Silicon Spintronics

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Integration of magnetism and mainstream semiconductor electronics could impact information technology in ways beyond imagination. 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 also remain.

1. COMBINING THE BEST OF BOTH WORLDS

Open up a computer or laptop, and you'll find two entirely different devices. One, the processor chip, is used to manipulate information and perform calculations, but it cannot remember the resulting information. The other device, the hard-disc, stores information for later usage, but cannot process the data. Why not combine both functions into a single component?

The above example illustrates the potential impact of integrating the two technologies on which the processor and hard-disc are based. These technologies, semiconductor electronics and magnetic data storage, respectively, have both gone through a remarkable, yet largely independent development to ever-higher density and smaller feature sizes over a time span of several decades. However, they are based on two entirely different types of materials, each having its own set of unique attributes that makes them so successful in their own field.

Computer chips contain semiconductor materials, configured into a network of switches that operate by manipulating the flow of electrical charge, with the silicon transistor as the workhorse. The ability to control the charge carrier density (and type) by doping and electric fields from a gate gives semiconductor materials unique functionality, and provides a key aspect, namely power amplification.

Magnetic materials, on the other hand, exhibit hysteresis and thus have a memory. Once the magnetic north and south poles are oriented in a certain direction, the magnetization will remain that way for many years. And, the magnetic state can be reversed by an external trigger in a very short time (nanoseconds are standard, but recent experiments have demonstrated reversal on a femtosecond time scale [1]).

Amplification and memory, magnetism and electrical conduction: imagine the possibilities if one could combine the best of both worlds. Can this provide a solution to the issues faced in future generations of conventional technologies? Or, more ambitiously, can we create a new type of information technology with much-improved performance, lower energy consumption, and/or entirely new functionality? Spintronics is aiming to achieve just that, by using, instead of the charge, the magnetic moment, or spin, that electrons possess. Needles to say, implementation of spin-functionality in silicon, the prevailing semiconductor material, is a crucial step.

2. TOWARDS A SPIN-TRANSISTOR

Semiconductor spintronics comes with an intriguing set of fundamental physics questions and challenging materials science and engineering aspects. From a device perspective, the initial focus has been on the development of a spin-transistor. Although different versions have been proposed [2-5], their common feature is the control of the current through the device via the spin. The simplest example of such a device, the spin-MOSFET, is shown in Fig. 1. It is similar to an ordinary MOSFET, except that the source and drain contacts are ferromagnetic. Hence, the conductance between source and drain depends not only on the gate voltage (that controls the number of charge carriers in the semiconductor channel), but also on the relative alignment of the magnetization of the source and drain contacts. The effect is similar to the giant magnetoresistance (GMR, described elsewhere in this issue) and involves spin-dependent conduction. According to quantum mechanics, the electron's spin can have two values, +1/2 or -1/2 (in units of Planck's constant h divided by 2π), often denoted as spin-up and spin-down, reflecting the opposite direction of the spin-angular momentum vector. Electrons that enter the channel from the source have their spin direction aligned according to the source magnetization, and can transmit into the drain contact much more easily if their spin is aligned with that of the drain ferromagnet. Hence, a larger conductance is expected if source and drain have their magnetization pointing in the same direction, while anti-parallel magnetization direction results in a reduced conductance.

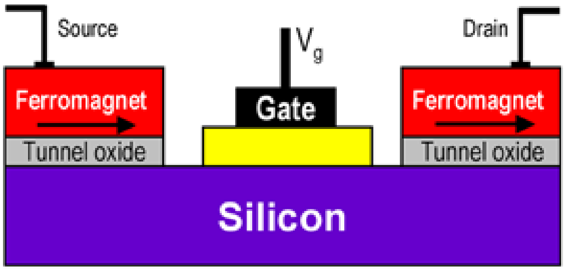

Fig. 1: Layout of the spin-MOSFET.

In order to achieve this, three basic requirements were identified:

1) The ability to inject electron spins from the source ferromagnetic contact into the semiconductor channel (spin-injection).
2) The transport of the electrons through the semiconductor channel from source to drain without losing the spin information.
3) The ability to transport the electron spins from the channel into the magnetic drain contact in a spin-selective way (spin-detection).

It should be noted that the first proposal for a spin-transistor, by Datta and Das [2], was actually more advanced then the device described above, as it involved active control of the orientation of the spins during their transport through the channel (i.e., step 2 is different). The idea is that when the magnetization of the source and drain ferromagnetic contacts is fixed, the device current can still be modulated if the spins can be controllably rotated in the channel over either 0 or 180 degrees, using a gate electrode. The latter involves use of the spin-orbit interaction, introducing an extra challenging aspect. Since, as we will see below, the demonstration of the simpler spin-MOSFET of Fig. 1 already turned out to be a major challenge, we will here focus on the latter device.

