Spin polarized electron transport and partial localization of photoelectrons in highly doped photocathodes

L G Gerchikov1,3, K Aulenbacher2, Yu A Mamaev1, E J Riehn2 and Yu P Yashin1

1St. Petersburg State Polytechnic University, St. Petersburg, Russia
2Institute of Nuclear Physics, Mainz University, Mainz, Germany

E-mail: lgerchikov@rambler.ru

Abstract. The results of experimental and theoretical studies of spin polarized electron transport in semiconductor SL used for photoemitter application are presented. The experimental study is based on the time resolved measurements of electron emission from the cathode after its photoexcitation by fs laser pulse. The response and spin relaxation times have been determined by means of measured time dependent intensity and polarization of electron emission. 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. Electron capture by localized states leads to unavoidable losses of quantum efficiency and polarization.

1. Introduction
At the present time, strained semiconductor superlattices (SL) are known as most effective basis of highly polarized electrons sources [1]. Such photoemitters combine the advantages of conventional polarized electrons sources based on a strained semiconductor layer with additional possibilities for band structure engineering of photocathodes working layers based on strained SL. The major goal of SL development for photoemitter applications in the past decade was the achievement of electron polarization more that 90%. For this purpose several types of SLs with highest possible valence band splitting had been developed, namely the SLs with strained quantum wells (QW) [2,3] and with strained barriers [4]. Valence band splitting in SL, i.e. the energy splitting between the upper heavy and light hole minibands, is formed due to the combination of two effects: the strain deformation of SL layers and the quantum confinement. The aim of the optimal SL design is to provide a valence band splitting of more than 70 – 80 meV together with good transport properties and high structural quality.

However, in spite of significant progress in electron polarization (P) the quantum efficiency (QE) at the polarization maximum of the developed photoemitters is rather small. The best combination of P = 92% and QE = 0.85% has been achieved for AlInGaAs/AlGaAs SL with strained QWs [3]. Thus the further progress of SL based photoemitters is shifted towards the developing of highly effective polarized electron sources in order to meet modern requirements of high energy physics [5]. The developing of photocathode structures with distributed Bragg reflector (DBR) is an important step in this direction. One of the most fundamental reasons limiting the QE is the fact that
the high polarization of electron emission is achieved at the expense of QE. Indeed, the maximum spin polarization of photoelectrons takes place at the photoabsorption threshold where the photoabsorption coefficient is rather small. Strained SL can not be made too thick due to the possible strain relaxation resulting in structural defects, smaller residual strain and lower polarization. Thus the thickness of the working layer is smaller by an order of magnitude than the photoabsorption length and most of the light intensity is lost in the photocathode substrate. To overcome this problem the photocathode structure with DBR at the back side of the photocathode has been proposed [6-8].

Another way to increase QE is to enlarge the working layer as much as possible and to minimize the losses of photoelectrons prior to their emission into the vacuum. However this traditional approach does not work in the case of SL based cathodes and this fact indicates that the spin polarized electron transport in SLs is still not understood as well as for the conventional photoemitters [9, 10]. The QE of conventional cathodes based on a GaAs working layer gradually increases with the growth of working layer thickness until it exceeds the absorption and/or diffusion length. On the contrary our measurements of QE at polarization maximum for a series of SL based cathodes with a different number of SL periods show that the QE of the cathodes with thick SL containing more that ten periods is not larger than the QE of the cathodes with a four or six period SL. It means that electron transport in thick SLs is suppressed and useful SL length and hence the QE is strongly limited.

The aim of the present work is to study the spin polarized electron transport in SLs in order to figure out the reasons that are responsible for the suppression of electron transport and QE losses. Another aim of our study is to determine the polarization losses that occur on the stage of electron transport from SL to band bending region (BBR). It will be helpful to clarify whether the polarization losses can be reduced even more and the achieved level of electron polarization can be exceeded.

