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InAlGaAs/AlGaAs superlattices for polarized electron photocathodes*

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Abstract

Highly efficient emitters of polarized electrons based on the InAlGaAs/AlGaAs superlattice give an optimistic prognosis to explorations of such structures as the sources for accelerators. A new set of these SL structures with minimized conduction band offset was designed and recently tested. A new technology of surface protection in MBE growth leads to a significantly reduced heat -cleaning temperature. At these lowered cleaning temperatures, the thermal degradation of the working structure parameters is avoided. As a result a polarization P of up to 91% at corresponding quantum efficiency (QE) of 0.3% was achieved at room temperature.

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Abstract. Highly efficient emitters of polarized electrons based on the InAlGaAs/AlGaAs superlattice give an optimistic prognosis to explorations of such structures as the sources for accelerators. A new set of these SL structures with minimized conduction band offset was designed and recently tested. A new technology of surface protection in MBE growth leads to a significantly reduced heat-cleaning temperature. At these lowered cleaning temperatures, the thermal degradation of the working structure parameters is avoided. As a result a polarization P of up to 91% at corresponding quantum efficiency (QE) of 0.3% was achieved at room temperature.

Introduction

The spin-polarized electron sources (PES) based on photoemission from GaAs or its relatives under excitation by circularly polarized light has proved to be the best for high energy electron accelerators applications [1]. New progress in development of polarized electron sources can be based on new structures with good structural quality, large valence band splitting and spin relaxation times resulting in larger polarization and quantum efficiency. The most obvious prospects for optimization of the PES structure are to increase both the quantum efficiency and electron spin polarization using superlattice (SL) structures with specially designed layer thickness and compositions. They consist of several thin strained films separated by layers of unstrained larger-bandgap material, specially designed to cause barriers for the hole transport but keep electron mobility high. From the point of view of growth of a perfect crystal, every separate strained film of the SL can be grown thinner than the critical thickness (CTh), but with a total thickness which can exceed CTh and be sufficient to obtain high quantum efficiency (QE). To suppress the depolarization during the transport to the band bending region (BBR), the working part of a structure has to be low p-doped (about 510^{17} cm^{-3}), which should help to suppress Bir - Aronov - Pikus spin relaxation mechanism [2]. At the same time the request for high QE at maximum polarization requires the top of a structure to be heavily p-doped to achieve high quality Negative Electron Affinity (NEA) surface. These two requirements can be simultaneously fulfilled with the modulation doping profile. Very high (not less than 510^{19} cm^{-3}) doping of the top layer helps as well to overcome surface charge limit (SCL), which appears at high pumping light power [3,4]. Below our recent results with InAlGaAs/AlGaAs superlattices are discussed. All SL samples were grown by solid-source molecular beam epitaxy on GaAs(100)-oriented substrates.

1. Highly strained InAlGaAs/AlGaAs SL structures

The main advantage of SL-based photoemitters is the possibility to vary the properties of the active layer over a wide range by the appropriate choice of layer composition, thickness, and doping profile. The initial polarization P_0 can be increased by choosing structures with a higher valence band splitting. The SL structures with strained quantum well (QW) layers in which heavy and light hole bands, in addition to the strain splitting, are moved aside due to different light and heavy-hole confinement energy in the QW layers, are the best for this purpose. The other benefit of the SLs is the possibility of a precise modulation doping providing small polarization losses during electron escape from the active layer and the band bending region into vacuum.

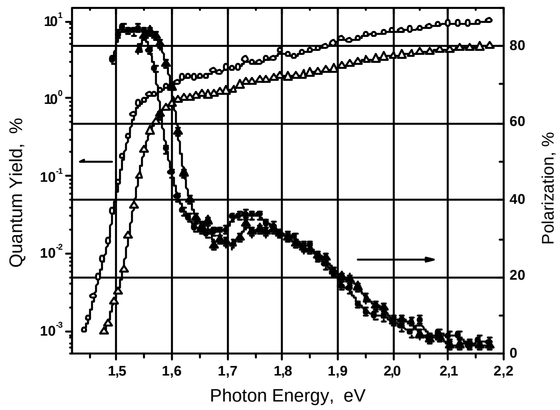

Fig. 2 .Polarization (solid symbols) and quantum efficiency (open symbols) spectra of highly-strained multilayer Al$_x$In$_y$Ga$_{1-x-y}$As/AlGaAs structure at room (circles) temperature and at T=130K (triangles).

New InAlGaAs/AlGaAs SL structures with thin (close to 2 nm) quantum well layers and the highest possible (up to 35 %) concentrations of In within the QW layers were developed and tested. The polarization and quantum efficiency spectra obtained at lowered activation temperatures are presented at Figure 1, revealed a rather wide plateau in the vicinity of the maximum polarization (about 85%) and a sharp edge of the quantum yield spectrum, which indicates the good structural qualities of these samples. Record high values of strain splitting are reproducibly obtained, though further optimization of the overall photocathode structures is still needed. InAlGaAs/AlGaAs SL structures are favorable candidates for photocathodes since they can be grown by a standard MBE technology and the structures are well controlled and reproduced during the growth. This gives an optimistic prognosis to explore such structures in the sources attached to accelerators.

