

would always be partially obscure: to see what happens (or has happened) there, we would need to make impossibly precise measurements on our side.

Clearly these investigations are still speculative. The hope is that models like this could be developed to yield quantitative predictions that could be compared with cosmological observations — such as imprints in the

spectrum of the cosmic background radiation, and gravitational radiation, whose remnants we hope to see using the planned space gravitational antenna LISA. This connection to the rapidly growing field of observational cosmology could provide the long-sought window of empirical verification for quantum gravity. The fact that questions about the physics of the Big Bang, and about

the observability of the other side of the bounce, can be cleanly formulated and tentatively answered in loop cosmology represents definite progress. But it must be remembered that no quantum theory of gravity has received any direct empirical support so far. Until one does, the application of any such theory to the Big Bang is certainly to be considered conjectural.

SPINTRONICS

Silicon takes a spin

An efficient way to transport electron spins from a ferromagnet into silicon essentially makes silicon magnetic, and provides an exciting step towards integration of magnetism and mainstream semiconductor electronics.

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Semiconductor electronics — the cornerstone of information technology for many decades — is based on the manipulation and storage of electrical charge. But as it becomes increasingly difficult to improve the performance of successive generations of conventional integrated circuits, the need to find alternatives becomes ever greater. Spintronics is one such alternative, which seeks to use the magnetic moment, or spin, that electrons possess, to achieve similar purposes for which their charge is used in electronics. Significant progress has been made in the transport and manipulation of spin in semiconductors such as GaAs (refs 1–3). But for spintronics to hit the big time commercially, these advances will need to be reproduced in silicon, the material on which most electronics is based. On page 542 of this issue⁴, Jonker and colleagues make the first important steps towards doing just this, by demonstrating an efficient and versatile way to inject electron spins from a ferromagnetic contact into silicon.

At first glance, it may seem that it should be straightforward to inject spin-polarized currents into a semiconductor. A ferromagnetic metal will contain an excess of carriers whose spin points in a preferred direction, depending on the direction of the metal's magnetization. This spin imbalance

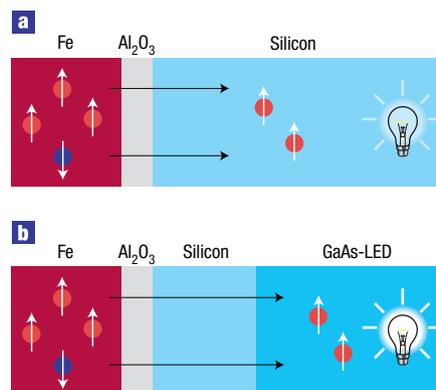


Figure 1 Demonstration of the injection of spin into silicon. **a**, By measuring the polarization of the light emitted by the recombination of carriers injected from a magnetized Fe contact across an Al₂O₃ tunnel barrier, Jonker *et al.*⁴ prove that polarized spin injection into silicon does indeed take place. **b**, By allowing spins injected in the silicon to pass through and into a GaAs light emitting diode (LED) structure, they were able to obtain a lower bound for the spin polarization of 10%. In future, this approach could be used to determine how far spins can travel in silicon, and to explore how different materials and structures affect the spin-polarization efficiency of the contacts. This will provide better understanding of the possibilities of silicon spintronic devices.

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.

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 behaviour 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 is known as the conductivity-mismatch problem⁵, and can be overcome by introducing an additional, spin-dependent, barrier at the boundary between a ferromagnetic contact and a semiconductor, for example a thin oxide. This provides a spin-dependent tunnel resistance that can be made comparable to, or larger than, the resistance of the semiconductor. The success of this approach for injecting spins into GaAs is demonstrated by the circular polarization of the light that is emitted when these spin-polarized electrons subsequently recombine with holes^{1,2}.

It was generally expected that using the same optical approach to that used to verify the injection of spins into GaAs would be difficult to apply in the case of silicon. Owing to its indirect bandgap, silicon is a much poorer light emitter than GaAs; moreover, although there is a direct relation between the circular polarization of the emitted light and the electron spin polarization for GaAs, the same cannot be said for silicon, whose electronic structure is qualitatively different⁶. This precludes a direct quantitative analysis of the spin

polarization of the electrons in silicon from its light-emitting behaviour. Yet, Jonker *et al.*⁴ show that both these problems can be overcome.

