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Citation for published version (APA):

Filip, A. T., LeClair, P. R., Smits, C. J. P., Kohlhepp, J. T., Swagten, H. J. M., Koopmans, B., & Jonge, de, W. J. M. (2002). Spin-injection device based on EuS magnetic tunnel barriers. *Applied Physics Letters*, 81(10), 1815-1817. <https://doi.org/10.1063/1.1503406>

DOI:

[10.1063/1.1503406](https://doi.org/10.1063/1.1503406)

Document status and date:

Published: 01/01/2002

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Spin-injection device based on EuS magnetic tunnel barriers

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(Received 26 February 2002; accepted for publication 3 July 2002)

We propose a spin-valve device consisting of a nonmagnetic semiconductor quantum well, sandwiched between ferromagnetic semiconductor layers that act as barriers. The total conductance through such a trilayer depends on the relative magnetization of the two ferromagnetic-barrier layers which act as “spin filters.” With respect to practical realization, EuS/PbS heterostructures may be a suitable candidate. The magnetoresistance should exceed 100% for a wide range of the thicknesses of both the quantum well and the ferromagnetic barriers. From a fundamental physics point of view, the device may not only give insight into the spin lifetimes of the nonmagnetic layer, but the strong spin accumulation taking place in the quantum well may lead to novel optical and nuclear magnetic resonance properties. © 2002 American Institute of Physics. [DOI: 10.1063/1.1503406]

The idea to exploit the spin degree of freedom in semiconductor devices has gained a lot of momentum lately,¹ fuelled by potential applications in the field of quantum computation,² magnetic field sensors, and memory devices.³ Achieving a good efficiency of spin injection into semiconductors is still an important challenge in the field of spintronics. So far, there has been only partial success with spin-polarized transport in semiconductors.^{4–7} Many problems arise simply from the growth of magnetic metals on semiconductors—formation of silicides, surface states, Schottky anomalies, and Ga or As compounds and alloys, just to name a few.⁴ The greatest success to date in this area has been in diluted magnetic semiconductors (DMS), in which high-efficiency spin injection was recently demonstrated by several groups.⁷

From a conceptual point of view, it has become clear that the most likely obstacle to inject spin from metals into a semiconductor is due to their huge resistance mismatch.⁸ One possible route to overcome this impedance mismatch obstacle is to insert a tunneling barrier between the metal and semiconductor.^{9,10} First results are already available, and spin injection into GaAs either via a tunnel barrier¹¹ or a Schottky barrier¹² has been demonstrated. However, the junction properties and injection efficiency are strongly dependent on the metal–barrier interfaces.¹³

In this letter, we propose another route for spin injection in semiconductors, by making use of the spin filter effect of a ferromagnetic tunnel barrier.¹⁴ In a ferromagnetic semiconductor, below the Curie temperature, the magnitude of the band gap depends on the spin direction. Its use as spin filter potentially alleviates the problem of strong interface sensitivity for standard tunnel barriers, as spin filtering is to first order a function of the barrier height alone. Moreover, a magnetic tunnel barrier has the added attractiveness of allowing near 100% (pseudohalf-metallic) efficiency of injection.

The device we envision consists of a nonmagnetic semiconductor quantum well that is sandwiched between two

larger gap ferromagnetic semiconductors that form the barrier layers. The two barriers are contacted by two metallization layers which form the source and the drain of the device (see Fig. 1). The total conductance of such a device depends on the relative alignment of the magnetizations of the two barrier layers. Our device is, to a certain extent, analogous to the one proposed by Worledge and Geballe,¹⁵ who suggested the use of a simple double-magnetic barrier. However, the presence of the intermediate nonmagnetic spacer layer between the two spin filters is essential, significantly changing the physics of the system. From the point of view of feasibility, it allows one to avoid a direct ferromagnetic exchange coupling between the two barrier layers. For certain thicknesses, an antiferromagnetic (AF) coupling between the magnetic layers may be obtained, thus insuring an easy control of the relative magnetization. Apart from that, the inherent technological difficulties related to finding and growing two different but compatible ferromagnetic semiconductor materials are avoided. More importantly, the device is expected not only to give insight into the spin transport prop-

FIG. 1. Schematic structure of the proposed device. When a voltage V is applied over the device and both the polarizer and the analyzer filters are aligned AP, and spin accumulation takes place in the PbS quantum well.