Our experimental method is based on time resolved measurements of electron emission from the cathode after its photoexcitation by a femtosecond (fs) laser pulse. This method has been developed by K. Aulenbacher et al [9] to study the spin polarized electron transport in conventional photocathodes. The observed time dependent intensity of electron emission determines the cathode response time while the time resolved measurement of electron polarization gives the spin relaxation time. We also developed a theoretical description of electron transport in SLs based on the time dependent kinetic equation and calculated the photocathode pulse response. The detailed comparison of the obtained results with the experimental data reveals a significant discrepancy between the observed electron emission and the pulse response of an ideal SL. We interpret this fact as a presence of partial electron localization in SL. Such localization which drastically changes the character of vertical electron transport in SLs has been already observed in heavily doped GaAs/AlAs SLs [11]. The high doping level is used within the photocathode structures in order to form a narrow BBR needed to minimize electron and polarization losses during electron emission into the vacuum. Besides the fluctuations of impurity potential and/or the SL’s layer composition the structural defects formed due to the strain relaxation in SLs can be also considered as a source of electron localization.

We developed a simple kinetic model to describe the electron transport in a SL in the presence of partial electron localization. It takes into account the electron diffusion along the SL axes, tunneling into the BBR, electron capture by localized states and reverse processes of electron detachment. The obtained results are in good agreement with the experimental observations. The employed model determines the capture time, portion of photoelectrons that have been localized by traps in SL, losses of QE and polarization.

2. Experiment

We have studied the pulse response of four 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$_x$Ga$_{1-x}$As ($x = 0.35 - 0.4$) buffer layer that is p-doped by Be to the level $6 \times 10^{18}$ cm$^{-3}$. On the top of the buffer the cathodes working layer was grown containing 4 to 15 periods of Al$_{1-y}$In$_y$Ga$_{1-x}$As(a)/Al$_x$Ga$_{1-y}$As(b) SL p-doped to a lower level of $3 \times 10^{17}$ 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 $7 \times 10^{18}$ cm$^{-3}$ (1$\times 10^{19}$ 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 the negative electron affinity. All experiments were performed at room temperature.

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

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 light pulses 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 [9].

3. Theoretical approach
To reproduce the experimentally observed photocathode pulse response we calculate the electron current $I(t)$ from SL to BBR. We neglect the time of electron emission from BBR into the vacuum because this time is smaller than the apparatus resolution time. This fact is proved by pulse response measurements for the cathodes with extremely thin working layers. The electron current $I(t)$ is found by the solution of the time dependent kinetic equation

![Figure 1. Experimental setup.](image-url)
\[
\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar} [\hat{H}\rho] + St\{\rho\},
\]

(1)

where \(\rho\) is the electron density matrix, \(H\) is the effective electron Hamiltonian for the first electronic miniband \(e_1\) which describes the quantum electron motion along SL axis. We calculate the miniband energy spectrum using the multiband Kane model, including the conduction band \(\Gamma_6\), the states of light and heavy holes of the valence band \(\Gamma_8\) and also the states of the spin-orbit splitted \(\Gamma_7\) band [12]. The width \(\Delta E\) of the \(e_1\) miniband along the SL axis in the considered samples is in the range 32 -37 meV. These values are much smaller than the conduction band offsets which appeared 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 only have to take into account the coupling matrix element between the neighboring QWs \(V \equiv H_{n,n+1} = \Delta E/4\). 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 total time of free electron motion within SL containing \(N\) QWs is \(N\) times larger \(\tau_{SL} = 2\pi\hbar N/\Delta E\).

The last term on the right hand side of equation (1) is the collision term which takes into account all processes of electron scattering on impurities, phonons etc, photoelectron generation under the optical pumping and electron extraction into BBR. The first contribution to the collision term we write in the constant relaxation time approximation

\[
St\{\rho\} = -\rho/\tau_p. 
\]

(2)

Due to the rather weak coupling between the QWs the momentum relaxation time \(\tau_p\) is connected mainly with electron scattering in SL’s heteroplane within each QW. For the numerical calculation we take \(\tau_p = 75\) fs. Note that \(\tau_p\) is about the time \(\tau_{QW}\) of electron tunneling between QWs. Thus the vertical electron transport in considered samples has the character of electron diffusion rather than ballistic motion.

