PERIOD DEPENDENCE OF TIME RESPONSE OF STRAINED SEMICONDUCTOR SUPERLATTICES

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Transport of spin polarized electrons in semiconductor AlInGaAs/AlGaAs superlattices with strained quantum wells used for photoemitter application is studied. The experimental study is based on the time resolved measurements of electron emission from the cathode after its photoexcitation by fs laser pulse. We report the variation of the SL response time with the number of superlattice periods. We also performed theoretical calculations of photocathode pulse response and compared the obtained results with experimental data. Our analysis testifies the presence of partial electron localization in SL. We demonstrate that electron localization suppresses electronic transport and strongly limits the cathode quantum efficiency.

1. Introduction

Semiconductor superlattices (SL) with strained quantum wells (QW) are known as a best material for the working layer of polarized electron source making it possible to develop the photoemitter with polarization of electron emission higher than 90 % [1, 2]. However, the significant progress in electron polarization (P) was achieved at the expense the quantum efficiency (QE) which does not exceed 1 % at the polarization maximum. Thus the further progress of polarized electron sources based on semiconductor SLs is shifted towards the developing of highly effective photoemitters in order to meet the modern requirements of high energy physics [3].

Our study demonstrates that the simple increase of the SL's thickness does not lead to increase of QE like it is observed in the case of conventional photoemitters with GaAs working layer. In order to understand this surprising phenomenon we perform the time resolved measurements of electron emission from the cathodes after their excitation by fs laser pulse. This method has been developed by P. Hartmann et al [4] to study the spin polarized electron transport in conventional photocathodes. The series of AlInGaAs/AlGaAs SLs containing from 6 to 15 periods have been fabricated and studied. In all samples we observe two exponential decays of electron emission which indicates the presence of partial electron localization in SL. The fast decay is caused by electron emission from the first electronic miniband while slow response decay is connected with electrons trapped by the localized states.

We also developed a theoretical description of electron transport in SL based on the time dependent kinetic equation and calculated the photocathode pulse response. The obtained results are in good agreement with the experimental observations. The employed model determines the time of electron transport in SL, electron capture and detachment times, portion of photoelectrons that have been localized by the traps in SL and corresponding losses of QE.

2. Experiment

We have studied the pulse response of six photocathodes based on AlInGaAs/AlGaAs SL with strained QWs. All samples were grown on a p-type (100) GaAs substrate by molecular beam epitaxy (MBE). The cathode structure contains a thick $Al_xGa_{1-x}As$ ($x = 0.35 - 0.4$) buffer layer that is p-doped by Be to the level $6\cdot10^{18}$ cm^{-3}. On the top of the buffer the cathodes working layer was grown containing 6 to 15 periods of $Al_xIn_yGa_{1-x-y}As(a)/Al_zGa_{1-z}As(b)$ SL p-doped to a lower level of $3\cdot10^{17}$ cm^{-3}. Layer composition, x, y, z, values of the QW- (a) and barrier- (b) layer thickness as well as the number of SL periods (N) are shown in Table 1. Above the SL a 6 nm GaAs heavily Be-doped to the level $7\cdot10^{18}$ cm^{-3} ($1\cdot10^{19}$ cm^{-3} for SL 5-998) surface layer was grown to produce thin BBR. Finally the GaAs surface was activated by repeating deposition of cesium and oxygen to achieve

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Table 1. Composition of photocathode working layer: number of SL's periods (N), concentration of Al (x) and In (y) in $Al_xIn_yGa_{1-x-y}As$ QW layer, Al concentration (z) in $Al_zGa_{1-z}As$ barrier layers and their thicknesses (a, b)

Samples	QW		Barrier	Thickness		Periods
	x, %	y, %	z, %	a, nm	b, nm	N
SL 5-998	20	16	28	3.5	4.0	15
SL 5-337	20	16	28	5.0	4.0	15
SL 7-395	20	19	40	5.4	2.1	12
SL 7-396	20	19	40	5.4	2.1	12
SL 6-905	20	15.5	36	5.1	2.3	10
SL 6-908	20	15.5	36	5.1	2.3	6

