Electric current-induced spin orientation in quantum well structures

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Abstract

A longstanding theoretical prediction is the orientation of spins by an electrical current flowing through low-dimensional carrier systems of sufficiently low crystallographic symmetry. Here we show by means of terahertz transmission experiments through two-dimensional hole systems a growing spin orientation with an increasing current at room and liquid nitrogen temperatures.
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The manipulation of the spin degree of freedom in electrically conducting systems by electric and/or magnetic fields is at the heart of semiconductor spintronics [1]. Spin control in low-dimensional systems is particularly important for combining magnetic properties with the versatile electronic characteristics of semiconductor heterojunctions. The feasibility to orient the spin of charge carriers in GaAs based quantum wells (QWs) by driving an electric current through the device was theoretically predicted about two decades ago [2–4]. Just recently a first direct experimental proof of this effect was obtained in semiconductor QWs [5,6] as well as in strained bulk material [7]. In this paper, we demonstrate by means of terahertz transmission experiments that an electric current which flows through a low-dimensional system leads to a stationary spin polarization of free charge carriers. Microscopically the effect is a consequence of spin–orbit coupling which lifts the spin-degeneracy in *k*-space of charge carriers together with spin dependent relaxation and represents the inverse spin-galvanic effect [8].

In the simplest case the electron's (or hole's) kinetic energy in a QW depends quadratically on the in-plane wave

vector components k_x and k_y. In equilibrium, the spin degenerated k_x and k_y states are symmetrically occupied up to the Fermi energy E_F. If an external electric field is applied, the charge carriers drift in the direction of the resulting force. The carriers are accelerated by the electric field and gain kinetic energy until they are scattered. A stationary state forms where the energy gain and the relaxation are balanced resulting in a non-symmetric distribution of carriers in *k*-space. This situation is sketched in Fig. 1a for holes, a situation relevant for the experiments presented here. The holes acquire the average quasi-momentum

$$\langle \boldsymbol{k} \rangle = \frac{e\tau_p}{\hbar}\,\boldsymbol{E} = \frac{m^*}{e\hbar p}\,\boldsymbol{j}, \qquad (1)$$

where $\boldsymbol{E}$ is the electric field strength, τ_p the momentum relaxation time, $\boldsymbol{j}$ the electric current density, m^* the effective mass, p the hole concentration and e the elementary charge. As long as spin-up and spin-down states are degenerated in *k*-space the energy bands remain equally populated and a current is not accompanied by spin orientation. In QWs made of zinc-blende structure material like GaAs, however, the spin degeneracy is lifted due to lack of inversion symmetry and low-dimensional

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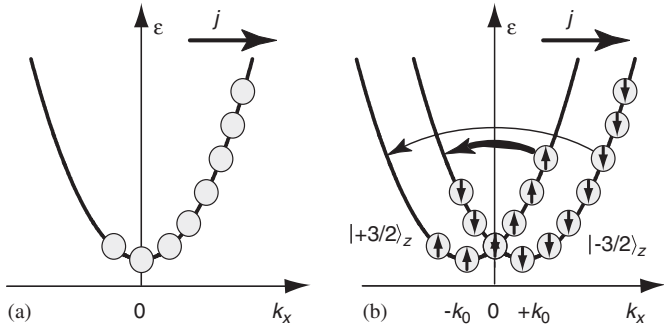E-mail address:* golub@coherent.ioffe.ru (L.E. Golub).

Fig. 1. Comparison of current flow in (a) spin-degenerate and (b) spin-split subbands. (a) Electron distribution at a stationary current flow due to acceleration in an electric field and momentum relaxation. (b) Spin polarization due to spin-flip scattering. Here only $\beta \sigma_z k_x$ term is taken into account in the Hamiltonian which splits a valence subband into two parabolas with spin-up ($+3/2$) and spin-down ($-3/2$) in z-direction. Biasing along x-direction causes an asymmetric in $\boldsymbol{k}$-space occupation of both parabolas.

