9th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 18–22, 2001

Electron optical orientation in strained superlattices

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Abstract. Optical spin orientation in the strained short-period semiconductor superlattices is investigated theoretically using 8-band effective mass Hamiltonian. We demonstrate that the strong features in the spin-polarization dependence on the electron energy are associated with Van-Hove singularities in absorption spectra and can be observed both for large and small barriers for the electrons. Calculated polarization spectra are close to the experimental spectra of polarized electron emission.

Introduction

Optical orientation in semiconductor structures has been extensively studied in recent years (see e.g. [1]). In quantum well (QW) and superlattice (SL) structures the 4-fold degenerate Γ_8 valence band state is splitted into only 2-fold spin-degenerate states Γ_6 (heavy-hole subband) and Γ_7 (light hole subband), the heavy-hole band being moved up. The splitting is enlarged with compressive layer strain. Therefore when the electrons are excited by circularly polarized light at the absorption edge from the heavy-hole subband the polarization of the excited electron is $P = 1$.

At higher energies the light holes contribute to the absorption, and smaller polarization is obtained, since the direction of the spin orientation is opposite for the electrons excited from the edge of heavy-hole and light-hole bands.

The electron optical orientation is widely used for the studies of the spin relaxation processes in the heterostructures (see e.g [2]). In addition, high electronic polarization have made strained GaAs-based superlattices (SLs) very promising as photoemitters of highly polarized electrons [3]. They have proven to provide reproducibly the emitted electron polarization as high as 86% with sufficiently high quantum efficiency at the polarization maximum [4].

In this paper, we report the first theoretical studies of the optical orientation of the electrons in the strained InGaAs-AlGaAs and GaAs-AlInGaAs superlattices studied experimentally (see [3, 4]) by the polarized electron emission spectroscopy with high energy resolution. The interpretation of the observed features in the spectrum is obtained.

Model, absorption and polarization spectra

We have calculated the miniband spectrum, optical absorption and spin polarization spectra of strained superlattices using the envelope-function approximation, in the framework of the 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 splitted band Γ_7 [5]. The miniband spectrum as a function of wave vector in the layer plane $k_\parallel$ and along the growth direction, k_z parallel to [100] axis is presented in Fig. 1(a), for a strained $GaAs-Al_{0.18}In_{0.16}Ga_{0.66}As$ SL with well and barrier thicknesses $d_w = d_b = 4$ nm. The positions of the band edges

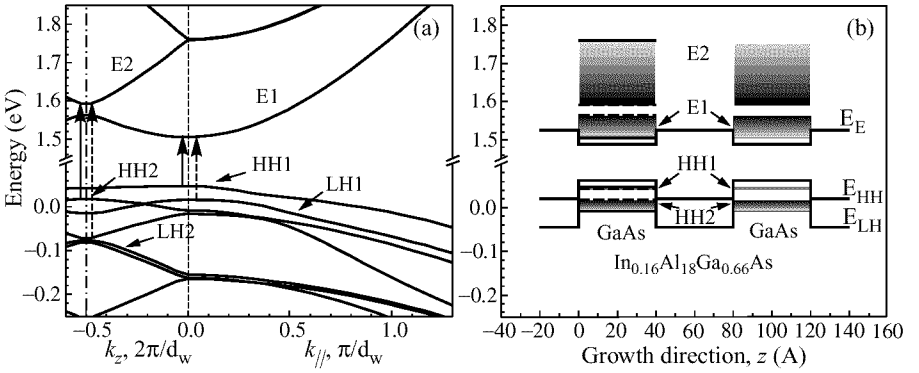

Fig. 1. (a) Miniband spectrum of GaAs-AlInGaAs superalttice and the major optical transitions (shown by vertical arrows) contributing to the absorption spectrum, and (b) the positions of the band edges.

are illustrated in Fig. 1(b). The composition of the SL layers in this SL is aimed to get large enough valence band splitting in addition to a small conduction band offset to provide high polarization and high mobility of the excited electrons. In Fig. 1 the small conduction band offset shows itself in a very small splitting between the 2-d and the 3-d electronic minibands at the center of the Brilluin zone. Still noticeable splitting between the first and the second electronic minibands remains at $k_z = \pi/d$, $d = d_w + d_b$.

For the circularly polarized light absorption the spin polarization of electrons excited in all minibands of the conduction band at the excitation moment was calculated as

$$P = \frac{\sum_n (K_\uparrow^n - K_\downarrow^n)}{\sum_n (K_\uparrow^n + K_\downarrow^n)} \tag{1}$$

Here $K_\uparrow^n$ ($K_\downarrow^n$) is the absorption coefficient for the excitation in the n electronic miniband state with spin up (spin down) from all the hole minibands. According to Eq. (1), the resulting electron polarization depends on the relative contribution of the light- and heavy-hole bands, the singularities in the polarization being originated from the Van-Hove singularities in the absorption spectra.

The transition rate for the electrons excited by the circularly polarized light from the minibands of the valence band states in the n-th conduction miniband state with spin up (↑) and spin down (↓) is proportional to the squared dipole matrix element and the interband density of states. The squared matrix elements $|M|^2_{i,k}$ for the main optical transitions in two electron spin states (↑ and ↓) are depicted in Fig. 2. Note that the dependence of $|M|^2_{i,k}$ on the lateral wave vector $k_\parallel$ is qualitatively similar to that calculated previously for the infinitely large band offsets (infinitely deep QW model) [6]. Then, the dependence of the matrix element on the momentum k_z along the SL axis is rather weak. Finally, the absolute value of the hh2 → e2 matrix element is found to be close to that for the hh1 → e1 transition even in the case of small conduction band offset.

