Tunneling-Recombination Mismatch in Ferromagnetic-Semiconductor heterostructures

I.V. Rozhansky[1,2], H.-J. Drouhin[2], H. Jaffres[3], Yuan Lu[4], V.I. Safarov[2]

[1]*National Graphene Institute, University of Manchester, Manchester M13 9PL, United Kingdom*
[2]*LSI, Ecole Polytechnique, CEA/DRF/IRAMIS, CNRS, Institut Polytechnique de Paris, 91128 Palaiseau, France*
[3] *Unite Mixte de Physique, CNRS, Thales, Universite Paris Saclay, 91767 Palaiseau, France*
[4] *Institut Jean Lamour, Universite de Lorraine, CNRS UMR7198, 54011 Nancy, France*

igor.rozhanskiy@manchester.ac.uk

Spin optoelectronics holds promise for revolutionizing telecommunications by converting photon spins into charges. Key components, such as spin lasers and solid-state helicity detectors, have garnered attention, although the fabrication of the latter remains challenging.

Our study examines the fundamental principles of spin-dependent current generation in ferromagnetic/semiconductor tunnel junctions under optical excitation. We find that the helicity-dependent current is influenced not just by electron spin polarization and tunneling spin asymmetry, but also by dynamic factors such as the interplay between tunneling and recombination in the semiconductor, and the charge polarization of the photocurrent. This dynamic interaction mirrors the well-known conductivity mismatch problem seen in electrical spin injection into semiconductors [1].

To shed light on these phenomena, we've developed a theoretical model to elucidate the spin dynamics in ferromagnetic/semiconductor heterostructures. Additionally, experimental investigations on a CoFeB/MgO/GaAs spin photodiode were conducted. By applying a weak longitudinal magnetic field, we observed a significant increase in the spin contribution to the helicity-dependent photocurrent. Our experimental results validate our theoretical framework, they not only demonstrate polarization enhancement through the so-called inverted Hanle effect but also confirm the importance of balancing recombination and tunneling times revealing that the performance of spin photo-diodes devices is hindered by a mismatch between recombination and tunneling times [2]. This limitation, akin to the conductivity mismatch problem, can be addressed by increasing tunnel resistance and optimizing relevant parameters. These insights pave the way for future optoelectronic devices capable of converting photon helicity into electrical signals efficiently.

The same mismatch phenomenon was also observed in a distinct GaAs/InGaAs heterostructure featuring a GaMnAs ferromagnetic layer adjacent to the InGaAs quantum well [3]. The emergence of spin electromotive force and photoluminescence upon optical excitation, attributed to spin-dependent electron tunneling between the quantum well and the ferromagnetic layer, demonstrates a dependence on the heterostructure parameters consistent with the developed theory, thus confirming the impact of the time mismatch effect.

Overall, addressing the balance between tunneling and recombination times could lead to improved optoelectronic devices capable of efficiently converting photon helicity into electrical signals, thereby opening up new possibilities in telecommunications and beyond.

References

[1] G. Schmidt, D. Ferrand, L. W. Molenkamp, A. T. Filip, B. J. van Wees, Phys. Rev. B **62**, R4790(R) (2000)

[2] V. I. Safarov, I. V. Rozhansky, Z. Zhou, B. Xu, Z. Wei, Z.-G. Wang, Y. Lu, H. Jaffrès, H.-J. Drouhin, Phys. Rev. Lett. **128**, 057701 (2022).

[3] I. V. Rozhansky, I.V. Kalitukha, G. S. Dimitriev, O. S. Ken, M.-V. Dorokhin, B. N. Zvonkov, D. S. Arteev, N. S.Averkiev, V. L. Korenev, Nano Lett. **23**, 3994 (2023).