3. SPIN-INJECTION INTO A SEMICONDUCTOR

At first glance, it may seem that it should be straightforward to inject spin-polarized currents into a semiconductor. A ferromagnetic metal contains an excess of carriers whose spin points in a preferred direction, depending on the direction of the metal's magnetization. This spin imbalance should then, in principle, be transferred to a semiconductor when charge carriers are injected into it from a ferromagnetic electrode. In reality, however, the situation is not so simple, because the electrical resistance of a ferromagnetic metal is much smaller than that of a semiconductor. And so, any voltage applied to a contact between them will drop completely within the semiconductor, the non-magnetic properties of which dominate the behavior of the contact. As a result, the current across such a contact will consist of carriers with no preferred spin direction, regardless of the relative population of spins within the ferromagnetic metal.

This problem is known as the conductivity mismatch [6], and can be overcome by introducing an additional, spin-dependent, barrier at the boundary between a ferromagnetic contact and a semiconductor. This provides a spin-dependent tunnel resistance that can be made comparable to, or larger than, the resistance of the semiconductor. As soon as this condition is met, spin-injection becomes possible, as schematically illustrated in Fig. 2.

The success of this approach for injecting spins was demonstrated several years ago for GaAs by detecting the circular polarization of the light that is emitted when these spin-polarized electrons subsequently recombine with holes [7, 8]. From these experiments, an injected electron spin-polarization in the GaAs of up to 30% has been deduced.

4. MAKING SILICON MAGNETIC

An important step forward was recently made with the demonstration of an efficient way to inject electron spins from a ferromagnet into silicon [9]. The authors used a thin Al_2O_3 insulator to separate a ferromagnetic Fe contact from the Si (see Fig. 3), and observed a spin-polarized flow of electrons tunneling from the Fe into the Si. Unexpectedly, the detection of the spins was made via the circular polarization of the recombination luminescence, much in the same way as was well established for GaAs. This by many was thought not to be possible, given the weak spin-orbit interaction in Si, and more importantly, the indirect bandgap, which causes the recombination time to be long, and much longer than the spin relaxation time. Hence, any spin-polarization was expected to have decayed and vanished by the time the recombination takes place. Nonetheless, significant light polarization was observed, tracking the magnetization of the Fe injector in sign and magnitude [9].

The electrical injection of preferentially one spin orientation causes a non-equilibrium spin-accumulation in the Si that can be described by a spin-dependent electrochemical potential. This reflects the fact that the occupation of the states in the Si becomes spin-dependent, rather than the electronic states (i.e., there is no energy splitting between the states for different spin). Yet, in some sense it makes silicon magnetic in a simple, efficient and controllable way, thus providing an exciting step towards integration of magnetism and mainstream semiconductor electronics.

5. ELECTRICAL SPIN DETECTION

The methods to obtain spin-injection in GaAs and Si, employing a spin-dependent

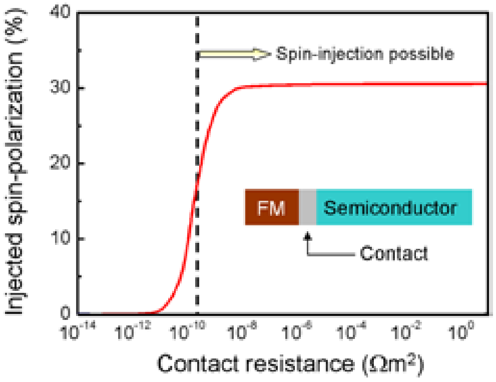

Fig. 2: The expected spin-polarization injected from a ferromagnetic contact into a semiconductor, as a function of the contact resistance.

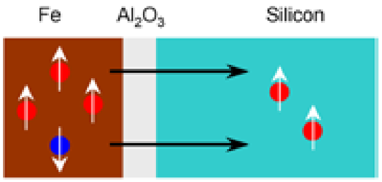

Fig. 3: Schematic illustration of a Fe/Al_2O_3/Si contact, for which electrical spin-injection into silicon was demonstrated [9].

