Space Charge Expansion for Time-resolved Spin-Polarized Electron Spectroscopy

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Time resolved spin-polarized electron photoemission spectra are investigated as a function of excitation pulse energy for the heterostructures with a single strained layer and with a strained-well superlattice. At an average current exceeding 10 nA the emission pulse profiles are modified by the space charge pulse expansion during the electron transport to detector. The pulse expansion enables the separation of electrons that have spent minimum time in the sample. For the superlattice structure these electrons showed maximum polarization above 90%. Variation in the pulse profiles for the two structures is interpreted as resulting from the difference in the effective NEA values.

Keywords: semiconductors, polarized electrons, strained layers, superlattices, photocathodes

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Introduction

Ultrafast spin-sensitive spectroscopy has drawn much attention in the last decade due to the proposal of novel electronic devices and circuits [1]. Spin-polarized spectroscopy of photoelectrons emitted in vacuum is shown to be effective in the studies of the absolute values of polarization and its temporal variations [2], polarized electron energy distribution [3], and the polarized electron kinetics at the surface [4].

Availability of high-intensity subpicosecond lasers has prompted the development of electron beam photocathodes with high emission currents. A high beam current leads to the space-charge effects and temporal expansion of the photoemission pulse [5]. In this report we use the pulse temporal expansion to improve time resolution in the spin-resolved photoemission studies of the semiconductor photocathode structures, known to be very effective as highly polarized electron sources.

The time resolved polarization measurements combined with space charge pulse expansion enabled us to distinguish polarization losses at the subsequent photoemission stages and to filter out the electrons that have spent minimum time in the sample and have maximum possible polarization.

Experimental details

Two heterostructures with deformation-splitted valence band were investigated: (1) MOVPE grown GaAs0.95P0.05 (120 nm) / GaAs0.68 P0.32 (0.5 mkm) Strained Layer Heterostructure (SLH) and (2) MBE grown modulation-doped In0.16Al0.2Ga0.64As / A10.28Ga0.72As Strained-well Superlattice (SWSL) structure consisting of 12 pairs of 5 nm x 4 nm layers grown on Al0.3Ga0.7As buffer layer, with narrow-band 6 nm-thick GaAs overlayer, both fabricated at Ioffe Physico-Technical Institut, St Petersburg, Russia.

Mode-locked Ti:Al2O3 laser with the wavelength λ= 799 nm close to polarization maximum in the emitted current was used to generate the emission pulses. The excitation pulse power was varied to result in variation of the average photoemission current in the range of Iemi= 1 – 300 nA.

Time-resolved polarization was obtained by the measurements of spin polarization of the electrons accelerated to the energy of 100 keV and passed through a microwave deflection cavity [6]. The apparative time resolution determined mainly by the finite beam size on the analyzer slit was estimated to be τapp = 2.5± 0.5 ps.

Results and discussion

Polarization spectra measured at cw regime were typical for these structures and showed polarization maxima centered at λ = 810 nm for the SLH with P = 83.8 % at quantum efficiency QE = 0.3 % and at λ = 799 for the SWSL with P = 84.4 % and QE = 0.7 %, which is very close to the former results for these structures. The emission current profiles for the SLH sample show the growth of the pulse width with Iemi due the space charge expansion, the rise time and decay time of the pulses remaining constant within the range of 3 ps for all current values. The observed variation of the polarization along the pulse at all Iemi is in the range of 2 %, while the variations of polarization at the pulse front and back are in the range of ≈ 5 %.

The pulse shapes for the SWSL structure show close to triangular shape of the emission pulse at low Iemi and a specific variation of the profiles with the pulse energy accompanied by a sizable temporal dispersion of the spin polarization along the pulse.

The temporal distribution of polarization and the pho-
toemission current profile at the maximum value of the average photocurrent $I_{emi} = 300 \text{nA}$ are presented in Fig. 1. The maximum value of polarization at the front of the emission pulse grows with the pulse charge and achieves $P \approx 91 \%$ at $I = 300 \text{nA}$. The pulse length as a function of the excitation energy is shown for the two structures in Fig. 2. For both structures the length of the pulse, measured as a time interval, during which 90 % of the pulse charge is emitted, grows starting from about 10 pA current and then closely follows a square-root dependence, $t_{90} \propto \sqrt{Q}$ where $Q$ is the pulse charge.

The profile of the current pulse is determined by the initial distribution of the electron velocities and emission moments. At small currents the average pulse duration depends on the extraction time from the working layer $t_d$ and the acceleration time dispersion $\tau_{acc}$ due to the spread of the electron initial velocities normal to the surface in the samples with high Negative Electron Affinity (NEA).

For the analysis of the experimental profiles we have used as an initial distribution function, a distribution generated by the diffusion of electrons from the working layer [2] and their subsequent energy relaxation in the band bending region [3]. The calculated pulse shapes differ for the case of $\tau_{acc} > t_d$ (large NEA) and for the opposite case. The profile for the small values of NEA (SLH) is determined by the experimental resolution and is close to Gaussian. For higher NEA the shape is non-gaussian and is close to experimental (triangular) assuming the homogeneous distribution of the electron velocities.

The electric charge of the pulse generates the electric field which changes the acceleration conditions through the field of the pulse remains by two orders of magnitude lower than the external accelerating field. The dispersion of the arrival time caused by the Coulomb repulsion $\delta t_0 = t_0 \delta a/a$, where $\delta a = eQ/ScOm$, $S$ is the excitation spot area, and $\delta a/a \approx 10^{-2}$ for the pulse charge of 4.5 nC. The estimation of the spread time due to Coulomb repulsion gives experimentally observed values and results in close to a square root dependence of the pulse length on its charge. Note that the time of electron flight to the reg-

![FIG. 1: Polarization distribution along the emission pulse profile.](image1)

![FIG. 2: Emission pulse length for strained GaAsP layer and for SW SL structures for different values of the $I_{emi}$.](image2)
close to the excitation moment. Then the polarization decay during the electron relaxation time in BBR result in average polarization decay of 6\% in the emission pulse. Note, that in this case the polarization losses in transport remain constant along the final part of the pulse, while the dispersion of polarization losses in BBR should prevail.

Conclusion

The achieved time resolution, increased by the space charge pulse expansion, allowed us to separate the first high-velocity electrons emitted at the high end of the electron energy distribution close to the excitation moment that have not experienced spin relaxation during the processes of transport to the surface or energy relaxation at the surface potential well. Their polarization is found to be above 90\%, which is apparently the highest spin polarization value registered for the present.

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