2. InAlGaAs/GaAs SL structures with minimized conduction band offset

A new strained-barrier short-period $Al_xIn_yGa_{1-x-y}As$/GaAs superlattice with a minimal conduction-band offset was proposed in [1]. The main advantage of such SL results from the band line-up between the semiconductor layers of the SL. The Al content determines the formation of a barrier in the conduction band, while adding In leads to conduction band lowering, so the conduction band offset can be completely compensated by appropriate choice of x and y, while barriers for the holes remain uncompensated. As a result high vertical electron mobility and simultaneously a small spin relaxation rate is achieved while also a large enough valence-band splitting is remained.

For the thermalised electrons at room temperature the influence of the resulting periodical potential should be negligible. Besides, as a result of the conduction-band line up, the residual 4-nm barriers for the electrons in the SL are transparent. Thus the changes of electron mobility and spin relaxation rate from the values typical for the bulk GaAs should be small.

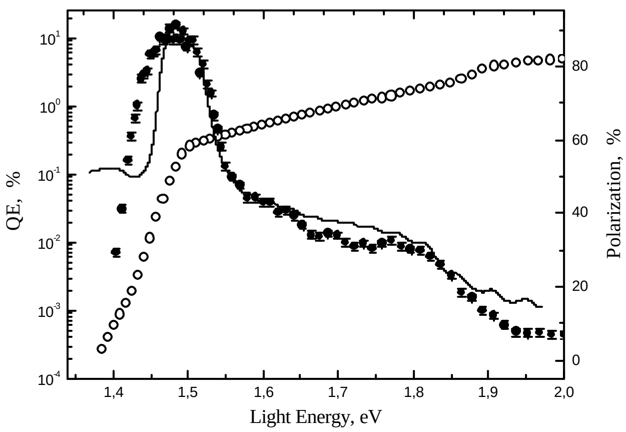

Fig. 2. Polarization (solid circles) and quantum efficiency (open circles) spectra of $Al_{0.21}In_{0.2}Ga_{0.69}As$ (4nm)/Ga As(1.5nm) 18.5 periods Superlattice sample at room temperature.
Heat cleaning temperature 450^0C. Solid line - calculated energy dependence of P(h?).

Using the structures based on quaternary $Al_xIn_yGa_{1-x-y}As$ alloy one can change the band gap by varying the Al content in the layers keeping In concentration unchanged to maintain high deformation and strain-induced valence band splitting. The choice of the layer thickness is dictated by the need to split the hole minibands. The splitting grows when barriers are broad enough and wells are narrow and deep.

A new set of the InAlGaAs/GaAs SL structures with minimized conduction band offset was designed and tested. The optimization of the design of these structures has recently become possible only with the development of more accurate calculation programs. In addition, a new technology of surface protection in MBE growth enabled us to significantly reduce the heat-cleaning temperature (for optimal activation it should not exceed 450^0C). At these lowered cleaning temperatures, the thermal degradation of the modulation doping profile is avoided. As a result a polarization P of up to 91% at corresponding quantum efficiency QE of 0.3% was achieved at room temperature (see fig. 2). These results are significantly better than our previous ones and are equal to or superior to the best results achieved anywhere. The lowered activation temperatures open the possibility for further improvements in photocathode parameters via optimization of the doping profile.

3. Summary

New structures based upon highly QW-strained InAlGaAs/AlGaAs SLs and barrier-strained InAlGaAs/GaAs SLs with minimized conduction band offset have been developed and tested. InAlGaAs/AlGaAs SL structures are favorable candidates for photocathodes since they can be grown by a standard MBE technology and the structures are well controlled and reproduced during the growth. A new technology of surface protection in MBE growth leads to considerable reduction of the heat-cleaning temperature (not more than 450^0C). At these lowered cleaning temperatures, the thermal degradation of the working structure parameters is avoided. As a result a polarization P of up to 91% at corresponding quantum efficiency (QE) of 0.3% was achieved at room temperature.

Acknowledgments.

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References

[1] A.V.Subashiev, Yu.A.Mamaev, Yu.P.Yashin, and J.E.Clendenin, Phys. Low-Dim. Struct. **1/2** , 1 (1999).
[2] F.Meier and B.P.Zakharchenya eds., Optical orientation, (North-Holland, 1984).
[3] G. A. Mulhollan, A. V. Subashiev, J. E. Clendenin, E. L. Garwin, R. E. Kirby, T. Maruyama, and R. Prepost, Phys. Lett. **A 282**, 309 (2001).
[4]T. Maruyama, A. Brachmann, J. E. Clendenin, T. Desikan, E. L. Garwin, R. E. Kirby, D.-A. Luh, J. Turner, and R. Prepost, Nucl. Instr. and Meth. **A 492**, 199 (2002).