Semiconductor Spintronics: Information Processing with Spin Currents

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1. Introduction

The electronics industry to date has relied upon the control of charge flow, and used size scaling to continuously increase the performance of existing electronics. However, size scaling cannot continue indefinitely, and new approaches must be developed. Basic research efforts have shown that spin angular momentum, another fundamental property of the electron, can be used to store and process information in solid state devices. The *International Technology Roadmap for Semiconductors* has identified the electron's spin as a new state variable which should be explored for use beyond CMOS.

Silicon's mature technology base and overwhelming dominance make it an obvious choice for implementing spin-based functionality. Its basic material properties result in low spin-orbit effects and long spin lifetimes, making it especially attractive for semiconductor spintronics. Electrical injection, manipulation and detection of spin-polarized electrons in silicon have proven elusive, but are essential in this endeavor.

We describe here a simple and efficient way to electrically inject spin-polarized electrons from an Fe thin film contact into silicon, achieving an electron spin polarization of at least 30% [1]. We generate both spin-polarized charge currents and *pure spin diffusion currents* in silicon using a non-local spin valve lateral transport device structure, and demonstrate that we can manipulate and electrically detect the polarization of the pure spin current in the silicon [2].

2. Electrical Spin Injection into Silicon

We electrically inject spin polarized electrons from a thin ferromagnetic Fe film through an Al_2O_3 tunnel barrier into a Si(001) *n-i-p* doped heterostructure (Figure 1), and observe circular polarization of the electroluminescence (EL). This signals that the electrons retain a net spin polarization before radiative recombination with unpolarized holes in the Si, and transfer their spin momentum to the optical field as required by momentum conservation, enabling detection and analysis. The spectra at T=50K and 80K are shown in Figure 2, analyzed for positive and negative helicity light (σ+, σ-). The magnetic field dependence of the circular polarization tracks the magnetization of the Fe contact, demonstrating that the spin orientation of the electrons in the Si originates with the Fe contact. A rate equation analysis which includes the electrons' radiative and spin lifetimes shows that the net spin polarization of the electrons in the Si at least 30% at low temperature. The spin injection process is therefore relatively efficient, given that the spin polarization of the Fe is only 45%.

This interpretation is confirmed by similar measurements on Fe/Al_2O_3/Si/AlGaAs/GaAs/AlGaAs quantum well structures, in which the spin polarized electrons drift under applied field from the Si and recombine in the GaAs QW. In this case, the polarized EL can be analyzed using the familiar quantum selection rules, yielding an electron spin polarization of 10%.

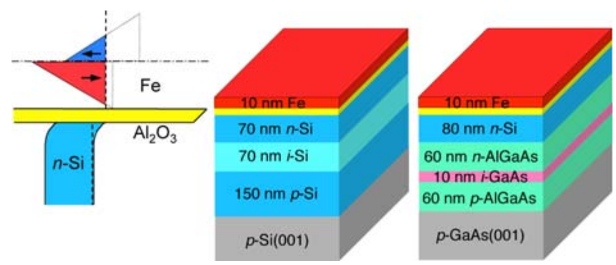

Figure 1. Band diagram of the Fe/Al2O3/Si contact and cross section of the two types of samples studied.

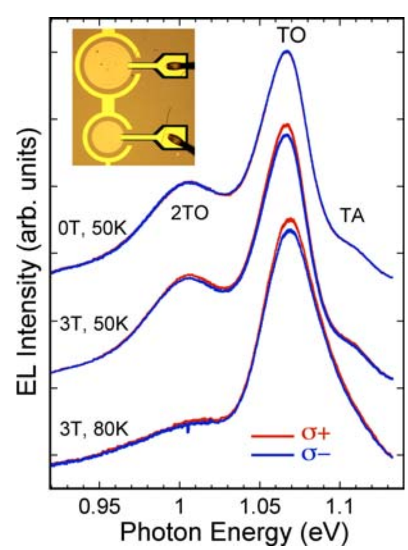

Figure 2. Electroluminescence spectra from the Si n-i-p structure with the Fe/Al2O3 contact at 50K and 80K, and at magnetic fields of zero and 3 T. The inset shows an optical photograph of the LEDs studied.

Details of the sample growth may be found in reference 1. It should be noted that the Si surface is air-exposed before the Fe/Al_2O_3 contact is deposited. Likewise, the AlGaAs surface is air-exposed before the 80-160 nm Si film is deposited. This attests to the remarkable robustness of spin as an alternative state variable in semiconductor devices.