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erties of the nonmagnetic layer (e.g., spin lifetimes), but also lead to other interesting effects. Spin accumulation, whose sign and magnitude scale with the applied voltage, is expected to take place in the quantum well. If used as a light-emitting diode, the device should emit circularly polarized light whose helicity could be controlled electrically by the applied voltage. Moreover, the voltage controllable nonequilibrium spin accumulation leads to a finite polarization of nuclear momenta,¹⁶ with implications for the field of quantum computing.¹⁷

As for the physical realization, we propose the PbS/EuS system.¹⁸ EuS is a well studied ferromagnetic semiconductor with a Curie temperature of 16.8 K, a semiconducting gap of 1.6 eV and a spin splitting of the gap of 0.36 eV.^{13,14} PbS is a diamagnetic semiconductor with a narrow gap of 0.4 eV.¹⁹ Despite the disadvantage of low Curie temperature that only allows such a device to work at low temperatures, EuS/PbS is an excellent starting system from both technological and fundamental points of view. First of all, EuS and PbS both crystallize in the rocksalt structure and the lattice mismatch is very small, of only 0.5%. In fact, the epitaxial growth of EuS/PbS superlattices has already been demonstrated.²⁰ Secondly, compared to standard DMS materials which require fields in the order of Teslas to reach saturation, EuS has very attractive magnetic properties, with coercive fields as low as 25 Oe.²¹ With respect to controlling the relative magnetization alignment, there are two distinct routes: Either the growth of two barriers with different thicknesses, as the coercive field of a thin EuS film is expected to depend on thickness,²² or the choice of the nonmagnetic PbS thickness that induces an AF coupling of the two magnetic layers.²³

Another notable advantage of EuS is the very high spin filter efficiency. As the tunneling probability depends exponentially on the barrier height, it is easy to check that, e.g., a 5 nm thick EuS barrier, the conductance is expected to be almost fully polarized, with a ratio $R_{\text{EuS},\uparrow}/R_{\text{EuS},\downarrow} > 10^6$, where $R_{\text{EuS},\uparrow}$ and $R_{\text{EuS},\downarrow}$ denote the barrier resistances for the majority and minority carriers respectively. Moreover, as the spin-injection efficiency depends only on the barrier heights and not on interface density of states, it should be very robust with respect to variations in interfacial properties. Even if a dead magnetic layer is present at the interfaces and the effective magnetic barrier thickness is reduced to only a few monolayers, the expected polarization remains effectively 100%. The presence of a dead magnetic layer only reduces the total transmission (and, consequently, the conductance) of the tunnel barrier, while the current polarization remains unaffected. Recently LeClair *et al.*²⁴ demonstrated the spin filter effect of a single EuS barrier, measuring a spin filter efficiency in the order of 90%.²⁴ We expect that in a well lattice-matched system like EuS/PbS, the spin filter efficiency will increase even more, reaching towards 100%.

Here, we discuss a simple model that still catches the fundamental physics of the device. For simplicity, we assume that the resistance of the EuS tunnel barriers is larger than the resistance of the PbS spacer ($R_{\text{EuS}} > R_{\text{PbS}}$) and the PbS thickness is smaller than the spin-flip length in PbS. As a consequence, the band gap bending and the spatial decay of the spin accumulation inside the quantum well can be ne-

glected, or, in other words, the chemical potentials for each spin subband may be taken constant inside the quantum well. We denote by P the polarization of the EuS tunnel barrier conductance:

$$P = \frac{R_{\text{EuS},\uparrow} - R_{\text{EuS},\downarrow}}{R_{\text{EuS},\uparrow} + R_{\text{EuS},\downarrow}}. \quad (1)$$

When a finite voltage is applied over the device, as injection and extraction rates differ, a nonequilibrium spin density accumulates in the nonmagnetic PbS spacer. Due to spin-flip processes, this nonequilibrium spin density tends to relax, leading to a spin-relaxation current:

$$I_{\uparrow\downarrow} = \frac{eN(E_F) \cdot \text{Vol}}{\tau_{sf}} (\mu_{\uparrow} - \mu_{\downarrow}), \quad (2)$$

where $I_{\uparrow\downarrow}/e$ gives the number of electrons per unit time that flip their spin from up to down, τ_{sf} is the spin lifetime of the PbS quantum well, Vol is the volume of the PbS quantum well, $N(E_F)$ the density of states at the Fermi level, and $\mu_{\uparrow}, \mu_{\downarrow}$ are the chemical potentials for the two spin directions.

