking curve measurements along the 004 and 224 directions were performed for all four cathodes. When compared with simulations the AlInGaAs layers for all samples appeared to be relaxed by about 5%. In addition, the AlInGaAs QW layers had a slightly higher fraction of Ga, while the AlGaAs layers had slightly lower Ga fraction than was designed.

The QE asymmetry has been measured for each of the four AlInGaAs/AlGaAs cathodes. The results of these measurements are shown in Fig. 5 for cathode 4A. This asymmetry is a result of the structural anisotropy introduced by the strain in the epilayer and causes the electron emission to vary with the direction of any linearly polarized light in the excitation laser beam [7]. All four cathodes exhibited QE asymmetries on the order of 5%, which is higher than that for some other superlattice structures, but somewhat lower than is typical for single-layer strained structures.

Measurements of the surface charge limit (SCL) effect were made using the 120 kV gun in the SLAC Gun Test Laboratory for the InAlGaAs/AlGaAs cathode that showed the highest polarization (cathode 3A). No SCL effect was observed. The results of these measurements are presented in Fig. 6. The maximum average electron current of 13 μA (corresponding to a maximum peak current of 2.8 A within the 60 ns pulse) was comparable with best GaAsP superlattice cathodes. The small non-linear curvature visible in Fig. 6 can be explained by the gun space charge limitation.

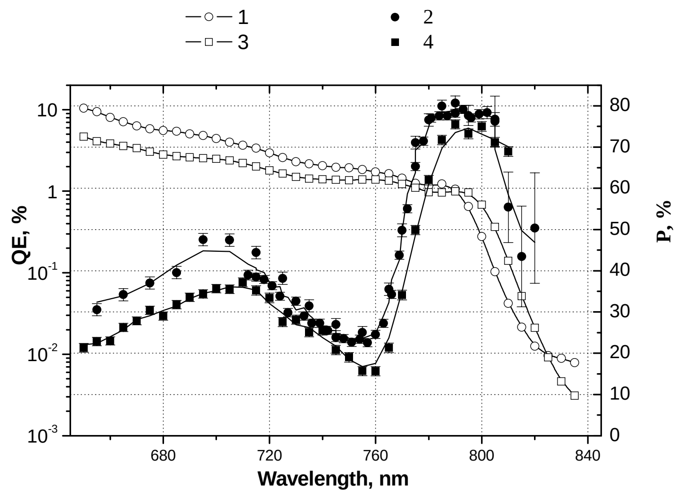

Figure 3. Polarization and quantum yield spectra of the emitted photoelectrons for set 3 of the superlattice cathodes with high-valence-band splitting: curves 1 and 2 – QE and P for cathode 3A ($In_{0.16}Al_{0.20}Ga_{0.64}As/Al_{0.28}GaAs_{0.72}$); curves 3 and 4 – QE and P for cathode 3B ($In_{0.20}Al_{0.20}Ga_{0.60}As/Al_{0.30}GaAs_{0.70}$).

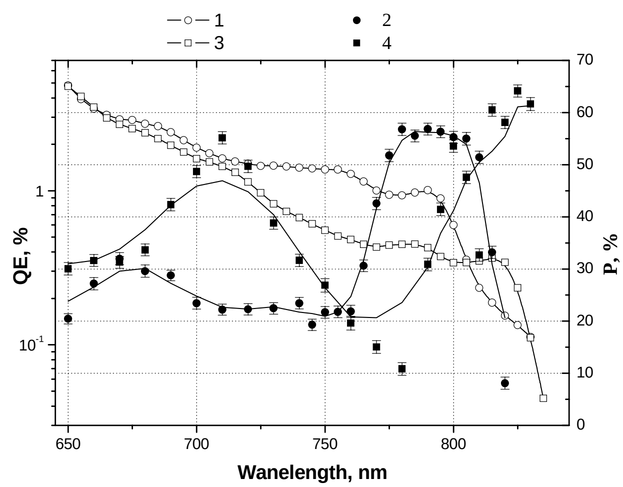

Figure 4. Polarization and quantum efficiency spectra of the emitted photoelectrons for set 4 of the superlattice cathodes with high-valence-band splitting: curves 1 and 2 – QE and P for cathode 4A ($In_{0.18}Al_{0.16}Ga_{0.66}As/Al_{0.40}GaAs_{0.60}$); curves 3 and 4 – QE and P for cathode 4B ($In_{0.18}Al_{0.14}Ga_{0.68}As/Al_{0.36}GaAs_{0.64}$).

