a recapture model that considers that a whale persists on the market with a particular half-life. The model takes observations of identical DNA genotypes in the same and different surveys, and estimates the flow of whales into the market and how long each one persists.

Individual identification was based on genotypes at multiple genetic loci. The regulations laid down by the Convention on International Trade in Endangered Species require permits to transfer whale-meat samples or DNA out of the country in which the whale was landed. So initial work had to take place in hotel rooms using a portable lab. An innovation in this study was the use of multi-gene microsatellite amplification methods, which allowed the archiving of a complete, synthetic set of gene markers from each individual whale for study elsewhere.

Baker and colleagues collected 289 samples in 12 surveys in South Korean markets between 1999 and 2003. Sometimes they found the same whale individual twice in one survey, but this occurred only 13% of the time. One individual was discovered four times in one survey. These low rediscovery rates during the same survey suggest that there are many different individual whales in the market at any one time. In nine cases the authors found the same individual in two surveys — always in subsequent trips. And once they found an individual in three consecutive surveys.

Fitting these data into the capture–recapture model, Baker *et al.*[1] conclude that minke whales in the Korean market are sold quickly. The half-life of a whale — the time during which half of the whale's meat is estimated to have been sold — is about 1.8 months. The only previous hint about the market half-life of whale products came from Japan and was far longer; products from a genetically unique fin/blue whale hybrid were purchased in Japan in 1993 and 1995, but came from an animal killed off Iceland on 29 June 1989, during the last scientific hunt of fin whales[6].

Poorly known features of Korean whale markets could affect the accuracy of the authors' estimates[1]: in particular, variance in the number of products from different whales, differences in half-life owing to different storage methods, or non-random distribution of products among markets. Baker *et al.* suggest that these factors would probably make their figures lower bounds. But an overestimate of whale flow might occur if products from a particular whale individual were sold to only one or a few vendors. This possibility can be investigated only with more complete sampling of single markets. A future refinement is that truly accurate estimates will probably benefit from more frequent sampling.

Although the current model is simple, Baker *et al.* argue that the value they calculate probably represents a minimum for the number of J-stock whales in the East Sea that are accidentally killed and sold in South Korea. Adding the figure of 827 to the 390 J-stock minkes that Japan reported killed accidentally in the Sea of Japan by their fishermen in 1999–2003 gives a total (assuming no under-reporting in Japan) of more than 1,200 whales taken from this protected stock during this period.

Models of minke-whale population dynamics suggest that the J stock cannot sustain this rate of loss. An earlier model, based on the current best models used by the IWC, concluded that killing 50–150 animals a year would drive the population to near extinction by mid-century[2]. Continued take of more than 200 animals a year will accelerate this collapse. Populations of minke whales in the offshore waters of the western North Pacific are larger than the J stock, and these whales are hunted under a permit that the Japanese government issues to itself every year to conduct lethal scientific research. The larger oceanic population might be able to sustain a catch of 200 animals a year, but the structure of whale populations is sometimes so local that small and isolated populations such as the J stock cannot support a loss rate that may seem minor on a whole-ocean scale.

Debate about a return to commercial whaling often runs up against the lack of clear information about the number of whales actually hunted, and the size of the local population from which those animals are drawn. The work by Baker *et al.*[1] takes forensic identification of whale products[7] to the individual level and provides a market-eye view of commerce in whale meat that would be unavailable from official reports. For J-stock minke whales, it shows that reform of rules for the legal sale of accidentally killed animals is required if the East Sea is to be the home of whales in the future. ■

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1. Baker, C. S. *et al. Mol. Ecol.* doi: 10.1111/j.1365-294X.2007.03317.x (2007).
2. Baker, C. S. *et al. Proc. R. Soc. Lond. B* **267,** 1191–1199 (2000).
3. Clapham, P. & Van Waerebeek, K. *Mol. Ecol.* (in the press).
4. Williams, B., Nichols, J. & Conroy, M. *Analysis and Management of Animal Populations* (Academic, New York, 2002).
5 Mills, L. S. *et al. Ecol. Appl.* **10,** 283–294 (2000).
6. Cipriano, F. & Palumbi, S. R. *Nature* **397,** 307–308 (1999).
7. Baker, C. S., Cipriano, F. & Palumbi, S. R. *Mol. Ecol.* **5,** 671–685 (1996).

SPINTRONICS

Silicon twists

Igor Žutić and Jaroslav Fabian

For decades, silicon has been the dominant material for conventional, charge-based electronics. A new twist makes silicon ripe to enter the domain of spintronics, where the new currency is electron spin.

Modern computers present serious challenges for conventional, silicon-based electronics. Ever-increasing demands on processor speed, memory storage and power consumption — the era of the laptop that can keep us warm in winter is fast upon us — are forcing researchers to explore unfamiliar territory in the quest for increased performance. In these endeavours, Appelbaum and colleagues (page 295 of this issue)[1] report a possibly decisive development: the first demonstration of the transport and coherent manipulation of electron spin in silicon.

