10th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 17–21, 2002

Removal of spin degeneracy in SiGe based nanostructures

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Abstract. The photogalvanic effects, which require a system lacking inversion symmetry, become possible in SiGe based quantum well (QW) structures due to their built-in asymmetry. We report on the removal of spin degeneracy in the **k**-space of SiGe nanostructures. This is concluded from the observations of the circular photogalvanic effect induced by infrared radiation in asymmetric *p*-type QWs. We discuss possible mechanisms that give rise to spin-splitting of the electronic subband states.

Introduction

The spin-degree of freedom of charge carriers and its manipulation has become a topical issue in material science under the perspective of spin-based electronic devices [1]. Recently it has been demonstrated that in QW structures based on III–V compounds, a directed current can be induced by circularly polarized light [2]. This effect belongs to the class of photogalvanic effects [3] known for bulk semiconductors and represents the circular photogalvanic effect (CPGE). In QWs this effect is caused by the optical spin orientation. The occurrence of the current needs the removal of spin degeneracy in the **k**-space i.e. **k**-linear spin splitting [2]. In zinc-blende semiconductors, like III–V and II–VI, the reduction of dimensionality leads to a such removal of spin degeneracy. On the other hand, the diamond lattice has a center of inversion and for SiGe based QWs with symmetrical interfaces CPGE is forbidden. However, this effect becomes possible due to the structure inversion asymmetry. This is demonstrated by the experiments presented below where the inversion symmetry was broken by preparation of compositionally stepped QWs and asymmetric doping of compositionally symmetric QWs. The observation of CPGE proves the removal of spin degeneracy in the **k**-space and is of importance in view of possible applications in spintronics based on SiGe.

1. Experiment

The measurements were carried out on *p*-type SiGe QW structures MBE-grown on (001)- and (113)-oriented substrates. The compositionally stepped samples consisted of ten QWs ($Si_{0.75}Ge_{0.25}$(4 nm)/$Si_{0.55}Ge_{0.45}$(2.4 nm)), separated by 6 nm Si barriers. The asymmetrically doped structures had a single QW of $Si_{0.75}Ge_{0.25}$ composition with boron acceptors on one side only. All these samples had free carrier densities of about $8 \cdot 10^{11}$ cm^{-2} and were studied at room temperature. Ohmic contact pairs were centered at opposite sample edges.

A high power pulsed mid-infrared (MIR) TEA-CO_2 laser and a far-infrared (FIR) NH_3-laser have been used as radiation sources delivering 100 ns pulses with radiation power P up to 100 kW. Several lines of the CO_2 laser between 9.2 and 10.6 μm and of the NH_3-laser [4] between $\lambda = 76\,\mu$m and 280 μm have been used for excitation in the MIR and FIR range, respectively. The laser light polarization could be modified from linear to circular using for the MIR light a Fresnel rhombus and quartz $\lambda/4$ plates for the FIR radiation . The helicity of the incident light was varied according to $P_{circ} = \sin 2\varphi$ where φ is the angle between the initial plane of linear polarization and the optical axis of the polarizer.

With illumination by the MIR radiation of a TEA CO_2 laser in (001)-oriented samples with asymmetric QWs a current signal proportional to the helicity P_{circ} is observed under oblique incidence indicating an observation of CPGE. The current changes sign if the circular polarization is switched from left to right handed. The spectral dependence of the photocurrent in the MIR corresponds to direct transitions between hole subbands. In the FIR range, where radiation causes indirect optical transitions within the lowest heavy-hole subband, a more complicated dependence of the current as function of helicity has been observed. In (001)-grown asymmetric QWs as well as in (113)-grown samples the dependence of the current on the phase angle φ may be described by a sum of two terms, one being $\propto \sin 2\varphi$ and the other $\propto \sin 2\varphi \cos 2\varphi$. The first term $\propto \sin 2\varphi$ is again caused by CPGE. The second term $\propto \sin 2\varphi \cos 2\varphi$ vanishes for the circularly polarized radiation and is caused by the linear photogalvanic effect [5], it is out of the scope of this presentation. In symmetrically grown and symmetrically doped SiGe QWs no photogalvanic current has been observed.

2. Microscopical theory

The principal microscopical aspect of a photon helicity driven current is the removal of spin-degeneracy in the subband states due to the reduced symmetry of the quantum well structure [2, 6]. Thus the experimental observation of CPGE in asymmetric SiGe nanostructures unambiguously proves the lifting of spin degeneracy. This is described by **k**-linear terms in the Hamiltonian,

$$H^{(1)} = \beta_{lm}\sigma_l k_m \tag{1}$$

where the real coefficients β_{lm} form a pseudo-tensor and σ_l are the Pauli spin matrices. Below several scenarios will be presented which could contribute to β_{lm} in SiGe QWs with symmetries C_{2v} or C_s corresponding to investigated structures. As discussed in [2] the coupling between the carrier spin (σ_l) and momentum (k_m) together with the spin-controlled dipole selection rules yields a net current under circularly polarized excitation.

Spin degeneracy results from the simultaneous presence of time-reversal and spatial inversion symmetry. If one of these symmetries is broken the spin degeneracy is lifted. In our SiGe QW systems the spatial inversion symmetry is broken (the point groups C_{2v} and C_s do not contain the inversion operation) and, as a consequence, **k**-linear terms appearing in the electron Hamiltonian lead to a splitting of the electronic subbands at a finite in-plane wave vector. Microscopically different mechanisms can lead to **k**-linear terms, which will be discussed here briefly.