quantization [9,10], and the resulting dispersion reads

$$\varepsilon = \frac{\hbar^2 \boldsymbol{k}^2}{2m*} \pm \beta_{lm} \sigma_l k_m \qquad (2)$$

with the spin–orbit pseudo-tensor $\boldsymbol{\beta}$ and the Pauli spin matrices σ_l. The parabolic energy band splits into two subbands of opposite spin directions shifted in $\boldsymbol{k}$-space symmetrically around $\boldsymbol{k} = 0$ with minima at $\pm k_0$. The corresponding dispersion is sketched in Fig. 1b. To be specific for the coupling constant β and the mechanism depicted in Fig. 1b we consider solely spin–orbit interaction due to a Hamiltonian of the form $H_{SO} = \beta \sigma_z k_x$. This corresponds to a subband splitting for eigenstates with spins pointing in z-direction, normal to the QW plane and detectable in experiment. In our QWs of C_s symmetry the x-direction lies along [1–10] in the QW plane. In the presence of an in-plane electric field the $\boldsymbol{k}$-space distribution of carriers gets shifted yielding an electric current. Due to the band splitting carrier relaxation becomes spin dependent. Relaxation processes including spin flips are different for the two subbands because the quasi-momentum transfer from initial to final states is different [11]. In Fig. 1b the $\boldsymbol{k}$-dependent spin-flip scattering processes are indicated by arrows of different lengths and thicknesses. As a consequence different numbers of spin-up and spin-down carriers contribute to the current causing a stationary spin orientation. For the moment we assume that the origin of the current-induced spin orientation is, as sketched in Fig. 1b, exclusively due to scattering and hence dominated by the Elliott–Yafet spin relaxation process [11]. The other possible mechanism of the current-induced spin orientation due to D'yakonov-Perel' spin relaxation will be addressed later.

In order to observe current-induced spin polarization we study transmission of terahertz radiation through samples containing multiple p-type QWs. In experiment we used direct inter-subband transitions between the lowest heavy-hole and light-hole subbands of the valence band excited by linearly polarized terahertz radiation of a far-infrared laser. A spin polarization in z-direction affects, in principle, incoming linearly polarized radiation by two mechanisms: (i) dichroic absorption and (ii) Faraday rotation. The first mechanism is based on different absorption coefficients for left and right circularly polarized light while the Faraday rotation is due to different indices of refraction for left and right circularly polarized radiation. The linearly polarized light can be thought of being composed of two circularly polarized components of opposite helicity. The resulting different absorption coefficients for left and right circularly polarized light changes the light's state of polarization. In particular, linearly polarized radiation gets elliptically polarized. The Faraday rotation, in contrast, becomes important for weak absorption and is proportional to the difference of the indices of refraction for left and right circularly polarized radiation. In this case only the phases of left and right circularly polarized light are shifted resulting in a rotation of the polarization axis of the incoming linearly polarized light. Without spin orientation in the lower subband, the absorption strength as well as the index of refraction for right- and left-handed polarized light are equal and transmitted light does not change its state of polarization. However, Faraday effect and dichroic absorption proof current-induced spin polarization.

As material we have chosen p-type GaAs QWs of low symmetry having only—in addition to identity—one plane of mirror reflection (i.e. C_s point group according to Schönflies's notation). This was achieved by growing modulation Si-doped QWs on (1 1 3)A- or miscut (0 0 1)-oriented GaAs substrates (tilt angle: $5°$ towards the [1 1 0] direction) by molecular-beam-epitaxy (MBE) or metal-organic-chemical-vapor-deposition (MOCVD), respectively. Two types of samples were prepared. Sample A: (1 1 3)A with QWs of width $L_W = 10$ nm, and a free carrier density of $p \approx 2 \times 10^{11}$ cm^{-2} and sample B: miscut (0 0 1) with $L_W = 20$ nm and $p \approx 2 \times 10^{11}$ cm^{-2}. To cope with the small absorption signals and/or rotation angles of an individual QW we fabricated multiple QW structures. Sample A contained $N = 100$ and sample B $N = 400$ QWs. The sample edges were oriented along [1–10] in the QW plane (x-axis) and perpendicular to this direction (y-axis). Two pairs of ohmic contacts were centered along opposite sample edges of 5 mm width. The resistances for both directions are found to be the same. In addition structures containing 100 QWs and having very thin barriers were taken as quasi-bulk reference samples.

A spin polarization is expected not for both current directions. For materials of the symmetry used here only an electric current along $x \| [1$ -$1 0]$-direction is expected to align spins. In contrast, current flowing in y-direction does not yield a spin orientation. By symmetry arguments it is straightforward to show that a current density j_x in the plane of the QW yields an average spin polarization S_z

normal to the QW plane according to

$$S_z = \boldsymbol{R}_{zx} j_x, \tag{3}$$

where $\boldsymbol{R}$ is a second rank pseudo-tensor [12]. However, for a current flowing along y-direction, $S_z = 0$ holds since, due to symmetry, $R_{zy} = 0$. Thus we expect to observe a spin polarization for current flow in one but not in the other (perpendicular) direction. Below we denote these directions as active and passive, respectively.