In spin electronics, or spintronics[2], information is represented by spin and by its proxy, the direction of magnetization. Ferromagnets such as iron or cobalt have a finite magnetization, because most of their electrons' spins are oriented either with or against the magnetization axis, depending on the material. This magnetization direction persists without an outlet power, and is therefore stable[2,3]. For that reason, spintronic applications based on metallic ferromagnetic nanostructures[3] — such as magnetic hard drives and, more recently, magnetic random access memories (MRAMs) — have already proved commercial hits. But for other applications, such as reprogrammable logic, spintronics has not yet broken through into the industrial mainstream.

For that to happen, spintronics must conquer silicon, the abundant, inexpensive and entrenched material of choice for conventional semiconductor electronics. The spin of silicon's electrons is believed to survive sufficiently long to allow the persistence of spin-encoded information, and silicon-based devices might offer significant improvements on proposed spin transistors and spin-based quantum-computation schemes[2,4–7]. Yet a demonstration of even basic spintronic ingredients, such as spin injection, transport, manipulation and detection, has been elusive in silicon[2]. So why has silicon resisted for so long, when other semiconductors, such as the gallium arsenide (GaAs) used in mobile-phone electronics, have proved more pliant?

The two established ways of introducing spin into semiconductor materials are optical and electrical spin injection[2]. In optical injection, a semiconductor absorbs circularly polarized light, generating, through transfer of angular

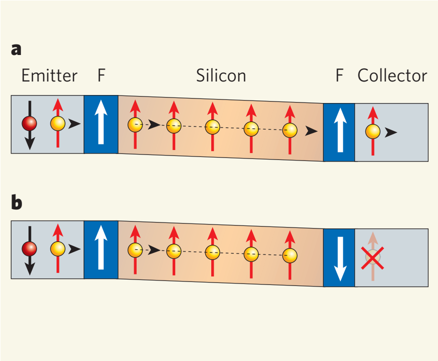

Figure 1 | Spin-valve effect. A ferromagnet (F), shown here as the perfect spin filter, causes electrons of the opposing spin orientation to bounce around and deprives them of energy, while letting electrons of the same orientation smoothly through, rather as a player in a football or hockey match deals with a member of the opposition or of his own team. As Appelbaum and colleagues demonstrate[1], putting such a filter on either side of a silicon substrate allows not only spin injection, but also spin detection. If both filters have the same orientation (**a**), electrons of that orientation will pass through the silicon from emitter to collector. If, however, the two orientations are antiparallel (**b**), electrons of neither spin will pass both filters. The relative difference in the collector current in these two cases is the spin-valve signal[3,9].

momentum, electron spin. The reverse process, the emission of circularly polarized light, is often used as smoking-gun proof of spin-injection. Unfortunately, the optical method, which works well with GaAs, is ineffective in silicon owing to subtleties of the element's electronic structure[4,8].

In electrical injection, a voltage drop typically drives spin-polarized electrons from a ferromagnetic electrode into the semiconductor. But difficulties associated with interfaces between ferromagnets and silicon, as well as a lack of a reliable method for spin detection, have hindered conclusive evidence for spin injection and transport in silicon[2,4].

Until, that is, Appelbaum *et al.* came along with their 'spin valve'[1,3,9]. In this device (Fig. 1), initially unpolarized electrons (with an equal mixture of spins pointing 'up' and spins pointing 'down') pass through a ferromagnet. This acts as a spin filter: it lets spins of only one orientation through to the silicon substrate. A second ferromagnet at the other end of the substrate will, according to whether its magnetization is the same as, or opposite to, that of the first, filter out either none or all of the remaining electrons. With this set-up, Appelbaum and colleagues observe a change in current with magnetization that provides direct evidence for the injection and transport of spin-polarized electrons in silicon.

Appelbaum and colleagues also provide[1] more subtle, but also more convincing, proof by exploiting the rotation, or precession, of spin. This precession is brought about by a magnetic field applied to the silicon substrate at right angles to the direction of the injected spins[2,10] (Fig. 2). If the magnetizations of the two spin filters are parallel, the current passing through the device will be much smaller if the electron spins precess by 180° in their passage through the silicon than if the rotation is by, say, 0° or 360°. The angle of precession is determined by the value of the applied electric and magnetic fields, but the current will exhibit peaks (and valleys) whenever the average spin arriving at the collector is parallel (or antiparallel) to the spin allowed by the second filter.

At very large magnetic fields, the spin-precession signal should disappear altogether, owing to the Hanle effect[2,10] (Fig. 2d): random scattering of the electrons on lattice imperfections causes electron transit times to differ. At high fields, this translates into spin-precession angles that differ in proportion to the transit times. If the spread in angles reaches 360°, electrons arriving at the second filter have spins pointing in all directions, and zero average spin. The collector current will cease to exhibit peaks and valleys, having instead a rather featureless dependence on the magnetic field. Remarkably, Appelbaum and colleagues observe[1] all these predicted behaviours.

