SPIN CURRENT IN (110)-ORIENTED GaAs QUANTUM WELLS

Volodymyr I. Ivanov[1*], **Vitalii K. Dugaev**[2,3], **Eugene Ya. Sherman**[4,5], **Józef Barnaś**[6,7]

1 Institute for Problems of Materials Science (Chernivtsi Branch), Ukrainian Academy of Sciences, Vilde 5, 58001 Chernivtsi, Ukraine
2 Department of Physics, Rzeszów University of Technology, al. Powstańców Warszawy 6, 35-959 Rzeszów, Poland
3 Department of Physics and CFIF, Instituto Superior Técnico, TU Lisbon,Av. Rovisco País 1049-001 Lisbon, Portugal
4 Department of Physical Chemistry, Universidad del Pais Vasco, Bilbao,Spain
5 IKERBASQUE Basque Foundation for Science, 48011, Bilbao, Spain
6 Adam Mickiewicz University, ul.Umultowska 85, 61-614 Poznań, Poland
7 Institute of Molecular Physics, Polish Academy of Sciences, ul. Smołuchowskiego 17, 60-179 Poznań, Poland

ABSTRACT

We consider a possibility of generation of the stationary spin current in (110) – oriented GaAs-basedsymmetric quantum well due to the nonlinear response to externalperiodic electric field. The model includes the Dresselhaus spin-orbit interaction and the random Rashbaspin-orbit coupling.

Key words: spin current, spin-orbit coupling, GaAs, quantum well

INTRODUCTION

Recently, symmetric GaAs (110) quantum wells (QWs) became the subject of extensive studies [1-3]. Spin orbit (SO) interaction in these systems, described by the Dresselhaus term [4], conserves the electron spin along the axis normal to the QW plane for any electron momentum **k**. As a result, the random motion of an electron does not lead to spin relaxation. In reality, this spin component relaxes very slowly, and its analysis provides a test for the rapidly developing spin-noise spectroscopy [2]. In the case of perfect z to -z symmetry (the axis z is perpendicular to the QW plane), the Rashba SO interaction is zero. But in real structures, however, the Rashba coupling still exists in the form of a spatially fluctuating SO field (though being zero on average) [5-7]. This interaction induces spin-flip processes leading to the spin relaxation [3], and can be also responsible for generation of non-equilibrium spin density due to the absorption of external electromagnetic field [7].

In this work we propose a new possibility of exciting a steadypure spin current, thus extending the abilities of spinmanipulation in real situations. In

---

[*] e-mail: volodya_iv@mail.ru; tel: (+30)322525155

contrast to the conventionalspin Hall effect, which is linear in external electric field, theproposed spin current is quadratic in periodic field.The effect is a result of the interplay of constant Dresselhausand spatially non-uniform Rashbainteractions. The exact mechanism of this effect does not involve real spin-flip transitions of electronsbetween the spin-split subbands in (110)-GaAs QW, but relies onvirtual spin-flip processes renormalizing the wave functionsof electrons in non-equilibrium state. This makes such anonlinear responsethe physically new phenomenon, which appears ifone takes into account more realistic cases than those describedby the conventional Rashba and Dresselhaus models.

MODEL AND GENERAL APPROACH

Hamiltonian of a two-dimensional electron gas with a constantDresselhaus term and spatially fluctuating Rashbaspin-orbit interaction, subjected to externalelectromagnetic field described by the vector potential **A**(**r**, t) takes the form (we use units with $\hbar = 1$)

$$H = -\frac{1}{2m}\left(\nabla - \frac{ie\mathbf{A}}{c}\right)^2 - i\alpha\sigma_z\left(\nabla_x - \frac{ieA_x}{c}\right)$$

$$-i\sigma_x\left\{\nabla_y, \lambda(\mathbf{r})\right\}/2 + i\sigma_y\left\{\nabla_x, \lambda(\mathbf{r})\right\}/2 + V\,, \qquad (1)$$

Where α is the Dresselhaus coupling constant,{ ,} denoting the anticommutator and λ(**r**) is the random Rashba SO interaction. The term Vdescribes coupling of the electron spin to theexternal field **A**(**r**,t) via the Rashba field.

Due to the assumed symmetry with respect to z-inversion, thespatially averaged Rashba interaction vanishes, $\langle \lambda(\mathbf{r}) \rangle = 0$ .We assume that the random-Rashba field can be described by the some correlation function relatedto fluctuating density of impurities near the QW [5, 7].

SPIN CURRENT

A nonzero pure spin currentcan be generated by anexternal field in the presence of random Rashba coupling. In the following we consider the z-component of spin current flowing along the x axis. The macroscopic spin current densityis then given by

$$j_x^z = iTr\sum_k \int \frac{d\varepsilon}{2\pi} \hat{j}_x^z G_{k\varepsilon} \qquad (2)$$

Where $\hat{j}^z_x = k_x\sigma_z/m + \alpha$ is spin current tensor component, $\mathbf{G}_{k\varepsilon}$ is the Green's functionof thesystem.