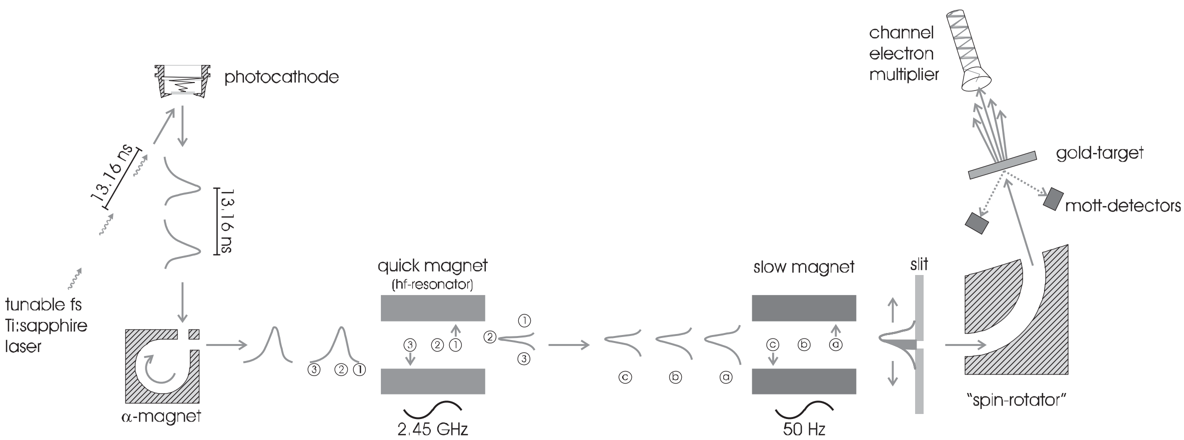

Figure 1. Experimental setup.

the negative electron affinity. All experiments were performed at room temperature.

The experimental setup is shown in Figure 1. The electron pulses are generated by an approximately 150 fs long laser pulse from a titanium-sapphire laser. An increase of pulse length to 300 fs takes place during optical beam transport to the cathode. These lightpulses are synchronized to the output of a klystron which drives a 2.45 GHz-deflection cavity. By passing the first deflection cavity (quick magnet in Figure 1), the longitudinal profile of the electron bunches is transferred into a corresponding transverse profile. The pulse profile can then be measured by moving the electron pulse in the second deflection cavity (slow magnet in Figure 1) over a narrow slit and detecting the transmitted current. By analyzing the spin polarization of the transmitted electrons with a Mott polarimeter a time resolved polarization measurement is obtained. Details of the apparatus are described by K. Aulenbacher *et al*. [5].

3. Theory

We describe the electron transport in SL by means of the time dependent kinetic equation:

$$\frac{\partial \hat{\rho}}{\partial t} = -\frac{i}{\hbar}\left[\hat{H}\hat{\rho}\right] + I\{\hat{\rho}\}, \qquad (1)$$

here ρ is the electron density matrix, H is the effective electron Hamiltonian for the first electronic miniband $e1$ which describes the quantum electron motion along SL axis. We calculate the miniband energy spectrum using the multiband Kane model, including the conduction band Γ_6, the states of light and heavy holes of the valence band Γ_8 and also the states of the spin-orbit split Γ_7 band [6]. The width ΔE of the $e1$ miniband along the SL axis in the considered samples is in the range 20 – 40 meV. These values are much smaller than the conduction band offsets which appear to be larger than 200 meV for all considered samples. Consequently, the vertical electron motion along SL axes can be well described within the tight binding approximation. For effective Hamiltonian H it means that we have to take

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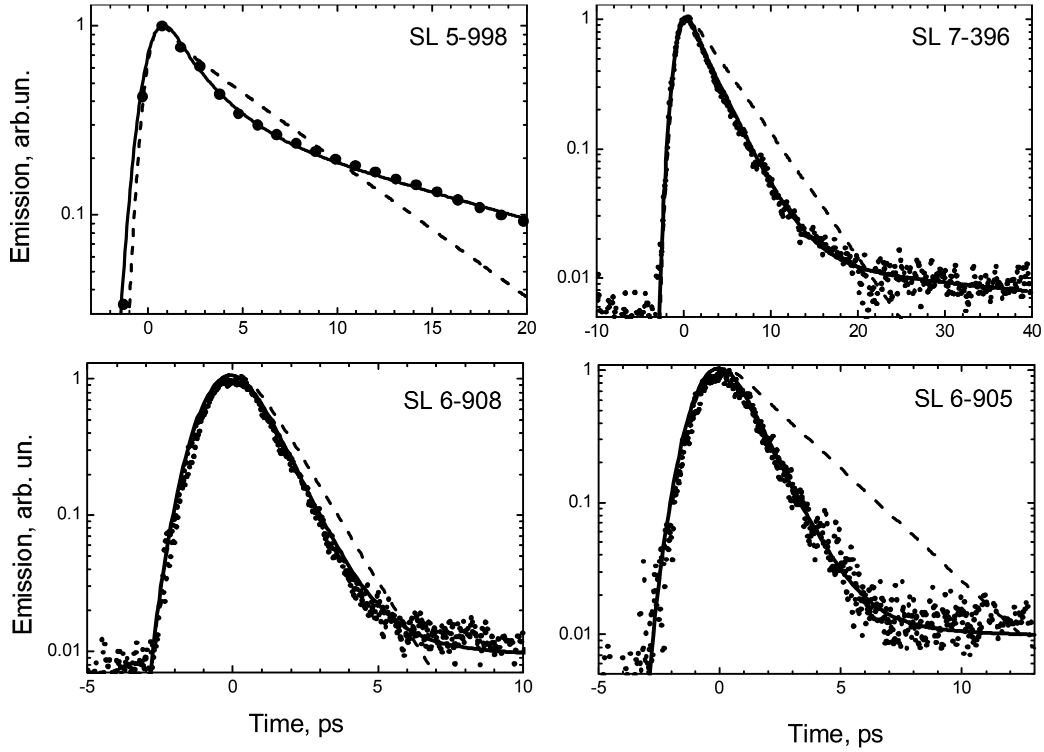

Figure 2. Pulse response of SL 5-998, SL 7-396, SL 6-905 and SL 6-908 samples. Experimental signal is shown by dots, solid and dashed lines show the pulse response calculated with and without partial electron localization respectively.

into account the coupling matrix element $V \equiv H_{n,n+1} = \Delta E/4$ between the neighboring QWs only. This matrix element determines the tunneling time between neighboring QWs $\tau_{QW} = \pi\hbar/2V = 2\pi\hbar/\Delta E$ which is about 100 fs for our samples.