Now that this proof of concept has been established, what remains to be done? First, we should find ways to raise the operating temperature from Appelbaum and colleagues' 85 kelvin to room temperature, and to increase the spin-valve signal, presently just 2%. A likely culprit for this small signal is that, because the ferromagnetic metal is grown directly on the silicon, a non-magnetic interface layer forms that is detrimental to spin transport. A similar scheme in GaAs gives a signal orders of magnitude higher[9]. There, spin injection has been achieved by using high-quality interfaces with a ferromagnetic semiconductor[2,4], or by inserting oxide tunnel barriers[11,12] between a ferromagnetic metal and the semiconductor. In silicon, low-resistance tunnel barriers next to the ferromagnets[13,14] might also help to increase the signal.

Second, whereas Appelbaum *et al.* use pure silicon, commercial electronics, as well as proposals for spintronic devices[2], relies on making silicon impure by the process known as doping. This doping creates extra charge carriers (electrons or holes), and the effect this will have on spin injection and spin precession must be investigated.

Finally, spin injection in silicon does not automatically mean that useful devices can be fabricated straight off — further ideas to explore the possibilities of silicon spin within realistic device settings are needed. Although we might not yet be quite ready for commercial silicon-based spintronics, nothing to stop the show is in sight. ■

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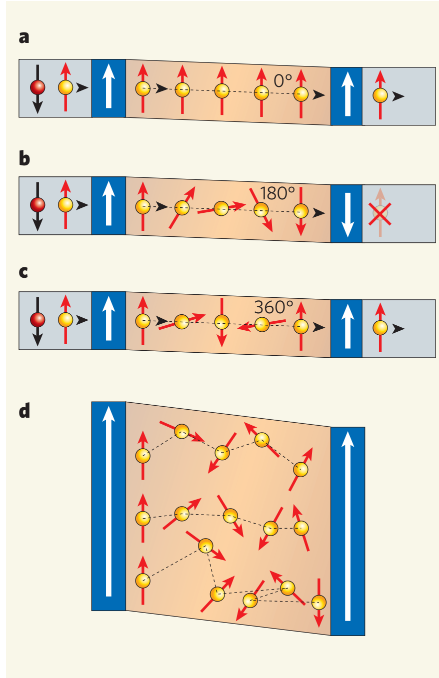

Figure 2 | Spin precession. In a magnetic field (applied perpendicular to the page here), electron spins precess with a frequency proportional to the field strength, giving rise to an oscillatory current. **a**, No precession, as in Figure 1: given two filters of the same orientation, a spin-polarized current will pass. **b**, 180° precession: no current can pass. **c**, 360° precession: a spin-polarized current passes again. **d**, If the applied field is very strong, the spins precess very fast, and the random or diffusive component of electrons' motion as they scatter off lattice imperfections comes to dominate. The angles of precession vary wildly, and spin precession is no longer detected.

1. Appelbaum, I., Huang, B. & Monsma, D. J. *Nature* **447,** 295–298 (2007).
2. Žutić, I., Fabian, J. & Das Sarma, S. *Rev. Mod. Phys.* **76,** 323–410 (2004).
3. Maekawa, S. & Shinjo, T. (eds) *Spin Dependent Transport in Magnetic Nanostructures* (Taylor & Francis, New York, 2002).
4. Žutić, I., Fabian, J. & Erwin S. C. *Phys. Rev. Lett.* **97,** 026602 (2006).
5. Sugahara, S. *IEE Proc. Circuit Devices Syst.* **152,** 355–365 (2005).
6. Tyryshkin, A. M., Lyon, S. A., Jantsch, W. & Schäffler, F. *Phys. Rev. Lett.* **94,** 126802 (2005).
7. Das Sarma, S., de Sousa, R., Hu, X. & Koiller, B. *Solid State Commun.* **133,** 737–746 (2005).
8. Lampel, G. *Phys. Rev. Lett.* **20,** 491–493 (1968).
9. Parkin, S. S. P. *et al. Proc. IEEE* **91,** 661–680 (2003).
10. Johnson, M. & Silsbee, R. H. *Phys. Rev. Lett.* **55,** 1790–1793 (1985).
11. Hanbicki, A. T. *et al. Appl. Phys. Lett.* **80,** 1240–1242 (2002).
12. Jiang, X. *et al. Phys. Rev. Lett.* **94,** 056601 (2005).
13. Min, B.-C., Motohashi, K., Lodder, C. & Jansen, R. *Nature Mater.* **5,** 817–822 (2006).
14. Žutić, I. *Nature Mater.* **5,** 771–772 (2006).