Strain-compensated AllInGaAs–GaAsP superlattices for highly polarized electron emission

A. V. Subashiev, L. G. Gerchikov, Y. A. Mamaev, and Y. P. Yashin
Experimental Physics Department, State Polytechnic University, Politekhnicheskaya 29,
St. Petersburg 195251, Russia

J. S. Roberts
Department of Electronic Engineering, University of Sheffield S1 3JD, United Kingdom

D.-A. Luh, T. Maruyama, and J. E. Clendenin
Stanford Linear Accelerator Center, Menlo Park, California 94025

(Received 1 December 2004; accepted 12 March 2005; published online 21 April 2005)

Spin-polarized electron emission from superlattice photocathodes developed with strain compensation is investigated. An opposite strain in the quantum well and barrier layers is accomplished using an InAlGaAs/GaAsP superlattice structure. The measured values of maximum polarization and quantum yield for the structure with a 0.18 μm thick working layer are excellent results for a strained superlattice photocathode structure, demonstrating the high potential of strain compensation for future photocathode applications. An analysis of the photoemission spectra is used to estimate the parameters responsible for the polarization losses. © 2005 American Institute of Physics. [DOI: 10.1063/1.1920416]

Strained short-period superlattice (SL) structures as candidates for the photocathodes of highly spin-polarized electron sources have been the subject of a number of studies; e.g., see Refs. 1–3. In these structures, the heavy-hole (hh) and light-hole (lh) minibands are split due to the difference in the hh and lh confinement energies in the SL quantum wells (QWs), which adds to the separation due to strain alone. The enlarged valence-band splitting results in a high initial electron polarization in the conduction band under excitation by circularly polarized light. However, the thickness of the stressed photocathode working layer necessary for achieving a high value of quantum yield exceeds the critical thicknesses for strain relaxation, which results in structural defects and smaller residual strain and thus lowers polarization. A second factor limiting the maximum polarization is the smearing of the interband absorption edge, which is mainly due to the valence-band tails and to the hole scattering processes. Consequently, the polarization in the band-edge absorption is less than 100%, polarization losses being typically about 6%.5

To overcome these problems the use of strain compensation was proposed,6 whereby the composition of the SL barrier layers is chosen to have opposite (tensile) strain from that of the QW layers. Due to the lowered barriers for the light holes formed by the tensile-strained barrier layers, the resulting valence-band splitting in the strain compensated structures is expected to be smaller than in the structures without strained barriers but with similarly strained wells. However, considerably larger strain values in the SL wells can be achieved with no critical thickness limitations on the overall thickness of the SL structure.7 The resulting enlarged valence-band splitting should ensure high electronic polarization.

In this letter, we report the results of our experimental and theoretical studies of polarized electron emission from strain-compensated InAlGaAs–GaAsP SLs. The viability of strain compensation for polarized electron sources is demonstrated. In addition, a comparison of the experimental and calculated polarization and quantum yield spectra enabled us to determine the absorption-smearing parameters for the edges of the hole minibands and also indicated that the surface band bending region (BBR) makes a crucial contribution to the near-band-edge absorption and to the maximum polarization value.

The design of the working layer SL was based on the band-edge line up across the heterointerface between the compressively and tensile strained layers.8 For strained SLs grown on GaAs substrates, the positions of the layer band edges can be calculated using the positions of the band edges in the GaAs layer as a reference. The range of available compositions of the InAlGaAs QW layer is restricted to x values that give a maximum valence-band splitting while retaining a high structural quality (i.e., x = 16–18%) and to y values that result in a SL band gap larger than that in GaAs (i.e., y ≥ 12%).

The choice for the composition of the GaAs1−xP, barrier layer is more complicated. For small z values, the tension in the barriers is not sufficient to compensate for the deformation of the well layers, while the average valence-band offset is too small to provide a large valence-band splitting. If z and y are too large, the enlarged valence-band splitting in the barriers confines the lh1 in the barrier rather than the well layer, which lowers the confinement energy of the light hole (lh1) miniband and also the hh1-lh1 splitting.

The SL structures were grown by metal-organic vapor phase epitaxy (MOVPE), which presents several potential advantages, the main being high structural quality and low defect densities at the interfaces. In addition, the growth of phosphide materials is greatly simplified, and a wide range of growth rates and composition variations is achievable.9 To separate absorption in the working layer from that in the substrate, a 0.5 μm thick Al0.3 Ga0.7 As p-doped buffer layer was grown on a p-type (100) GaAs substrate with a 3° mis-
FIG. 1. Polarization and quantum yield spectra of the emitted photoelectrons for In_{0.18}Al_{0.12}Ga_{0.68}As-GaAs_{0.83}P_{0.17} SL for various preactivation temperatures (discrete symbols) and the calculated energy dependence of $P(h\nu)$ and $Y(h\nu)$ spectra for $\gamma=7$ meV with the valence-band smearing and hole scattering (dashed line, $\delta=11$ meV) and with the contribution of the BBR added (solid line, $\delta=15$ meV). The inset shows the SL band structure and the main optical transitions. Only the minibands are labeled.