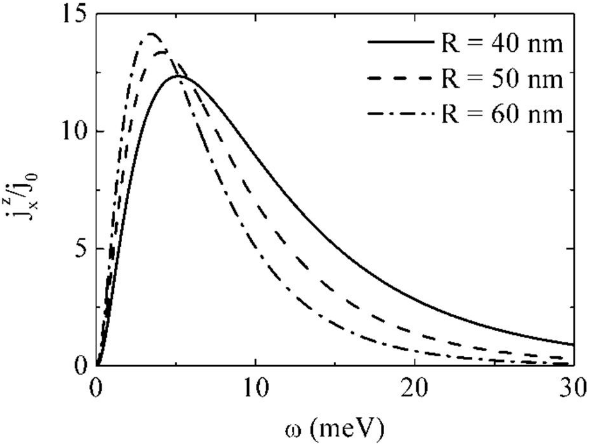

Fig. 1 – Dependence of the light-induced spin current on thefrequency ω for different values of the correlation length R

The stationary spin currentis excited by the external electromagneticfield described by$\mathbf{A}(t)=2\mathbf{A}_0\cos\omega t$. We point out that only Rashba SO interaction can generate the spincurrent since the field-induced perturbation in Dresselhaus term commuteswith σ_z and thus does not lead to spin dynamics. After expanding Green's functionup to the first order inα and secondorder in $\mathbf{A}(t)$ we obtain the following form of the spin current

$$j_x^z = C(\omega)\int_0^{k_F}\frac{kdk}{4\pi^2}\int_0^{q_c}\frac{qdq}{2\pi}|\lambda_q|^2$$

$$\times\left(k\frac{3q\beta_2+4k\beta_2^2+2k}{(\beta_2^2-1)^{5/2}}+\frac{4k^2\beta_1^2+2k^2+2q^2\beta_1^2+q^2+9kq\beta_1}{(\beta_1^2-1)^{5/2}}\right) \qquad (3)$$

Where$q_c = -k/2 + (k^2/4 + 2m\omega)^{1/2}$, $\beta_{1,2} = 2m\omega/kq \pm q/k$.

RESULTS AND DISCUSSION

Numerical results on $j^z{}_x$ are shown in Fig. 1 for different values of the parameter R. We used the parameters typical for GaAs: $m = 0.067\, m_0$, $k_F = 1.8{\bullet}10^6$ cm^{-1} and $\mu = 18.5$ meV.

We emphasize here that the calculated spin current is a stationary nonlinear effect proportional to the intensity of incident light, in contrast to the spin current generated by pulse excitations, where the result is proportional to the total influence in the pulse [6]. In the flux-dependent processes the pulse changes the real occupation of the spin-up and spin-down states. The calculated current is also not related to the linear response at frequency ω.

CONCLUSIONS

We have proposed a new effect which consists in thenonlinear generation of a steady pure spin currents in GaAs (110) quantum wells by electromagnetic wave. The spin current isproportional to the intensity of the external monochromaticradiation. Physical mechanism of the effect is related to thevirtual spin reorientation of electrons filling the spin subband(split by Dresselhaus interaction) in the presence of a non-uniformRashba coupling. As a result, a 'spin hole' virtually appears inthe subband, leading to the light-induced spin current.

Acknowledgements

This work is partly supported byFCT Grant PTDC/FIS/70843/2006 in Portugal and by PolishMinistry of Science and Higher Education as a research project in years 2011-2013. The work of EYS was supported by theUniversity of Basque Country UPV/EHU grant GIU07/40, MCI of Spaingrant FIS2009-12773-C02-01, and "GruposConsolidados UPV/EHU delGobierno Vasco" Grant IT-472-10.

REFERENCES

[1] Y. Ohno, R. Terauchi, T. Adachi et al. Phys. Rev. Lett., 1999, Vol. 83, No20, P. 4196-4199.
[2] G.M. Muller, M. Oestreich, M.L. Romer, J. Hubner, Physica E, 2010, Vol. 43, No2, P. 569-687.
[3] Y. Zhou, M.W. Wu, EPL, 2010, Vol. 89, No5, P. 57001.
[4] R. Winkler, Spin-Orbit Coupling Effects in Two-dimensional Electron and Hole Systems, Springer, New York, 2003.
[5] E.Ya. Sherman, Phys. Rev. B, 2003, Vol. 67, No16, P. 161303(R).
[6] E.Ya. Sherman, A. Najmaie, J.E. Sipe, Appl. Phys. Lett., 2005, Vol. 86, No12, P. 122103.
[7] M.M. Glazov, E.Ya. Sherman, V.K. Dugaev, Physica E, 2010, Vol. 42, No9, P. 2157-2177.
[8] V.K. Dugaev, E.Ya. Sherman, V.I. Ivanov, J. Barnaś, Phys. Rev. B, 2009, Vol. 80, No8, P. 081301(R).