The second contribution to the collision term comes from photoelectron generation. Calculation of the photogeneration rate is described in details in Ref. [12]. The third contribution to the collision term is connected with electron tunneling from the last QW to BBR. The corresponding electron current can be written via the number of electrons in the last QW, \(\rho_{NN}\), and tunneling time through the last barrier, \(\tau_f\):

\[
I = \frac{\rho_{NN}}{\tau_f}. 
\]

(3)

To calculate \(\tau_f\) we solve the separate quantum mechanical problem of free electron motion through the single QW to BBR, find the electron density and current and determine eventually \(\tau_f\) via equation (3). It is worth to note that the obtained \(\tau_f\) is larger than \(\tau_{QW}\), e.g. for SL 5-998 \(\tau_f = 0.25\) ps. It is quite natural because the tunneling between the neighboring QWs is a resonant process and its probability is proportional to the first order of the tunneling exponent \(\exp(-\kappa b)\), where \(\kappa\) is the electronic wave vector under the barrier and \(b\) is the barrier width. The tunneling through the last barrier is a non resonant process and its probability is smaller since it is proportional to the second order of the tunneling exponent \(\exp(-2\kappa b)\). Thus the total tunneling time through the whole SL to BBR is determined by the slowest process, i.e. by the tunneling throw the last barrier.
Equation (3) can be considered as the boundary conditions for the kinetic equation (1) at the heterojunction of SL and BBR. At the opposite SL’s side, at the heterojunction with the buffer layer, electron current is zero. In the bulk case the boundary condition is written via the so named surface recombination velocity, \( j = n/S \), where \( n \) is the electron density. Comparing this with equation (3) we conclude that the surface recombination velocity in our case is equal to

\[
S = \frac{d}{\tau_f},
\]  

where \( d = a + b \) is the SL period. Surface recombination velocities for our SL based cathodes calculated according to equation (4) are smaller than in the case of conventional photoemitters, e.g. for SL 5-998 \( S = 3 \times 10^6 \text{ cm/s} \), for SL 6-905 \( S = 5 \times 10^6 \text{ cm/s} \) while in the bulk GaAs \( S = 10^7 \text{ cm/s} \) [9].

For numerical simulation of the cathode response we solve the time-dependent kinetic equation (1) with time dependence of the laser pulse intensity described by the Gaussian profile. The obtained electron current \( I(t) \) (3) is compared then with experimental pulse response (see next section). The calculated pulse response exponentially decays and we define a corresponding decay time as electron transport time \( \tau_t \). It is possible to derive the approximate explicit expression for \( \tau_t \). In the steady state under the stationary pumping kinetic equation (1) has an analytical solution if the miniband width \( \Delta E \) is smaller than the photoelectron energy distribution. The transport time defined in the stationary case as the ratio of number of electrons inside the SL to the generation rate is equal to

\[
\tau_t = \frac{\hbar^2 (N - 1/2)(N - 1)}{6|V|^2 \tau_p} + N \tau_f ,
\]  

According to equation (5), the transport time is a sum of the diffusion time within the SL given by the first term on the r.h.s. of equation (5) and the time \( N \tau_f \), taken to penetrate through the last barrier to the BBR. For 12 periods SL 5-998 equation (5) gives the transport time \( \tau_t = 5 \text{ ps} \). The main contribution, \( 3 \text{ ps} \), comes from the tunneling through the last barrier to BBR.

Note that in the limit of thick SL, \( N >> 1 \), equation (5) transfers to a corresponding expression of the standard diffusion model

\[
\tau_t = \frac{L^2}{3D} + \frac{L}{S},
\]  

where \( L = Nd \) is the SL’s length. The surface recombination velocity \( S \) is given by equation (4) and diffusion coefficient \( D \) of SL is equal to

\[
D = \frac{2|V|^2 d^2 \tau_p}{\hbar^2}.
\]  

The typical value of \( D \) is about 15 cm²/s, e.g. for SL 5-998 \( D = 12 \text{ cm²/s} \) and for SL 6-905 \( D = 17 \text{ cm²/s} \). It is a few times smaller than the diffusion coefficient \( D = 40 \text{ cm²/s} \) in the bulk GaAs.
4. Results and Discussion