These parameters are excellent for strained superlattice photocathode structures, indicating the high potential of strain compensation.

The comparison of the experimental and calculated spectra showed that the maximum polarization value at the top of the first polarization maximum is sensitive to the smearing of the absorption edge associated with two main factors. The first is the interband absorption smearing due to the band-edge fluctuations, which can be evaluated by fitting the $Y(h\nu)$ dependence allowing nonhomogeneous Gaussian broadening of the absorption spectra. Such a fitting results in a smearing (band-tail) energy parameter, $\delta$, of $\approx 15$ meV. The second factor originates from the processes of hole scattering between the hh and lh states, which leads to a nonzero contribution of the lh miniband to the absorption near the edge and that populates the second spin state. We have calculated the characteristic energy associated with the broadening of the lh absorption spectra, $\gamma$, in terms of the appropriate transition rate. The hole scattering rate on the acceptor impurity centers, estimated also from the mobility data for similar samples, is found to dominate and can result in $\gamma=10$ meV, while the evaluated contribution of the other competing mechanism, scattering on the optical phonons, is $\gamma\approx 4$ meV at room temperature. The calculated spectra for $\gamma=7$ meV and $\delta=11$ meV are depicted in Fig. 1 by the dashed line giving the maximum value of electron polarization, $P_{\text{max}}$, of $\sim 92\%$.

Finally, a sizeable contribution to the total photoabsorption at the polarization maximum should come from the GaAs surface layer forming the BBR and having a smaller band gap. In structures with less phosphorus in the barriers, the surface layer may even be tensile strained, resulting in excitation of electrons with predominantly opposite spin direction. This contribution manifests itself as a sharp decrease in the polarization below the absorption edge since the polarization of electrons excited in the surface layer does not exceed 50%.

The results of the calculation of the $P(h\nu)$ and $Y(h\nu)$ spectra allowing absorption in a BBR layer with a thickness of 10 nm, assuming it to be unstrained, are shown in Fig. 1 by the solid line. The good agreement with experimental data shows the importance of this contribution to the total polarization losses. An additional argument favoring this mechanism is the substantial spread of the results with $T_h$ (at least $\sim 3\%$), which presumably affects only the surface layer and distribution of the acceptors near the surface. The relative contribution of the surface layer depends on the doping profile and can be reduced in structures having a thinner BBR region due to a heavier surface layer doping and in structures with a thicker working layer.

The calculated hh1-lh1 splitting, $\Delta \varepsilon_{\text{hh1-lh1}}$, varies with the AlInGaAs well thickness from 27 meV to 44 meV. The observed variation of $P_{\text{max}}$ with the valence-band splitting for all samples for different $T_h$ and the calculated dependence for various values of the smearing parameters are presented in Fig. 2. It shows that unrealistically high values of $\gamma$ and $\delta$ are required to get the calculated curves to even roughly fit the experimental data, while the correspondence is quite good when BBR absorption is allowed. Though the calculated dependence almost saturates above $\Delta \varepsilon_{\text{hh1-lh1}}=40$ meV, larger values of the splitting are preferable, since they should correspond to smaller smearing. Note that the thickness of the working layer of the sample with the highest polarization...
(0.18 µm) was considerably larger than that (0.1–0.12 µm) for the formerly used and studied strained-layer samples and strained-well SLs with similar polarization values,\textsuperscript{1–3} which directly confirms the validity of the strain compensation idea.

To summarize, photocathode SLs structures with strain compensation have been grown and studied as candidates for highly polarized electron emission. These photocathodes are based on InAlGaAs–GaAsP structures grown by MOVPE. Allowing for the electron spin relaxation and weakly polarized optical absorption at the surface, the calculated polarization spectra are in a good agreement with the observed excitation spectra of polarized electron photoemission. The prevention of strain relaxation and the smaller relative contribution of the BBR region in comparison with strained-well structures can make these structures advantageous.

This work was supported by CRDF under Grant No. RP1-2345-ST-02, by NATO under Grant No. PST.CLG 979966, by Russian Ministry of Industry, Science, and Technology under Contract Nos. 40.012.1.1.1152 and 40.072.1.1.1175, by UK EPSRC support for the National Centre for III-V Technologies at the University of Sheffield under Grant No. GR/R65534/01, and also supported in part by the U.S. Department of Energy under Contract No. DE-AC02-76SF00515.


\textsuperscript{4} A. D. Andreev and A. V. Subashiev, Physica E (Amsterdam) \textbf{13}, 556 (2002).