In Fig. 3 calculated spectra of the electron polarization at the excitation as a function of the excitation energy for GaAs–Al$_{018}$In$_{0.16}$Ga$_{0.66}$As superlattice are presented. The dependence of the polarization and absorption spectra on excitation energy reproduces the sequence of the miniband transitions. The polarization in the first maximum is found to

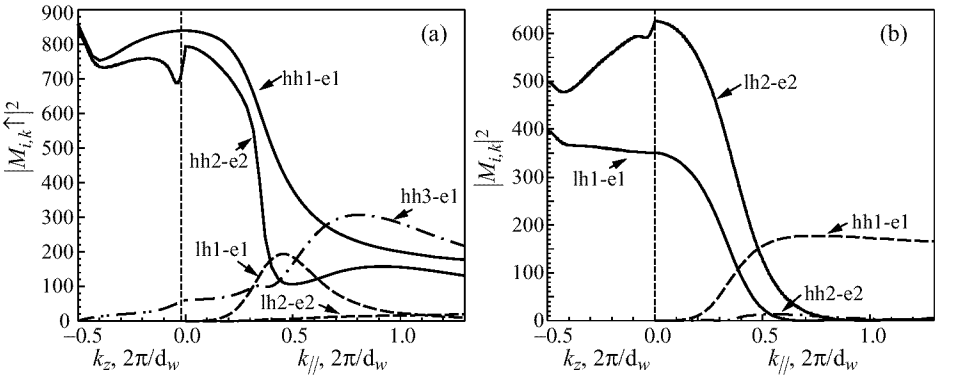

Fig. 2. Matrix elements for the interband optical transitions induced by circularly polarized light to the final state with spin up (a) and spin down (b) as a function of excitation energy for the GaAs-AlInGaAs strained superlattice.

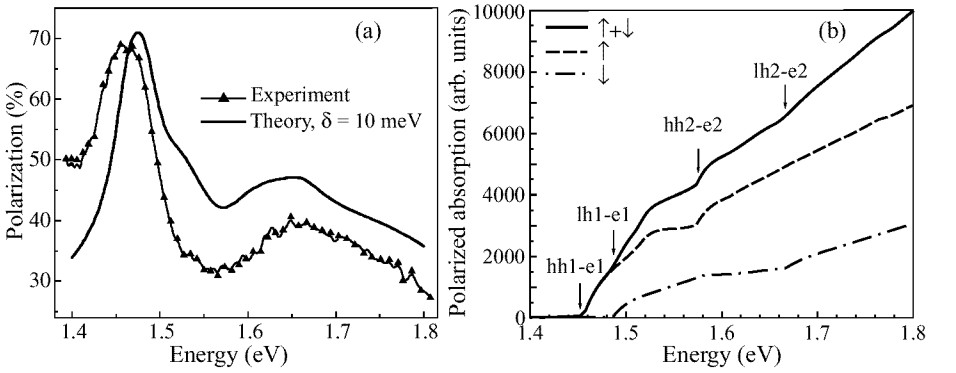

Fig. 3. (a) Polarization of the excited electrons (solid line) for the circularly polarized excitation of GaAs/AlInGaAs superlatice structure and the experimentally observed spectra of polarized photoemission from Ref. [4] (shown by triangles), $T = 300$ K; (b) absorption coefficients for two final electronic states and resulting sum as a function of excitation energy, $\delta = 1$ meV.

be very sensitive to the smearing of the absorption edge by the electron and the hole scattering processes, as well as the band edge fluctuations. In our calculations this factor is parametrized by a Lorentzian broadening of the interband transitions with the half width δ. While the minimum in the polarization spectra is definitely associated with lh1$\rightarrow$e1 transitions, the second maximum in the polarization spectra is found to be due to the transitions at $k_z = \pi/d$ of the miniband edge. For both considered superlattices it corresponds to electronic states with the energy above the barriers in the conduction band. Therefore the structure of the maximum and its contribution to polarization is sensitive to the barrier height (i.e. conduction band offset). The maximum polarization in this peak is found to exceed 50%. Taking into account the electron spin relaxation, the calculated spectra are in very good agreement with the observed excitation spectra of polarized electron photoemission both for AlGaAs-InGaAs and GaAs-AlInGaAs strained superlattices.

Conclusions

Thus, we have preformed the optical orientation calculations within 8-band Kane model for the strained superlattices. Three features originating from hh1→e1, lh1→e1 at $k_z = 0$ and hh2→e2 at $k_z = \pi/d$ are shown to dominate in the polarization spectra. This result is in line with the experimental data on the polarized electron emission. The last feature is sensitive to the band offset in the conduction band and can be used for the band offset evaluation and fine tailoring of the band structure.

Acknowledgments

This work was supported by the Russian State Program "Physics of Solid State Nanosrtuctures" under grant 97-1091, Russian Foundation for Basic Research under grant 00-02-16775, INTAS under grant 99-00125 and SNSF under grant 7IP 062585.

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