The experimentally observed pulse response of SL 5-998 sample is shown in figure 2 together with the results of our numerical calculations. The figure shows the significant discrepancy between experiment and theory. Namely, the calculated emission current exponentially decays with a transport time of $\tau_t = 6$ ps while the experimental signal reveals the non-exponential decay. During the first six picoseconds after excitation the experimental signal decays faster than theoretically predicted with decay time $\tau_1 = 4$ ps. Then its decay slows down and can be fitted by an exponent with a decay time of $\tau_2 = 13$ ps which is larger than $\tau_t$. This picture is similar for all four samples. We can distinguish in the cathodes pulse response a fast decay followed by a rather long tail with decay times related to the calculated transport time as $\tau_1 < \tau_t < \tau_2$.

In figure 3 the pulse response of SL 7-396 sample is shown together with polarization of electron emission. The polarization decay is fitted by the exponent with spin relaxation time $\tau_s = 81$ ps. Note that electron polarization even 30 ps after the pulse excitation is larger than 60%. It means that the long tail of pulse response is connected with electrons generated in the SL.

These results can be explained by partial electron localization within the SL. Indeed, in the presence of electronic traps the emission current will decrease faster just after the photoexcitation because of combination of two processes depopulating $e_1$ miniband states: electron tunneling to BBR and capture by localized states in SL. The existence of long tails in pulse response can also be well understood within the model of partial localization. This slow part of emission current is connected with trapped electrons that return to miniband states due to the thermoactivation detachment processes.

To verify the proposed model we apply the very simple kinetic scheme which takes into account two groups of electron states: delocalized electron states in the $e_1$ miniband and localized electronic states below the mobility edge. We will describe the rate of the detachment processes by a single detachment time $\tau_d$ instead of the broad distribution of $\tau_d$ for various localized states. The rate of the electron capture we denote as $1/\tau_c$ and the extraction rate of miniband electrons to BBR is $1/\tau_t$. Then the kinetics of the miniband (delocalized) and localized electrons is described by the following equations:

\[ \text{Intensity, arb. u.} \]

\[ \text{Time, ps} \]
\[
\frac{dn_1}{dt} = -\frac{n_1}{\tau_c} - \frac{n_1}{\tau_t} + \frac{n_2}{\tau_d},
\]

\[
\frac{dn_2}{dt} = -\frac{n_2}{\tau_c} - \frac{n_2}{\tau_d},
\]  

(8)

where \(n_1\) and \(n_2\) denotes the number of miniband and localized electrons respectively. To reproduce the decay of pulse response we use the following initial conditions: \(n_1 = 1, n_2 = 0\), which assumes that on the instant of excitation there are no localized electrons. In this case the solution of equations (8) is given by the sum of two exponents

\[
n_{1,2}(t) = \left(\frac{\tau_2 - \tau_1}{\tau_2 - \tau_1}\right) \exp\left(-\frac{t}{\tau_2}\right) + \left(\frac{\tau_t - \tau_1}{\tau_2 - \tau_1}\right) \exp\left(-\frac{t}{\tau_1}\right),
\]

\[
\tau_{1,2}^{-1} = \frac{1}{2} \left(\tau_t^{-1} + \tau_c^{-1} + \tau_d^{-1} \pm \sqrt{\tau_t^{-2} + \tau_c^{-2} + \tau_d^{-2} + 2\tau_t^{-1}\tau_c^{-1} + 2\tau_t^{-1}\tau_d^{-1} - 2\tau_c^{-1}\tau_d^{-1}}\right).
\]  

(9)

The capture and detachment times \(\tau_{c,d}\) in equations (8,9) are used as fitting parameters while the miniband transport time \(\tau_t\) is calculated according to equation (5).