In the context of spin related phenomena in QW structures most frequently the so-called Rashba term [7] is taken into account. It is a prototype spin-orbit coupling term of the form $\alpha(\nabla V \times \mathbf{p})\cdot \sigma$, where $\mathbf{p}$ is the momentum of the particle moving in the potential V and σ is the vector of the Pauli spin matrices. The weighting factor α depends on the material in which the QW structure, giving rise to the potential V, is realized. The Rashba term has an axial symmetry and can exist as well in systems invariant under C_{2v} and C_s. ∇V can be identified with the electric field leading to the asymmetric confinement and is parallel to the growth direction of the QW structure. In the context of $\mathbf{k}\cdot\mathbf{p}$ theory the Rashba term can be understood as resulting from the couplings between conduction and valence band states mediated by the momentum operator ($\mathbf{k} \cdot \mathbf{p}$-coupling) and the space coordinate z in the electric field term $V = eFz$. The Rashba term has the form $\sigma_x k_y - \sigma_y k_x$ and leads to a **k**-linear contribution to the subband dispersion. For hole states it has been discussed in [8].

Invoking the theory of invariants [9], the Hamiltonian acting in the twofold space of particles with spin 1/2 can be represented in terms of 4 independent 2×2 matrices (the unit matrix and the Pauli spin matrices). In addition to the Rashba term (which has this form) there could be similar expressions but with higher powers of the wave vector (or the electric field). The 4×4 Hamiltonian for holes, usually described in the basis of angular momentum eigenstates with $J = 3/2$, $M = \pm3/2, \pm1/2$, requires for its most general form 16 independent matrices formed from angular momentum matrices J_x, J_y, J_z, their powers and products. Thus in combination with tensor operators, composed of components of the momentum (or wave vector) and the electric field, new terms are possible under C_{2v} and C_s. Some of these, which can be regarded as generalized Rashba terms, give rise to **k**-linear contributions in the hole subbands. The 4×4-Luttinger Hamiltonian, describing the valence band dispersion of bulk Si or Ge close to the center of the Brillouin zone, can be split into a spherical symmetric part (giving rise to an isotropic dispersion of spin degenerate bands) and an anisotropic term causing warping of these bands. In (hhl)-grown QWs with symmetry C_s the spherical part leads to a subband Hamiltonian, which includes heavy-light hole coupling even at zero in-plane wave vector (angular momentum M ceases to be a good quantum number under C_s). In addition the warping term mediates also a coupling between light and heavy hole states. Combining these two couplings, that derive from the Luttinger Hamiltonian, yields terms of the form $J_z k_x$. These terms are invariants under C_s and result in a spin-splitting of the hole subbands.

Finally we mention a mechanism to create **k**-linear terms and spin-splitting which comes from the C_{2v} symmetry of a (001)-grown SiGe interface and gives rise to coupling between heavy and light hole states [10]. The mixing may be described by the coupling Hamiltonian

$$H_{l\text{-}h} = \frac{\hbar^2}{m_0 a_0 \sqrt{3}} t_{l\text{-}h} \{J_x, J_y\} \delta(z - z_{if}) \,. \qquad (2)$$

Here $\{J_x, J_y\}$ is the symmetrized product of angular momentum matrices with $J = 3/2$, z_{if} is the interface coordinate along the growth axis, m_0 the free electron mass, a_0 the lattice constant, and $t_{l\text{-}h}$ a dimensionless coupling coefficient. Note that a shift of the interface by one atomic layer interchanges the role of the axes $[1\bar{1}0]$ and $[110]$, which as a consequence, leads to a sign change of $t_{l\text{-}h}$ reversing the current. This heavy-light hole coupling in combination with that one inherent in the Luttinger Hamiltonian for QWs leads again to spin-dependent **k**-linear terms.

3. Conclusions

In our experiments carried out for different p-doped SiGe based nanostructures, we have demonstrated a possiblity to create a photon helicity driven stationary current due to the circular photogalvanic effect. We analyze the symmetry of the QWs under investigation and present different scenarios that can lead to spin-dependent **k**-linear terms in the hole subband Hamiltonian, which are prerequisite for the appearance of the observed photocurrent. Our results provide the important information that spin-related phenomena, which so far have been considered to be specific for QW strucures based on zinc-blende materials, exist also in the SiGe QW systems. In particular spin sensitive bleaching of optical absorption may be recorded by the saturation of CPGE at high power levels allowing to conclude on spin relaxation times [11].

Acknowledgements

Financial support from the DFG, the RFBR, INTAS and NATO Linkage Grant is gratefully acknowledge.

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10th Int. Symp. "Nanostru
St Petersburg, Russia, June

Hole transport in

A. I. Yakim
Institute of

Abstract. We report on
10-nm-diameter Ge self-
current versus gate volta
holes in the fourfold-dege
energy of ~43 meV (i.e.
determined from the osci
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Introduction

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for application in QDFET
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1. Samples

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Published by
Ioffe Physico-Technical Institute
26 Politekhnicheskaya, St Petersburg 194021, Russia
http://www.ioffe.rssi.ru/

Publishing license ΛP No 040971 of June 16, 1999.

ISBN 5-93634-008-2

The International Symposium "Nanostructures: Physics and Technology" is held annually since 1993. The first Symposium was initiated by Prof. Zh. Alferov and Prof. L. Esaki who are its permanent co-chairs. More detailed information on the Symposium is presented on the World Wide Web **http://www.ioffe.rssi.ru/NANO2002/**

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The volume was composed at the Information Services and Publishing Department of the Ioffe Institute from electronic files submitted by the authors. When necessary these files were converted into the Symposium $\LaTeX 2_\varepsilon$ style without any text revisions. Only minor technical corrections were made by the composers.

Design and layout: N. Vsesvetskii
Desk editor: L. Solovyova

Information Services and Publishing Department
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26 Politekhnicheskaya, St Petersburg 194021, Russia
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Printed in Russian Federation