The transmission measurements were carried out at room temperature and at $T = 77$ K using linearly polarized $\lambda = 118\,\mu$m radiation. The radiation source was an optically pumped cw far-infrared laser emitting 2 mW power. The electric current was applied as 10 μs long pulses with a repetition rate of 20 kHz. The largest current applied (20 and 180 mA at $T = 77$ and 295 K, respectively) was limited by the requirement not to increase the sample temperature more than 3%. This was controlled by a comparison of the sample resistance at highest current used in experiments with the temperature dependence of the sample resistance. The schematic experimental set up is shown in Fig. 2a: the sample was placed between two metallic grid polarizers and the cw terahertz radiation was passed through this optical arrangement. The transmitted radiation was detected in-phase with the current modulation frequency using a highly sensitive Ge:Ga extrinsic photodetector operated at 4.2 K.

In order to detect a current dependent change of the polarization of the transmitted light the polarizers were crossed. The crossed polarizers are expected to let pass only light whose state of polarization was changed by the current through the sample. The photodetector signal which is proportional to the transmitted radiation intensity is shown in Fig. 2b as function of the current strength, I, for both the passive and the active directions. Though the signal in the active direction is by a factor 2/3 higher than for the passive one, the transmission signal increases in both cases with I. As will be pointed out below the observed transmission for the 'passive' case is a polarization independent background signal while the difference of transmission between the 'active' and the 'passive' traces is the sought-after polarization dependent transmission signal caused by current-induced spin polarization in QWs.

Why is there a signal at all for current flow along the passive direction? The reason is the unavoidable hole gas heating due to the current pulses and the non-perfect polarizers. For ideal crossed polarizer and analyzer ($\Theta = 90°$) there would be no transmission unless the direction of polarization is rotated by the sample. However, polarizer and analyzer are not ideal in the terahertz range. Measuring the transmission of an unbiased sample between polarizers we obtained even for crossed polarizers a signal. This indicates that a small fraction α_{90} of the radiation is still transmitted though we used far-infrared polarizers of highest available quality. The transmission of crossed polarizers ($\Theta = 90°$) was measured to be $\alpha_{90} = 5.4 \times 10^{-3}$. Hence any change in transmission results in a change of the measured signal without being due to a change in polarization. The current pulse through the
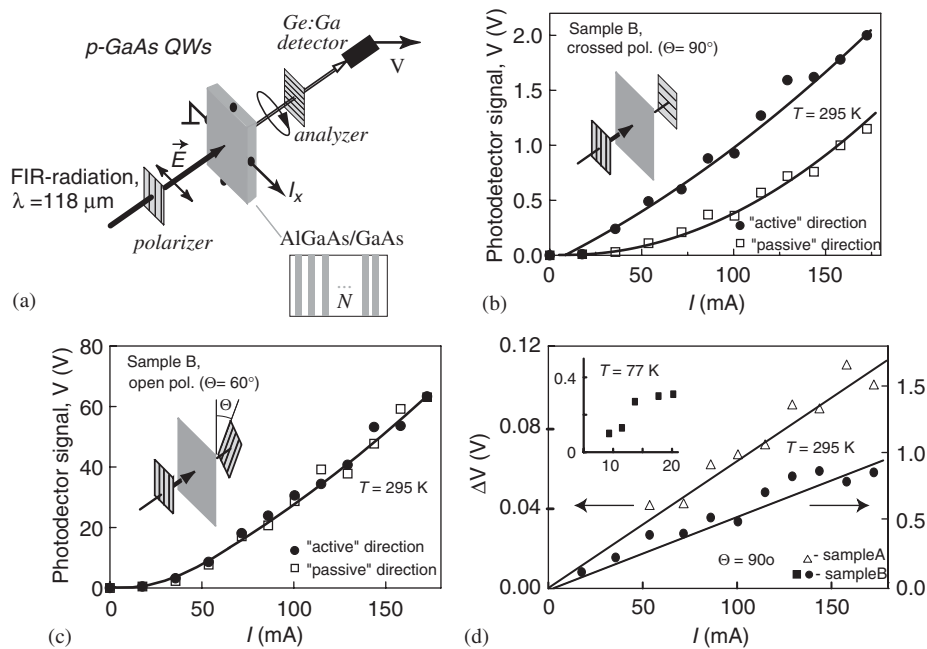