Total current conservation for each spin consideration has also to be taken into account. Using the current conservation condition and Ohm's law, the device resistance can be determined for both the parallel (P) and the antiparallel (AP) alignment of the injector and detector barriers. Finally, the magnetoresistance (MR) ratio can be computed as

$$\text{MR} = \frac{R_{\text{AP}} - R_P}{R_P} = P^2 \frac{1}{1 - P^2 + R_{\text{EuS}}\Gamma}, \quad (3)$$

with

$$\Gamma = \frac{eN(E_F) \cdot \text{Vol}}{\tau_{sf}} = \frac{1}{R_{\text{PbS}}} \cdot \frac{t_{\text{PbS}}}{\lambda_{sf}}, \quad (4)$$

where λ_{sf} is the spin-flip length and t_{PbS} the thickness of the PbS. Γ has the unit of a conductance and is related to the spin relaxation strength in the nonmagnetic semiconductor. The condition to have an efficient device is that the denominator in Eq. (4) is small ($R_{\text{EuS}}\Gamma < 1$). On the other side, if the EuS tunnel barrier resistance becomes comparable, the resistance of the PbS spacer, the contribution of the latter cannot be neglected anymore and the MR will be reduced. In first order, the effective MR ratio will be given by $\text{MR}_{\text{eff}} = \text{MR} \cdot (R_{\text{EuS}}/R_{\text{EuS}} + R_{\text{PbS}})^2$, thus "recovering" the conductance mismatch predicted by Schmidt *et al.*⁶ Combining the two, we arrive to the working condition for our device

$$R_{\text{PbS}} < R_{\text{EuS}} < R_{\text{PbS}} \cdot \frac{\lambda_{sf}^2}{t_{\text{PbS}}^2}. \quad (5)$$

In Fig. 2, the effective MR ratio is plotted as function of the ratio $R_{\text{EuS}} = R_{\text{PbS}}$. For values expected for real-life devices, e.g., $\tau_{sf} = 100$ nm (a conservative estimate, taking into consideration values reported in literature for other materials), $t_{\text{PbS}} = 10$ nm, a spin filter efficiency of 90% as reported in Ref. 24, and a ratio $R_{\text{EuS}}/R_{\text{PbS}} = 10$, the expected MR should exceed 200%. What is even more relevant is that for a large range of two orders of magnitude in the EuS tunnel barrier resistance, the expected effective MR ratio exceeds 100%, confirming the expected robustness of the device.

FIG. 2. Effective magnetoresistance ratio plotted as function of the ratio $R_{\text{EuS}}/R_{\text{PbS}}$. Top panel: MR dependence for different spin filter efficiencies ($t_{\text{PbS}}/\lambda_{\text{sf}}=0.1$); bottom, for different spin relaxation strength in the PbS quantum well ($P=0.9$).

Two clear trends in the MR can be observed: First, the MR shows a broad maximum at low barrier values and then decreases with increasing the EuS barrier resistance relative to the resistance of the PbS spacer layer and, second, the MR decreases with increasing the PbS spacer layer thickness. The former indicates that, as the probability to escape via the tunnel barriers decreases, the electrons spend more time inside the well, therefore, increasing the probability that spin information is lost before the electron reached the drain. Actually, the spin-injection efficiency conditions, we derived are very general and expected to apply to any spin-injection/detection type devices. They are in agreement with the predictions of Fert and Jaffres,¹⁰ who studied metallic double-tunnel junctions, also taking into consideration the spatial dependence of the nonequilibrium spin density.

When the magnetizations of the two barriers are aligned parallel, the injection and extraction rates are identical and no spin accumulation takes place in the PbS quantum well. For the AP alignment, the injection and extraction rates are different, therefore a nonequilibrium spin population accumulates, leading to a spin splitting of the chemical potentials. Its magnitude is

$$\Delta\mu = eV \frac{P}{1 + R_{\text{EuS}}\Gamma}. \quad (6)$$

The expected spin splitting is in the order of 10 mV, assuming an applied voltage of 100 mV. As the magnitude of the spin splitting is higher than kT , the spin population inside the PbS quantum well will be outside thermal equilibrium.

Finally, we would like to note that the strong spin accu-

mulation may open the door for other applications for the device. The light emitted due to recombination processes in the quantum well will be circularly polarized. The sign and degree of circular polarization depends on the spin splitting, therefore, it can be controlled by varying the applied voltage. Moreover, the nonequilibrium electron spin density is expected to also induce a polarization of the nuclear spins via the hyperfine interaction^{16,17} with potential impact in the field of quantum computation.²⁵

This work was supported by the Dutch Foundation for Fundamental Research on Matter (FOM) and by the Stichting Technische Wetenschappen (STW). The authors acknowledge useful discussions with T. Story.

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²⁵In PbS, approx 20% of the nuclei are expected to be ²⁰⁷Pb, carrying a nuclear spin $I=1/2$, the having $I=0$.