Magnetoelectronic Phenomena at a Ferromagnet-Semiconductor Interface

In a recent Letter [1], Hammar, Bennett, Yang, and Johnson (HBYJ) describe measurement of the interfacial resistance in a ferromagnet/insulator/semiconductor ($F/I/S$) structure. They argue that hysteretic features observed between temperatures of 75 and 296 K are evidence for spin-dependent transmission through the interface. We believe that their observations can be attributed to other effects.

Despite concerted effort in multiple laboratories, a *conclusive* demonstration of electrical spin injection phenomena in $F/I/S$ (or F/S) structures remains elusive, primarily due to three factors. (i) Given their low carrier density, two-dimensional electron gases (2DEGs) are extremely sensitive, via the "local" Hall effect (LHE), to strong magnetic fringe fields near the ferromagnets [2]. (ii) In recent relevant experiments with optically excited electrons [3], the detailed nature of the $F/I/S$ interface has proved crucial. In all experiments on metallic-F/S devices to date, this interface is nonideal. (ii) Electron transport in high mobility 2DEGs can be ballistic. Previous modeling of electrical spin injection phenomena [4], valid only in the diffusive region, requires revision [5].

Based upon our experience with F/S systems, we believe that the hysteretic phenomena displayed by HBYJ result from local Hall voltages in the InAs channel. These authors asserted that fringe magnetic fields are unimportant in their devices, since the edges of the NiFe film are far away from the contact area. However, their 86-nm-thick NiFe film is deposited on top of a ~76-nm-high mesa. The abruptness of the resulting step edge is not mentioned, micromagnetic domain fluctuations are to be expected in this locale. Quantitative assessment of the magnitude of the resulting LHE requires detailed knowledge of the domain structure within the ferromagnetic overlayer (which varies with applied field), the orientation of the fringing fields that result, and the current distribution in the InAs near the interface. For the system described by HBYJ, only 0.1% of the ferromagnet's saturation field is sufficient to induce a Hall resistance of 0.4Ω within the InAs. This is of comparable magnitude to the observed effect. Such spurious signals will exhibit the magnetic field and current symmetries found in the HBYJ data; these are entirely expected from the device symmetry combined with the reciprocity relations of Büttiker.

HBYJ's description of a spin-diode effect within their devices is questionable. We contend that it is fundamentally incorrect to associate the direction of the *drift* velocity in a diffusive device with a "spin quantization axis" via the Rashba effect. Transport in the HBYJ structures is *diffusive*; we estimate their momentum mean free path to be as short as 400 nm, i.e., just 1/100 of the effective channel length. Momentum is not conserved beyond a mean free path and, therefore, the direction of the Rashba field will vary randomly along the diffusive paths taken by the electrons. In effect, spin will not remain a good quantum number beyond this length scale. Even in the ballistic limit, unless conduction is strictly one dimensional, i.e., involves only a single occupied subband, the current will be carried by a *distribution* of momenta. The resulting variance in precession among the ensemble of contributing trajectories will act to suppress any spin effect.

The temperature dependence observed does not support the authors' interpretation of the data. Their arguments for "spin-diode" phenomena are based upon a spin splitting ΔE, which is of order 2–5 meV in InAs. In these experiments, at $T = 296$ K, one expects the momentum lifetime τ comparable to the inverse Rashba frequency $\omega_R^{-1} \sim \hbar/\Delta E$. Hence it is highly unlikely that spin-diode phenomena will remain observable in this regime, yet a spin-dependent effect in $\Delta R_i/\overline{R}_i$ is found to persist to room temperature *without diminution.* By contrast, phenomena based on the LHE will indeed show weak temperature dependence in this regime (i.e., consistent with the data). At 4.2 K, where $\omega_R \tau > 1$ can hold, data have not been provided. Furthermore, the temperature dependence of the interfacial conduction itself appears anomalous. It may be indicative of an increasing role of parallel conduction processes at higher temperatures, which is pervasive with InAs heterostructures.

In summary, with a low density 2DEG it is extremely difficult to separate magnetoelectronic phenomena involving local Hall fields from those possibly based on spin transport [6]. We believe that an unambiguous demonstration of electrical spin injection can be provided only by observation of *precessional* phenomena (Hanle effect), e.g., in a device with two ferromagnetic contacts that serve as spin polarizer and analyzer. To our knowledge, only once to date has such a demonstration been reported in the literature—in an all-metal device [7].

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[1] P. R. Hammar *et al.*, Phys. Rev. Lett. **83**, 203 (1999).
[2] F. G. Monzon and M. L. Roukes, J. Magn. Magn. Mater. **198**, 628 (1999); F. G. Monzon, D. S. Patterson, and M. L. Roukes, J. Magn. Magn. Mater. **195**, 19 (1999).
[3] M. W. J. Prins *et al.*, J. Phys. Condens. Matter **7**, 9447 (1995); A. Filipe *et al.*, Phys. Rev. Lett. **80**, 2425 (1998).
[4] P. C. van Son, H. van Kempen, and P. Wyder, Phys. Rev. Lett. **58**, 2271 (1987); Mark Johnson and R. H. Silsbee, Phys. Rev. B **35**, 4959 (1987).
[5] See, however, H. X. Tang, F. G. Monzon, R. Lifshitz, M. C. Cross, and M. L. Roukes (to be published).
[6] F. G. Monzon, Ph.D. thesis, California Institute of Technology, 1999.
[7] Mark Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985).

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