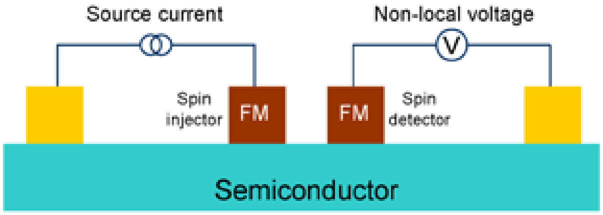

Fig. 4: Non-local device geometry for spin-injection and detection. The left pair of contacts is used to drive current through the device. The pair of contacts on the right is used to detect the spin-dependent non-local voltage induced by electrons that diffuse from the left to the right FM contact. The separation between the two FM contacts is less than a spin-diffusion length.

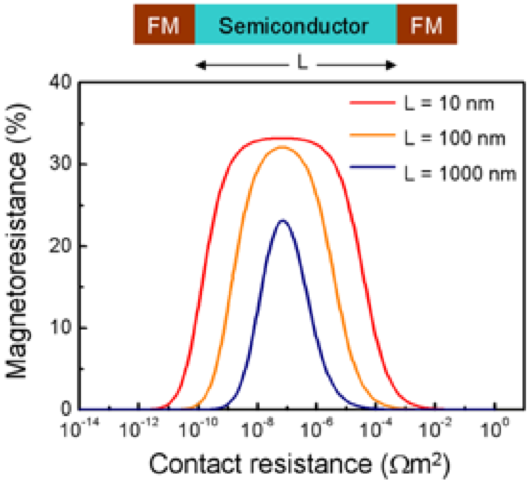

Fig. 5: Calculated magnetoresistance of a two-terminal FM/SC/FM structure, showing an optimum as a function of the resistance of the two FM/SC contacts.

interface resistance in the form of a tunnel barrier, are sufficient when optical spin-detection is used. It also works fine when the spin-accumulation in the semiconductor is detected electrically in the so-called non-local geometry [Fig. 4]. Despite many attempts, this was demonstrated only very recently in a GaAs-based structure [10]. The experiment involved the injection of spins into GaAs at one FM contact, the diffusion of the spin-polarization through several microns of GaAs, and the subsequent detection of the spin-polarization at a second FM contact [10]. As shown in Fig. 4, in the non-local geometry one uses a separate pair of contacts for the current (and spin) injection and the voltage (and spin) detection, while there is no current between the pair of voltage probes. This was the first realization of a device with fully electrical spin-injection/detection, presenting another major advance in the development of a spin-transistor. A similar type of non-local experiment has recently been reported for a Si-based structure [11].

6. WHAT ABOUT MAGNETORESISTANCE?

The non-local geometry has been extremely valuable for electrical detection of spins in semiconductors, and also in metals [12] and organic materials such as graphene [13]. Yet, major disadvantages are the need for 4 contacts, and the small signals of the order of only 10μV, limiting their practical use in electronic circuits. Ideally, a spin-MOSFET has, besides the gate, only two contacts (source and drain), and exhibits a large difference in device resistance between parallel and anti-parallel magnetization of the two electrodes. In order to achieve this, Fert and Jaffrès made a crucial realization [14, 15]. Calculating the magnetoresistance (MR) of a two-terminal FM/SC/FM device (FM=ferromagnet, SC=semiconductor), they pointed out that the MR exhibits an optimum value as a function of the resistance of the FM/SC contacts (see Fig. 5). While the absence of MR for small contact resistance is due to the conductivity mismatch, preventing spin-injection from the source contact, the decay of MR for large contact resistance has a different origin. In essence, it is due to spin-relaxation of the electrons during the time spent in the semiconductor channel, a time that becomes very long for large contact resistance. The effect is specific for the case of MR in two-terminal devices, and does not appear when the injected spin-polarization is detected in non-local geometry or optically, in which case too high contact resistance is not a problem [see for instance Fig. 2]. It also means that an optimized contact that shows very large spin-injection when detected optically, may not function in a two-terminal spin-MOSFET. If anything, it shows that precise engineering of the properties of the magnetic contacts to the semiconductor is essential.

7. ENGINEERING MAGNETIC CONTACTS TO SILICON

The spin-dependent interface resistance of a magnetic contact to a semiconductor can be a Schottky barrier [16], which constitutes a tunnel barrier when the associated depletion region is sufficiently narrow. While this has been shown to yield efficient spin-injection [7], the upper limit on the contact resistance discussed in the previous section leads to the requirement of a semiconductor with an ultrathin (few nm) surface layer with a very high doping concentration. This is difficult to create with current CMOS technology and even with MBE techniques for III-V semiconductors. Instead, the depletion region of a Schottky contact is generally too wide to support tunneling, giving rise to a contact problem [17]. The problem is generic and exists for magnetic contacts on many other inorganic semiconductors as well as organic and carbon-based semiconductors (nanotubes [18] and graphene [13]) used in organic spintronics. We illustrate this problem for Si, and describe a solution.