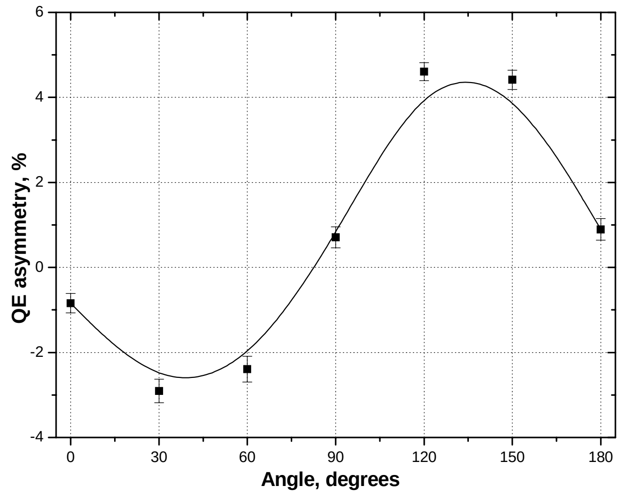

Fig. 5. Quantum efficiency asymmetry data for the InAlGaAs-AlGaAs superlattice cathode 4A ($In_{0.18}Al_{0.14}Ga_{0.68}As/Al_{0.36}GaAs_{0.64}$).

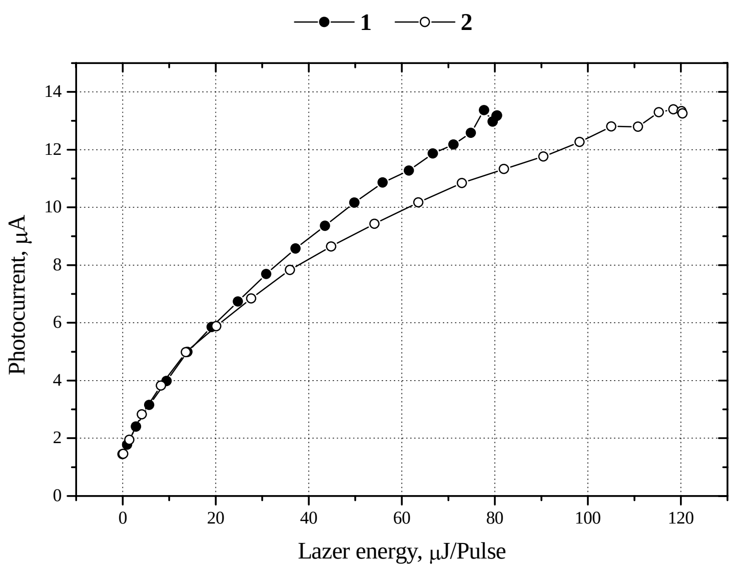

Figure 6. Average electron current extracted using the superlattice cathode 3A ($In_{0.16}Al_{0.20}Ga_{0.64}As/Al_{0.28}GaAs_{0.72}$): curve 1 for λ =780 nm; curve 2 for λ =788 nm. The laser operated at 60 Hz with a pulse length of 60 ns. (The abscissa scale should be reduced by a factor of 1.67, e.g., the maximum laser energy for curve 2 should be 72 μJ.)

4. Summary and conclusions

Two new cathode samples based on the InAlGaAs/GaAsP strain-compensated superlattice design with high structural quality have been grown and studied as candidates for highly polarized electron emission. Since the composition of such structures is very complicated and precision optimization is difficult, the results with strain-balanced structures at the present time are inferior to those with the more conventional strained superlattice design. Nevertheless, the results obtained are very important for further perfection of such cathodes. AlInGaAs/AlGaAs superlattice samples with high valence-band splitting were also grown and studied. They showed very good characteristics, comparable with the best GaAs/GaAsP superlattice cathodes. Further optimization of such structures is underway.

5. Acknowledgements

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