The results of the proposed model for four samples SL 5-998, SL 7-396, SL 6-905 and SL 6-908 are shown in figure 4 and table 2. The calculated emission current is shown in figure 4 by solid lines and is proportional to the number of miniband electrons \(n_1(t)\) given by equation (9). Good agreement
between calculated results and experimental data verifies the applicability of the proposed model. Parameters of the model used in the calculations are presented in table 2. The capture and detachment times are chosen in order to match decay times $\tau_{1,2}$ in equation (9) with decay times of experimental signal. The portion of localized electrons which is equal to $\tau_t/(\tau_t + \tau_c)$ shows what part of photoelectrons have been trapped in SL. The average transport time is the total time that electrons spend in SL prior to their extraction to BBR averaged according to equation (9). Finally we calculate the value of electron and polarization losses in SL using the electron life-time $\tau_e = 50$ ps [13] and spin relaxation time $\tau_s = 81$ ps.

![Figure 4. Decay of the pulse response calculated according to equations (9) for SL 5-998, SL 7-396, SL 6-905 and SL 6-908 samples.](image)

Electron localization slows down the electron transport which leads to disappointing losses of QE and polarization. Let us estimate the maximal QE at polarization maximum that could be achieved in the case of ideal SL, i.e. SL without electronic traps. The diffusion length $L_D = (D \tau)^{1/2}$ for SL 6-908 is equal to 0.29 $\mu$m which is equivalent $N_D = L_D/d = 39$ QWs. The maximal QE of the photocathode with BBR as in SL 6-908 sample and with infinite SL with composition identical to SL 6-908 is equal to 2.2%. Photocathode SL 6-908 has the best transport properties of all considered samples. It has the lowest level of electron localization and hence the minimal electronic losses. If it would be possible to grow cathode structure with the same parameters as SL 6-908 and containing $N = N_D$ SL periods its QE will be 1.9%, i.e. three times larger than QE = 0.57% of SL 6-908 sample.
However our study demonstrates that the longer SL has worse transport properties than the shorter one. Indeed, SL 6-905 sample containing ten periods SL with the same composition as SL 6-908 has electronic losses which are six times larger than in SL 6-908 samples. It means that the density of electronic traps and hence the level of electron localization in this sample is much higher than in SL 6-908. Larger density of electronic traps leads to shorter capture time and higher localization level (see table 2). Another important parameter depending on trap density is the ratio of capture and detachment times which is equal to the ratio of miniband and localized electrons at the equilibrium. For SL 6-905 this parameter is smaller by the order of magnitude than for SL 6-908. The large difference of electron localization and corresponding electronic losses in SL 6-905 and SL 6-908 samples explains why the cathodes with ten and six period SLs have close values of QE.

Table 2. Parameters of vertical electron transport, transport time of $e_1$ miniband ($\tau_t$), capture time ($\tau_c$), detachment time ($\tau_d$), portion of localized electrons, total transport time, losses of photoelectrons and spin polarization in SL.

| Samples  | Number of periods | Miniband transport time, ps | Capture time, ps | Detachment time, ps | Partial localization, % | Average transport time, ps | Electron losses, % | Spin losses, % |
|----------|-------------------|-----------------------------|-----------------|---------------------|-------------------------|----------------------------|-------------------|--------------|
| SL 5-998 | 15                | 6.0                         | 5.6             | 4.3                 | 52                      | 11                         | 17                | 9            |
| SL 7-396 | 12                | 4.5                         | 9.4             | 66                  | 32                      | 36                         | 19                | 11           |
| SL 6-905 | 10                | 2.5                         | 1.7             | 27                  | 60                      | 45                         | 37                | 11           |
| SL 6-908 | 6                 | 1.3                         | 4.8             | 7.6                 | 21                      | 3.4                        | 6                 | 3            |

