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Silicon Spintronics

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1. Introduction

The use and control of the spin of electrons in solid-state devices lies at the heart of spintronics [1,2]. Ferromagnetic metal devices that exhibit large magnetoresistance (MR) effects have already had great impact on magnetic data storage and the development of magnetic random access memory. Following the success of metal-based spintronics, the integration of magnetic technology and mainstream semiconductor electronics is actively explored, and combining the best of both technologies could impact information systems in a profound way. A pivotal step is implementation of spin-based electronic functionality in silicon devices. Remarkable progress made during the last two years gives confidence that this is within reach, although significant challenges remain. Here we briefly describe three key advances: (i), the interface engineering of magnetic contacts to silicon using low-work-function interlayers, (ii), the control of spin-polarization in a silicon two-dimensional electron gas (2DEG) by a gate electric field, and (iii) the observation of electrical spin-signals in Si devices at room temperature.

2. Results

While implementing spin-functionality into silicon is potentially highly rewarding, it has turned out to be a major challenge. Amongst the key advances to be made are to develop robust and efficient ways to inject electron spins into Si, and to develop suitable (optical, electrical) methods to detect and manipulate the spin-polarization in the Si. However, perhaps the most challenging aspect is to design fully electrical silicon based spin-devices with useful functionality and large spin-signals at room temperature, and in a simple two- or three-terminal geometry. With respect to the latter, efforts have so far focused on devices such as the spin-MOSFET, a transistor with a Si channel and a ferromagnetic (FM) source and drain (Fig. 1). It is now clear that this demands careful consideration of the properties of the FM injector and detector contacts [3–5], going beyond the obvious need for a high spin polarization of the contacts. For example, it is found that Schottky barrier formation on Si can be detrimental to the spin-transport of such a device [3,4]. This is partly because of the resulting large resistance area (RA) product of the contacts and partly because of the potential energy landscape, which affects spin flow across the interface [5].

As a solution, we have developed novel approaches to control the Schottky barrier height and resistance-area product of spin tunnel contacts to Si, e.g. using low work function materials [4]. These include ferromagnets (Gd and GdCo alloys) as well as non-magnetic materials, inserted as ultrathin (sub-nm) interfacial layers into FM/Al_2O_3/Si spin-tunnel contacts on either side of the tunnel barrier. In this way, the Schottky barrier can be completely suppressed and the RA product of the FM/Al_2O_3/Si contacts can be tuned over 8 orders of magnitude (Fig. 2). Equally important, complementary measurements show that a reasonable tunnel spin-polarization is simultaneously maintained [4].

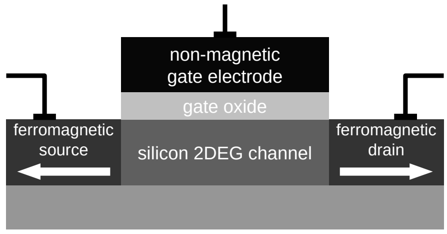

FIG. 1. Layout of the spin-MOSFET, having a ferromagnetic source and drain contact, a silicon channel, and a gate electrode which is used to control the current via the spin of the electrons that traverse the channel.

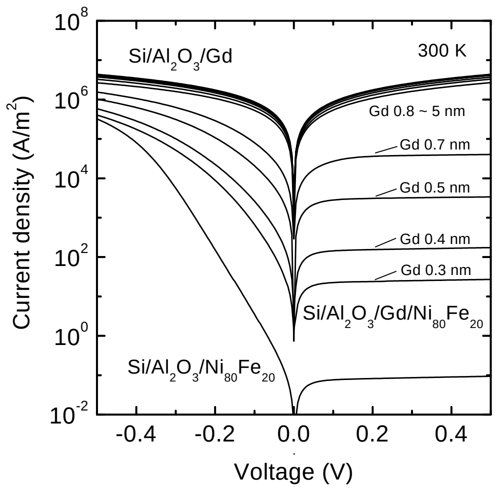

FIG. 2. Electrical current-voltage characteristics of silicon/Al_2O_3/Gd/$Ni_{80}Fe_{20}$ spin-tunnel contacts for different thickness of the low-work function Gd interlayer, as indicated. The Schottky diode behavior gradually disappears with increasing Gd thickness, and is fully suppressed for 0.8 nm of Gd, with a corresponding reduction of the RA product of the contacts by 8 orders of magnitude.

Interestingly, using these approaches the Schottky barrier can even be inverted, such that even in the absence of an applied bias, an interfacial accumulation layer (i.e. a 2DEG) is established at the Si surface adjacent to the oxide insulator (Fig. 3). Such engineered spin-tunnel contacts with low work function materials therefore not only qualify as resistance-matched source and drain electrodes for spin-transistors, but also open up new avenues to design spin devices based on Si quantum structures for application in silicon spintronics.

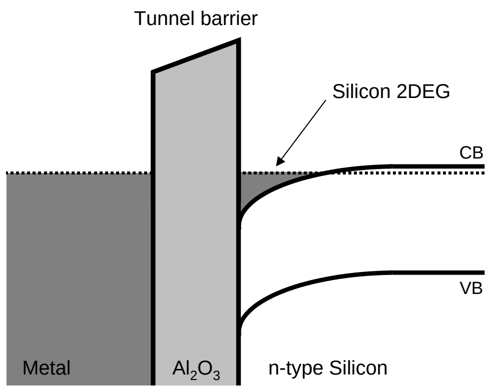

FIG. 3. Energy band diagram of a silicon 2DEG /Al_2O_3/metal contact, depicting the tunnel barrier, the Fermi levels (dashed lines), the Si conduction (CB) and valence (VB) band, and the Si 2DEG adjacent to the tunnel barrier.

Another crucial aspect in silicon spintronics is to be able to control the electron spin in silicon with an electric field from a gate electrode, which, in turn, can modulate the device current. We have recently explored new methods to achieve this using a Si 2DEG structure such as shown in figure 3. In particular, we have demonstrated [6] electric field control of spin-polarization in a silicon quantum well, and detection thereof via tunneling into a ferromagnet, producing prominent oscillations of tunnel magnetoresistance of up to 8%. The electrostatic modification of the spin-polarization in the Si two-dimensional electron gas is enabled by its discrete electronic structure. This concept is particularly suited for Si, organics and carbon-based materials in which the weak spin-orbit coupling leaves known methods for electrostatic control, such as proposed for a spin-transistor, ineffective. We also proposed further extensions to discontinuous electric field control of spin-diffusion and spin-accumulation [6].

An important requirement of semiconductor spintonics is device operation at room temperature, which has hitherto not yet been achieved in electrical semiconductor devices. We have recently achieved injection of a spin-polarized current from a ferromagnet into silicon, and electrical detection of the resulting spin-accumulation, at room temperature [7]. Such a spin-accumulation corresponds to a non-equilibrium spin-polarization of the conduction electrons of the silicon, and in essence turns Si into a magnetic material. The demonstration of spin-signals at room temperature is a key advance that brings silicon spintronics technology a step closer to reality.

3. Conclusion

The implementation of spin-based electronic functionality in silicon devices is a pivotal step towards the integration of magnetism and mainstream semiconductor electronics. Important progress has been made in (i), the interface engineering of of magnetic contacts to silicon using low-work-function interlayers, (ii), the control of spin-polarization in a silicon 2DEG by a gate electric field, and (iii) the observation of electrical spin-signals in Si devices at room temperature.

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