Fig. 2. (a) Experimental setup. The sample is placed between crossed polarizer and analyzer blocking optical transmission at zero current through the sample. Injecting a modulated current in the sample yields a signal at the detector. (b) and (c) Detector signal as a function of the current in the active (full symbols) and the passive (open symbols) directions for sample B and two states of the analyzer: (b) crossed polarizers ($\Theta = 90°$) and (c) partially opened polarizers ($\Theta = 60°$). (d) Differences ΔV between the signal at current in active and passive directions as a function of current for two samples, A (open triangles, left axis) and B (circles, right axis) for crossed polarizers. Inset shows the same dependence ($\Delta V(I)$) for sample B at $T = 77$ K (full squares).

sample yields such a modulation of transmission due the hole gas heating. Heating redistributes the occupation of hole states and the transmission of the sample increases with increasing current [13]. This is the origin of the signal increase for the passive direction in Fig. 2b. This mechanism is isotropic and hence also present for the active direction with the same strength. However in the active direction rotation of the polarization plane due to current-induced spin-polarization, additionally contributes to the signal.

The experiment with opened polarizers displayed in Fig. 2c rules out other spurious effects, which do not rotate the polarization plane and could lead to the observed asymmetry for the passive and active directions, like e.g. contact specific asymmetry. At $\Theta = 60°$, in contrast to the closed polarizer arrangement, we obtained nearly the same detector signals for current flow in active and passive directions. This fact cannot be explained by polarization independent mechanisms where both signals equally scale by rotation of the analyzer. If the signal for the current flow in the active direction results from the sum of the polarization dependent and polarization independent contributions such behavior is expected because of their different Θ-dependencies. While the polarization independent part of the signal scales by change of Θ by nearly two orders of magnitude the polarization dependent part of the signal varies much weaker. Thus, the observed signal difference at closed polarizers for the current flowing in active and passive directions is due to rotation of the polarization plane.

Are there other mechanisms which can result in a polarization rotation and cause an anisotropic signal for the two current directions? A possible alternative explanation might be strain- or heating-induced birefringence. However, both may be ruled out by our phase sensitive detection technique. Only signals which change with current are detectable and consequently strain-induced birefringence can be excluded. Lattice heating in an ideal crystal gives no rise to birefringence. Assuming for the moment that nevertheless lattice heating-induced birefringence is possible, it is unlikely that this mechanism contributes to the signal. Since the current pulses have a period of $50\,\mu s$, compared to typical sample cooling times in the ms range, the temperature is in the steady state essentially constant. These arguments are also supported by the measurements carried out on the quasi-bulk reference sample where the polarization dependent contribution was not observed. Thus, we conclude that the purely spin polarization-induced signal can be consequently extracted from the transmission difference between active and passive directions for the crossed polarizer arrangement.

The spin polarization-induced signals for samples A and B are shown in Fig. 2d. The signal, reflecting the build up of spin polarization with increasing current, increases almost linearly. Control experiments on the quasi-bulk sample give—in accordance with theory which forbids

current-induced spin orientation for T_d point group symmetry—the same signal for x- and y-directions.

While the experiment displays clear spin polarization due to the driving current, it is not straightforward to determine the value of spin polarization. Due to lack of compensators for the far infrared regime it is difficult to judge whether the transmitted signal is linearly (Faraday effect) or elliptically polarized (dichroic absorption). In case of dominating dichroic absorption the average spin polarization of a QW is given by [14]

$$\langle S \rangle = \Delta p / p = 8 \sqrt{\alpha_{90} \Delta V / V^{(p)}} / K_0. \qquad (4)$$