First, they show that despite silicon's indirect bandgap, the current passing from an Fe contact via an Al₂O₃ tunnel barrier into a silicon p–i–n diode structure is sufficient to produce enough polarized light emission (at temperatures below 80 K) to demonstrate the successful injection of spin-polarized electrons (Fig. 1a). This in itself is an important achievement. Yet it demonstrates that spin has been injected, but not precisely how much. To show this, the researchers grow their Fe/Al₂O₃/Si structure on top of a GaAs light-emitting diode (LED) structure. Analysis of the emission generated by the current passing from Fe through Si into the GaAs enables the authors to determine the lower bound of the polarization ratio of the spins injected into the Si, which they find to be 10% (Fig. 1b). The size of this ratio not only demonstrates the effectiveness of the Fe/Al₂O₃/Si contacts, but more surprisingly the robustness of the spins as they pass across the inevitably rough and potentially detrimental interface between the Si and the GaAs.

Now that we can confidently inject spin-polarized currents into silicon, the

next step will be to make functioning silicon-based spintronic devices. From a technological point of view, the Fe tunnel contacts are simple and efficient. They do not suffer from the low current levels associated with a recently reported approach⁷ in which hot electrons are driven across complicated multi-terminal device structures, only a small fraction of which are injected into the semiconductor. And although it is expected that electron spins in silicon should survive long enough to perform useful spin functions, data on how far they can travel is scarce. Building on the present work of Jonker *et al.*⁴ — by simply fabricating several Si-on-GaAs LED devices with silicon layers of varying thickness, for example — should fill in the gaps in this knowledge.

Perhaps the most intriguing device possibility enabled by the present work is the silicon spin-FET — a field-effect transistor with ferromagnetic source and drain contacts, the relative magnetization of which determines the transistor's channel conductance. It should be noted that the requirements for the source and drain contact of a spin-FET differ from that of optical detection — their resistance should not be too high⁸. For the source of such a device, this is vital to being able to supply

spins into the channel at sufficiently high rate. And for the drain, if the probability of spin-polarized electrons transiting across the interface of such a contact is too low, the electrons could be forced to dwell too long within the channel and lose their polarization. The resistance of the Fe/Al₂O₃ contacts thus needs careful consideration. Thankfully, an approach to forming spin-tunnel contacts to silicon with low and tunable resistance has also been reported⁹. Together with the spin-injection contacts of Jonker *et al.*⁴ everything is now in place to design novel silicon electronic devices based on spin, and explore the possibilities (and limitations) of such devices and systems. An exciting new era of silicon spintronics could thus soon be upon us.

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SINGLE-MOLECULE DETECTION

Identification without labels



The properties of molecules are traditionally inferred from bulk measurements. But, some 20 years ago, fluorescence spectroscopy made it possible to look at the behaviour of single

molecules, and thus investigate properties that are averaged out in bulk studies. In these experiments, however, a fluorescent label must be attached to the target molecule, which limits the scope of the approach. Andrea Armani and colleagues report that single molecules can now be detected without fancy labels (*Science* doi: 10.1126/science.1145002; 2007).

The alternative to amplifying the signal of a single molecule by attaching a label — as required in fluorescence spectroscopy — is to sample the unmodified molecule many times over. This can be done using a high-quality optical microcavity — a device in which light is confined and circles at discrete frequencies. Armani *et al.* use silica toroids of about 80 μm diameter; light circulating in such a structure passes a molecule sitting on its surface more than 100,000 times, enough for even a single molecule to leave a signature.

The microtoroid sensor exploits the time that the light spends in the cavity in two ways. On the one hand, the long confinement time results in narrow

resonance lines, and therefore good resolving power for small shifts in the resonant wavelength (which occur because the presence of the molecule increases the path length of the light). On the other hand, the molecule is heated by the high-intensity light inside the cavity; the molecule, in turn, heats up the cavity, leading to a more pronounced shift.

As well as achieving single-molecule sensitivity, Armani and co-workers can make their technique selective to specific molecules by sensitizing the resonator surface — for example, by coating it with antibodies. Such specificity, together with the possibility of operating the device in an aqueous environment, opens the door to biological applications, in which the sensor could be used to sensitively determine concentrations of marker molecules. Using the biomolecule interleukin-2 as an example, the authors show that concentrations from micromolar to attomolar — an impressive twelve orders of magnitude — could be detected.

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