3. Electrical Detection of Pure Spin Currents

Having established a simple, efficient and reliable means of spin injection in a vertical transport structure like the spin-LED, we use the Fe/Al_2O_3 tunnel barrier contacts to create and analyze the flow of *pure spin current* in silicon in a lateral transport device. Using the non-local spin valve geometry shown in Figure 3, we generate both a spin-polarized charge current which flows from contact 3 to the right, and a pure spin diffusion current which flows from contact 3 to the left.

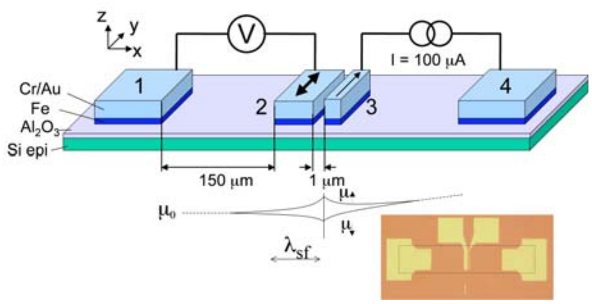

Figure 3. Schematic layout of four terminal device and depiction of the spin-dependent electrochemical potential.

This pure spin current produces a net spin polarization and an imbalance in the spin-dependent electrochemical potential, which is detected as a voltage by the magnetic contact 2 relative to the reference contact 1. No charge current flows in the detection circuit defined by contact 1 and magnetic detector contact 2, thus excluding spurious contributions from AMR and local Hall effects.

The voltage measured at contact 2 is sensitive to the relative orientation of the contact magnetization and the net spin orientation in the Si itself. The spin orientation in the Si is determined by the magnetization of the injector contact 3. As the relative orientation of contacts 2 and 3 is changed from parallel to antiparallel by a small transverse field, the voltage at the detector contact 2 changes from low to high, respectively. This demonstrates that pure spin currents can be used to process information.

Further confirmation of spin transport and a demonstration of spin modulation in the silicon is provided by the Hanle effect, in which a magnetic field perpendicular to the surface induces precession of the spins in the silicon transport channel between the injecting and detecting contacts, resulting in a modulation of the detected NL MR signal. The Hanle measurements shown in Figure 5 were obtained at 5 K using the same bias condition and measuring technique described above.

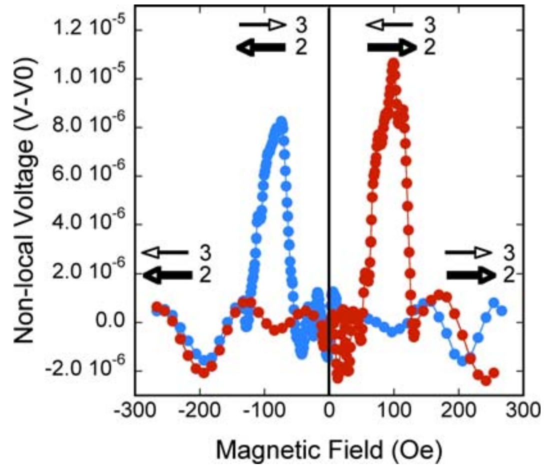

Figure 4. NL voltage versus in-plane magnetic field at 10K, for a contact 2-3 spacing of 3 um. The device is biased at 100 μA from contact 3 to 4.

The non-local voltage at contact 2 is plotted as a function of the perpendicular magnetic field (B_z) for parallel alignment of the magnetizations of contacts 2 and 3. The NL voltage is at a minimum at zero Hanle field, as expected from Figure 4. As the Hanle field B_z is increased, the injected spins in the silicon are caused to precess during transit to the detector contact, resulting in an increasing degree of anti-parallel alignment relative to the detector spin orientation and a corresponding increase in the NL signal.

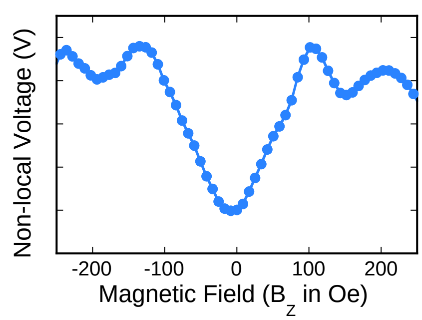

Figure 5. Hanle effect at 5K for parallel orientation of injector and detector contact magnetizations.

4. Summary

We have demonstrated the injection, modulation and detection of pure spin diffusion current in silicon in a lateral transport geometry compatible with existing device design, fabrication and scaling. This approach injects spin-polarized electrons near the silicon conduction band edge with near unity conversion efficiency and low bias voltages (~ 2 eV) compatible with CMOS technology.

Acknowledgements

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References

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[2] O.M.J. van ‘t Erve *et al*, Appl. Phys. Lett. **91** (2007) 212109.