Due to the wide depletion region, transport across the barrier is thermally activated, and the contact acts as a diode exhibiting current rectification [Fig. 6(a), bottom curve in brown]. It was shown that

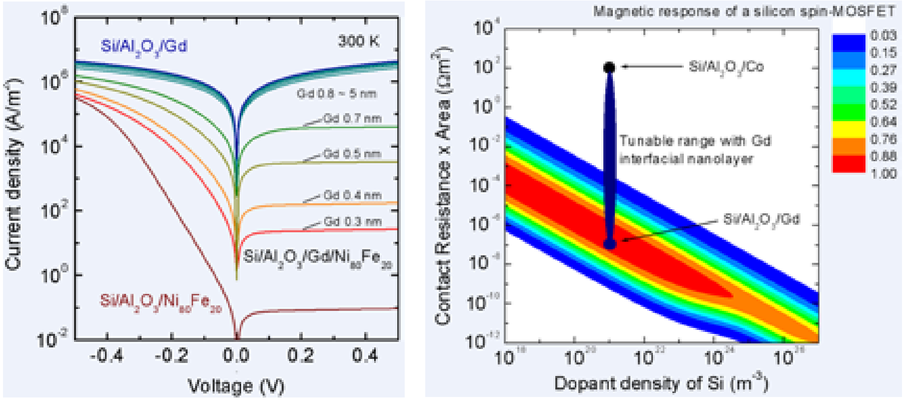

Fig. 6: (a) Current density (absolute value) versus voltage for $Si/Al_2O_3/FM$ contacts with $Ni_{80}Fe_{20}$ (brown, bottom curve), Gd (blue, top) and Gd nanolayers of different thickness (as indicated). (b) Calculated magnetic response (color scale) of a silicon spin-MOSFET versus contact resistance and doping density of the Si channel. Also indicated are experimental data for $Si/Al_2O_3/Co$ as well as $Si/Al_2O_3/Gd$ contacts, and the range that is accessible using interfacial nanolayers of Gd.

the contact resistance is limited by transport across the depletion region even when an artificial tunnel barrier is introduced [17]. As a result, the contact resistance is many orders of magnitude higher than the optimum value required for the observation of a two-terminal MR, as illustrated in Fig. 6(b) for $Co/Al_2O_3/Si$ contacts on n-type Si with doping density of ~10^{21} m^{-3}. Hence, such contacts will prevent the successful operation of a spin-MOSFET. It has also been pointed out that the depletion region complicates non-local detection of a spin-accumulation [19].

Fortunately, a solution for the contact problem was developed recently [17], based on the use of ferromagnetic electrode materials with a low work function. As shown in Fig. 6(a), the incorporation of an ultrathin nanolayer of a low work function material, such as Gd, at the FM/Al_2O_3 interface can be used to tune the Schottky barrier height. In fact, a nanolayer thinner than 1nm is sufficient to eliminate the Schottky barrier and depletion region completely. Hence, the only energy barrier that remains is that of the artificial Al_2O_3, providing a spin-dependent tunnel barrier with a resistance that can be brought in line with the optimum value required for MR observation. Complementary, it was shown that the Gd nanolayer is not detrimental to the tunneling spin-polarization of such contacts [17]. Hence, this approach, which can be applied also to other semiconductor materials, solves a major hurdle on the way to a spin-MOSFET that exhibits a large two-terminal magnetoresistance.

8. CHALLENGES

Despite the significant advances described above, several challenges still remain. The combination of ferromagnetic materials with silicon raises many materials issues related to integration and compatibility. From the fundamental point of view, the challenge lies in understanding spin-transport in semiconductor structures, and in finding new ways to control and manipulate spins in semiconductors. In particular, low-dimensional semiconductor structures such as the two-dimensional electron gas exhibit a rich variety of physical phenomena, which when combined with spin-transport offers many new avenues still to be explored. And from a technological point of view, the main goal is to design silicon spintronic devices that transform spin-information into large electrical signals, operate at room temperature, and have a simple, preferably two-terminal geometry. But perhaps the biggest challenge is to create spin-devices with improved performance or entirely new electronic functionality, such that a major impact on information technology can be made. The remarkable scientific progress made during the last two years gives confidence that this may be within reach.

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