Here Δp is the difference of spin-up and spin-down hole densities, ΔV is the spin-induced photosignal plotted in Fig. 2d, and $V(p)$ is the photodetector signal obtained for a current in the passive current direction, plotted for sample B in Fig. 2b. The absorption K_0, which determines the ratio of incoming (J_0) and transmitted (J_T) intensity through the multi-QW structure, $J_0/J_T = \exp(-K_0)$, is obtained from an independent transmission experiment, carried out on unbiased devices. For sample A we obtained $K_0 = 2.7$, for sample B, $K_0 = 3.4$. This would result in spin polarization of 0.12 for sample A and 0.15 for sample B at current densities 3 and $0.75\,\mathrm{mA/cm}$ per QW, respectively. If the increased signal, however, is due to Faraday rotation a different analysis has to be applied. The angle of Faraday rotation can be determined by rotating the analyzer for current along the passive direction until the signal becomes equal to the signal obtained for the current in active direction for crossed polarizers. At room temperature and current $I = 150\,\mathrm{mA}$ we obtain a rotation angle per QW of $0.4\,\mathrm{mrad}$ for sample A and $0.15\,\mathrm{mrad}$ for sample B. Lowering the temperature of sample B to $77\,\mathrm{K}$ yields an angle of $0.1\,\mathrm{mrad}$ per QW at a current of $20\,\mathrm{mA}$. At the same current the rotation angle at room temperature is $0.05\,\mathrm{mrad}$, two times smaller than that at liquid nitrogen temperature. In the case of dominating Faraday effect no straightforward way to extract the value of the spin polarization from the Faraday rotation angle is at hand.

According to the theory [2], a current should yield a spin polarization of the order of $\langle S \rangle \approx \beta \cdot \langle k \rangle / k_B T$. Using Eq. (1) we estimate this value as

$$\langle S \rangle = Q \frac{\beta}{k_B T} \frac{m^*}{e \hbar p} j, \qquad (5)$$

where $Q{\sim}1$ is a constant determined by momentum scattering and the spin relaxation mechanism [15]. For a situation where Fermi statistic applies the factor $k_B T$ needs to be replaced by $2E_F/3$. Calculating $\langle S \rangle$ from Eq. (5) with the experimental parameters $p = 2 \times 10^{11}\,\mathrm{cm}^{-2}$, $m^* = 0.2 m_0$ and spin splitting constant $\beta = 5\,\mathrm{meV\,nm}$ [16,17], we obtain an average spin polarization of 3.2×10^{-4} and 0.8×10^{-4} for the experimentally relevant current densities 3 and $0.75\,\mathrm{mA/cm}$ per QW, respectively. Since the values obtained from an analysis of our data under the assumption of dominating dichroic absorption is

by a factor of more than 1000 higher than expected we assume that Faraday rotation and not dichroic absorption dominates the change of polarization of the transmitted light. Also the fact that the spin orientation-induced signal increases linearly with current (see Fig. 2d) and not quadratically, as expected from dichroic mechanism (see Eqs. (4) and (5)), points to the Faraday rotation as the dominating mechanism proofing current-induced spin orientation. Faraday rotation and dichroic absorption may show completely different dependencies on a spin polarization because Faraday rotation is non-dissipative and vanishes at a peak of absorption while dichroic absorption assumes a maximum at this frequency. In case of Faraday rotation we cannot extract the value of spin polarization. We note, however, that the increased Faraday rotation observed at 77 K is in agreement with Eq. (5) which predicts a higher spin polarization with decreasing temperature.

So far we assumed that the subband spin splitting occurs for spin eigenstates pointing normal to the QW. However, if the hole subbands are also split due to a spin–orbit coupling of the type $\sim \sigma_x k_y$ in the Hamiltonian, an additional mechanism of spin orientation, the precessional mechanism [2,15], needs to be taken into account. The difference in the spin relaxation rates for spin-up and spin-down subbands is now determined by the D'yakonov-Perel' spin relaxation process. In this case the relaxation rate depends on the average $\boldsymbol{k}$-vector [10], equal to $k_{3/2} = -k_0 + \langle k \rangle$ for the spin-up and $k_{-3/2} = k_0 + \langle k \rangle$ for the spin-down subband. Hence also for the D'yakonov-Perel' spin relaxation mechanism a current through the hole gas causes spin orientation. If this type of spin–orbit interaction is present, the magnitude of spin orientation is also given by Eq. (5), only the constant Q is different but also of order of unity [15].