Within the present work we do not determine the nature of the localized electronic states as well as possible dependence of their density on SL’s thickness. The photocathode structure is heavily p-doped in order to achieve thin BBR. The highest doping level about $10^{19}$ cm$^{-3}$ is applied in BBR, but the working layer is also heavily doped up to $3\times10^{17}$ cm$^{-3}$. Fluctuations of impurity potential might be responsible for the formation of localized electron states. Such phenomena have been observed earlier in GaAs/AlAs SLs at a comparable doping level of $1\times10^{17}$ - $7\times10^{17}$ cm$^{-3}$ [11]. The 60% of localized states in the lowest electron miniband $e_1$ at a doping level of $4\times10^{17}$ cm$^{-3}$ have been reported. The drop of vertical electron conductivity caused by partial electron localization was observed. Unavoidable fluctuations of the layer composition and thicknesses can also contribute to partial electron localization. However one can assume that the density of electronic traps formed due to these mechanisms should not depend on the SL’s length. On the contrary, the density of structural defects such as dislocations formed in SL due to the strain relaxation increases for thick SLs. Lattice mismatch deformation of the QW layers shifts the conduction band edge upwards by approximately 0.1 eV. Thus the deformation potential of dislocation plays a role of deep well for miniband electrons and can form the localized electron states. Note that the strong deformation of the SL is needed to produce sufficient energy splitting between light- and heavy-hole minibands to achieve high electron polarization. Further work will focus on the nature of electron localization. Its main goal will be to determine the maximal number of SL’s periods that can be grown keeping good transport properties in combination with high electron polarization.

5. Conclusions
The spin polarized electron transport in photocathodes based on AlInGaAs/AlGaAs SLs with strained QWs has been studied. The pulse response of the cathodes has been measured and response and spin relaxation times have been determined. We develop the theoretical description of vertical electron transport in SL and compare the obtained experimental data on pulse response with results of our calculations. 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 data and theoretical results. We demonstrate that electron localization slows down electron transport and leads to losses of photoelectrons and polarization. Partial electron localization limits maximal QE and useful thickness of SL based cathodes working layer.

6. Acknowledgments
This work was supported by Russian Ministry of Education and Science under grant 2.1.1/2240 and by DFG through SFB 443.

References
[1] Subashiev A V, Mamaev Yu A, Yashin Yu P, Clendenin J E 1999 Phys. Low-Dim. Struct. 1-2 1
[2] Nishitani T et al 2005 J. Appl. Phys. 97 094907
[3] Mamaev Yu A, Gerchikov L G, Yashin Yu P, Vasiliev D A, Kuzmichev V V, Ustinov V M, Zhukov A E and Mikhrin V S 2008 Appl. Phys. Lett. 93, 81114
[4] Gerchikov L G, Mamaev Yu A, Subashiev A V, Yashin Yu P, Vasil’ev D A, Kuz’michev V V, Zhukov A E, Semenova E S, Vasil’ev A P and Ustinov V M 2006 Semiconductors 40, 1326
[5] Brachmann A, Clendenin J E; Garwin E L, Ioakeimidi K, Kirby R E, Maruyama T, Prescott C Y, Sheppard J, Turner J and Zhou F 2007 17th International Spin Physics Symposium: AIP Conference Proceedings (Kyoto, Japan, 2-7 October 2006) 915, pp 1091-4
[6] Groebli J C, Oberli D, Meier F, Dommann A, Mamaev Yu A, Subashiev A V and Yashin Yu P 1995 Phys. Rev. Lett. 74 2106.
[7] Bakarov A K, Jaroshevich A S, Toropov A I, Scheibler H E, Terekhov A S 1999 Int. Workshop on Polarized Sources and Targets (PST 99): Proc. (Erlangen, Germany, 29 September - 2 October 1999) p 238
[8] Gerchikov L G, Mamaev Yu A, Yashin Yu P, Vasil’ev D A, Kuz’michev V V, Ustinov V M, Zhukov A E, Vasil’ev A P and Mikhrin V S 2009 Semiconductors 43 463
[9] Aulenbacher K, Schuler J, Harrach D, Reichert E, Roethgen J, Subashev A, Tioukine V and Yashin Ya 2002 J. Appl. Phys. 92 7536
[10] Oskotskij B D, Subashiev A V and Mamaev Yu A 1997 Phys. Low-Dim. Struct. 1-2 77
[11] Pusep Yu A, Chiquito A J, Mergulhao S and Galzerani J C 1997 Phys. Rev. B 56 0163
[12] Subashiev A V, Gerchikov L G, Ipatov A I 2004 J. Appl. Phys. 96 1511
[13] Matsuyama T, Takikita H, Horinaka H, Wada K, Nakanishi T, Okumi S, Nishitani T, Saka T and Kato T 2004 Jap. J. Appl. Phys. 43 3371