The collision term $I\{\rho\}$ on the right hand side of Eq. (1) takes into account all processes of electron scattering on impurities and phonons within the constant relaxation time approximation. For numerical calculations we take the momentum relaxation time equal to τ_p = 75 fs. Note that τ_p is comparable to the time of free electron tunneling between neighbouring QWs τ_{QW}. Therefore electron transport along SL axis is diffusion, not the ballistic motion.

The collision term includes also the processes of photoexcitation, recombination and electron extraction into band bending region (BBR). Calculation of the photogeneration rate is described in details in Ref. [6]. The extraction electron current from SL to BBR can be written via the number of electrons in the last QW, ρ_{NN}, and tunneling time trough the last barrier, $\tau_f : I = \rho_{NN} / \tau_f$. To calculate τ_f we solve the separate quantum mechanical problem of free electron motion through the single QW to BBR. It is worth to note that the obtained τ_f is larger than the tunnelling time between neighbouring QWs τ_{QW}, e.g. for SL 5-998 τ_f = 0.25 ps.

The pulse response of the studied samples indicates the presence of partial electron localization. That is why we include in the density matrix ρ the localized electron states besides the delocalized mimiband states and introduce in the collision term $I\{\rho\}$ processes of electron capture and detachment with characteristic times τ_c and τ_d respectively.

4. Results and discussion

The cathode pulse response has been calculated by the numerical solution of Eq. (1). The obtained results together with the experimental signal are shown in Figure 2 and presented in Table 2. The dashed lines in Figure 2 show the pulse response calculated without electron localization. It exponentially decays with the decay time equal to the time of miniband electron transport from SL to BBR. The calculated miniband electron times τ_t are presented in the third column of the Table 2. Figure 2 demonstrates that in all samples experimental signal decays faster than τ_t. We interpret this fact as an evidence of partial electron localization. Indeed, in the presence of electronic traps the electron current will decay faster due to combination of two processes: electron transport from SL to BBR with subsequent emission into the vacuum and electron

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capture by the traps. Roughly, the decay (or response) time can be approximated as $\tau = 1/(1/\tau_t + 1/\tau_c)$. The resulting response times are presented in the sixth column of the Table 2. The solid lines in Figure 2 show the pulse response calculated taking into account electron capture and reverse detachment processes. Figure 2 demonstrates quite good agreement of experiment and theory. The capture and detachment times are used as fitting parameters and their values are shown in the Table 2. These times depend on the trap density and strongly vary from one sample to another. This fact masks the response time dependence on the number of SL periods. Thus six and ten periods samples have close response times though the miniband transport time of the longer SL is more than two times larger than for the shorter one.

Table 2. Parameters of vertical electron transport, transport time of $e1$ miniband (τ_t), capture time (τ_c), detachment time (τ_d), response time (τ), diffusion length and losses of photoelectrons SL

Samples	Number of periods	Miniband transport time, ps	Capture time, ps	Detachment time, ps	Response time, ps	Diffusion length, periods	Electron losses, %
SL 5-998	15	5.8	4.5	6.0	2.3	36	12
SL 5-337	15	15.8	5.5	160	4.0	8	64
SL 7-395	12	4.5	3.7	200	2.1	11	45
SL 7-396	12	4.5	9.0	110	3.0	18	23
SL 6-905	10	2.5	2.1	130	1.1	10	41
SL 6-908	6	1.2	4.5	50	0.95	19	9

Samples with shorter capture and larger detachment times have the larger level of electron localization. In these samples electron transport is suppressed because considerable part of photoelectrons is localized by the traps. To demonstrate the effect of localization on QE we show in the last two columns of the Table 2 the diffusion length and electronic losses in SL. In the samples with high localization level the diffusion length is comparable with SL thickness which in turn leads to considerable electronic losses. This fact explains why QE does not increase with growth of SL thickness. The increase of the SL thickness beyond the diffusion length just leads to needless electronic losses.

5. Conclusions

The pulse response of series photocathodes with AlInGaAs/AlGaAs SLs with different number of periods has been studied. The analysis performed argues the presence of partial electron localization in SL. The proposed kinetic model taking into account transport of miniband electrons from SL to BBR, their capture by electronic traps and the reverse detachment process provides a good agreement between experimental findings and theoretical results. We demonstrate that electron localization slows down electron transport and leads to detrimental losses of photoelectrons. Partial electron localization limits maximal QE and useful thickness of SL based cathodes working layer.

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