Finally, we discuss our results in the light of related experiments. Based on theoretical predictions made by Ivchenko and Pikus [18], Vorob'ev et al. [19] observed a current-induced spin polarization in bulk tellurium. This is a consequence of the unique band structure of tellurium with hybridized spin-up and spin-down bands and is, other than in our experiment, not related to spin relaxation. More recently for spin injection from a ferromagnetic film into a two-dimensional electron gas, Hammar et al. [20] used the above concept of a spin orientation by current in a 2DEG (see also Refs. [21,22]) to interpret their results. Though a larger degree of spin polarization was extracted the experiment's interpretation is complicated by other effects [23,24]. We would also like to note that Kalevich and Korenev [25] reported an influence of an electric current on the spin polarization achieved by optical orientation. The current itself does not align spins, but the effective magnetic field due to the current causes a spin depolarization like the Hanle effect in an external magnetic field. In Ref. [7] experimental results were obtained on strained InGaAs bulk material. Analyzing Faraday rotation the authors also report on the build-up of a spin polarization under current bias, however, in three-dimensional system. Recently, Silov et al. [6] observed also a surprisingly large degree of spin polarization of holes (2.5%) in p-type GaAs QWs caused by the same mechanism we demonstrated here. The authors point out that for holes, as investigated here, the degree of spin polarization may be even larger but is difficult to estimate.

References

[1] D.D. Awschalom, D. Loss, N. Samarth (Eds.), Semiconductor Spintronics and Quantum Computation, Springer, Berlin, 2002.
[2] A.G. Aronov, Yu.B. Lyanda-Geller, JETP Lett. 50 (1989) 431.
[3] V.M. Edelstein, Solid State Commun. 73 (1990) 233.
[4] F.T. Vas'ko, N.A. Prima, Sov. Phys. Solid State 21 (1979) 994.
[5] S.D. Ganichev, S.N. Danilov, P. Schneider, V.V. Bel'kov, L.E. Golub, W. Wegscheider, D. Weiss, W. Prettl, cond-mat/0403641, 2004.
[6] A.Yu. Silov, P.A. Blajnov, J.H. Wolter, R. Hey, K.H. Ploog, N.S. Averkiev, Appl. Phys. Lett. 85 (2004) 5929.
[7] Y. Kato, R.C. Myers, A.C. Gossard, D.D. Awschalom, Phys. Rev. Lett. 93 (2004) 176601.
[8] S.D. Ganichev, E.L. Ivchenko, V.V. Bel'kov, S.A. Tarasenko, M. Sollinger, D. Weiss, W. Wegscheider, W. Prettl, Nature 417 (2002) 153.
[9] Yu.A. Bychkov, E.I. Rashba, JETP Lett. 39 (1984) 78.
[10] M.I. D'yakonov, V.Yu. Kachorovskii, Sov. Phys. Semicond. 20 (1986) 110.
[11] N.S. Averkiev, L.E. Golub, M. Willander, J. Phys.: Condens. Matter 14 (2002) R271.
[12] S.D. Ganichev, W. Prettl, J. Phys.: Condens. Matter 15 (2003) R935.
[13] L.E. Vorob'ev, D.V. Donetskii, L.E. Golub, JETP Lett. 63 (1996) 977.
[14] A.Ya. Shul'man, S.D. Ganichev, unpublished.
[15] A.G. Aronov, Yu.B. Lyanda-Geller, G.E. Pikus, Sov. Phys. JETP 73 (1991) 537.
[16] R. Winkler, Spin–Orbit Coupling Effects in Two-dimensional Electron and Hole Systems, Springer, Berlin, 2003.
[17] P. Schneider, J. Kainz, S.D. Ganichev, U. Rössler, W. Wegscheider, D. Weiss, W. Prettl, V.V. Bel'kov, M.M. Glazov, L.E. Golub, D. Schuh, J. Appl. Phys. 96 (2004) 420.
[18] E.L. Ivchenko, G.E. Pikus, JETP Lett. 27 (1978) 604.
[19] L.E. Vorob'ev, E.L. Ivchenko, G.E. Pikus, I.I. Farbstein, V.A. Shalygin, A.V. Sturbin, JETP Lett. 29 (1979) 441.
[20] P.R. Hammar, B.R. Bennett, M.J. Yang, M. Johnson, Phys. Rev. Lett. 84 (2000) 5024.
[21] M. Johnson, Phys. Rev. B 58 (1998) 9635.
[22] R.H. Silsbee, Phys. Rev. B 63 (2001) 155305.
[23] F.G. Monzon, H.X. Tang, M.L. Roukes, Phys. Rev. Lett. 84 (2000) 5022.
[24] B.J. van Wees, Phys. Rev. Lett. 84 (2000) 5023.
[25] V.K. Kalevich, V.L. Korenev, JETP Lett. 52 (1990) 859.