be zero at zero temperature and remain a small number, much less than one, at room temperature.

Qazilbash *et al.*[3] show that the value of $K_{\mathrm{exp}}/K_{\mathrm{band}}$ at room temperature is indeed close to one for simple metals and is considerably smaller than one for a Mott insulator. The value for the parent iron arsenide, $\mathrm{BaFe_2As_2}$, is about 0.3 — the same order of magnitude as the optimally doped copper oxides or the incipient Mott insulator $\mathrm{V_2O_3}$. For the parent iron phosphide, LaFePO, the value is about 0.45, which is somewhat larger than for $\mathrm{BaFe_2As_2}$ but still not close to one.

One natural interpretation of these results is that the parent iron arsenides are indeed located near the boundary between itinerancy and localization. Further support for this interpretation can be inferred from the optical conductivity measurements of several other groups[4–6], which have shown that changes in temperature can induce transfer of optical spectral weight from the low-energy part of the spectrum to the part at high energies, greater than 1 eV. Such a spectral-weight transfer is a hallmark of bad metals close to Mott localization, which feature incoherent electronic excitations in the form of 'precursor Hubbard bands' (Fig. 1) at some distance from the Fermi energy.

To fully establish that the incipient Mott localization operates in the iron pnictides, the precursor Hubbard bands need to be probed. One difficulty lies in there being several *d* bands, as the precursor Hubbard bands can be embedded in other high-energy features associated with interband transitions. (This makes the temperature-induced spectral-weight transfer mentioned above especially illuminating.) In addition, it remains to be seen whether the system can be tuned across the Mott transition and into a Mott insulator state. The observations of Qazilbash *et al.*[3] provide a clue to this. The phosphides are shown to be less correlated than the arsenides, presumably because they have larger chemical pressure (as the phosphorous ion is appreciably smaller). Will the replacement of arsenic by antimony or bismuth give rise to Mott insulators?

Despite these cautionary considerations, it is tempting to draw implications of the strong-coupling picture for low-energy physics. The existence of substantial incoherent weight in the excitation spectrum makes it meaningful to consider nearly localized magnetic moments, coupled by superexchange interactions, which have been shown to lead to the observed magnetic structure. This strong-coupling approach seems to provide a good basis for understanding the magnetic dynamics as well. Inelastic neutron scattering experiments[7,8] have recently identified spin-wave-like excitations all the way to the antiferromagnetic zone boundary. The spin waves have a fairly high energy (~200 meV) that, incidentally, bodes well for a magnetic mechanism for superconductivity. They also have a very large spectral weight.

Superconductivity comes further down the energy hierarchy. The observation of sizeable electronic correlations supports strong-coupling approaches to superconducting pairings. More generally, it supports the widely held belief that the mechanism for superconductivity in the iron pnictides lies in electron–electron interactions, and not in the standard electron–phonon coupling. ❐

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SPINTRONICS

Spins take sides

The conventional photovoltaic effect has now been given a spin twist, enabling spin control in a non-magnetic structure. This concept could yield new methods of detecting and tailoring spin-dependent phenomena in semiconductors.

Igor Žutić

The spin of an electron and the associated magnetic moment are crucial to our understanding of magnetism. However, when it comes to non-magnetic materials, the spin is only an elusive quantum mechanical property. Conventional electronics, which relies on the motion of electrons in non-magnetic semiconductors, is completely oblivious to spin — with no net imbalance between spins pointing in different directions (say 'up' and 'down'), spin is not considered relevant for the motion of electrons in semiconductor devices.

On page 675 of this issue[1], Wunderlich *et al.* show that even in a non-magnetic semiconductor spins can be effectively tamed — the electrons can be guided on the basis of the direction of their spin to yield a measurable voltage transverse to the flow of charge current. This work is a clever demonstration of taking advantage of relativistic effects in a semiconductor device. Although the average speed of the electrons is much less than the speed of light, the electrons may still scatter from impurities at relativistic speeds. Spin and orbital motion are usually considered independent and separately controllable by electric and magnetic fields. However, the relativistic scattering produces spin–orbit coupling and the roles of the electric and magnetic fields become intertwined: electric fields can manipulate spins in the same way as magnetic fields of varying direction, which changes with the direction of the electron momentum[2]. If the effective magnetic field and the spin are not aligned, the spin will precess, like a spinning top (with the frequency proportional to the magnetic field). The spin–orbit coupling is also the main culprit for the temporal and spatial decay of the initial spin imbalance[2].

In their work, Wunderlich *et al.*[1] use meticulously designed GaAs p–n junctions similar to those used in solar (photovoltaic) cells. Simple solar cells (Fig. 1a) comprise p and n regions mostly populated by carriers of opposite charge: holes and electrons, respectively. A large net charge between these regions generates a built-in electric field, *E*. Photons incident on the p–n junction create electron–hole pairs that are separated and swept away by *E* and thereby create a voltage, V_L, along the direction of charge current. Using circularly polarized light adds a spin twist to the solar cell[3]. Because of the spin–orbit coupling, the photon angular momentum preferentially aligns electron spins and a spin-polarized current (with spin imbalance) flows[3]. However, this still does not explain the existence of a transverse voltage[1]; this is yet another subtle manifestation of spin–orbit coupling.

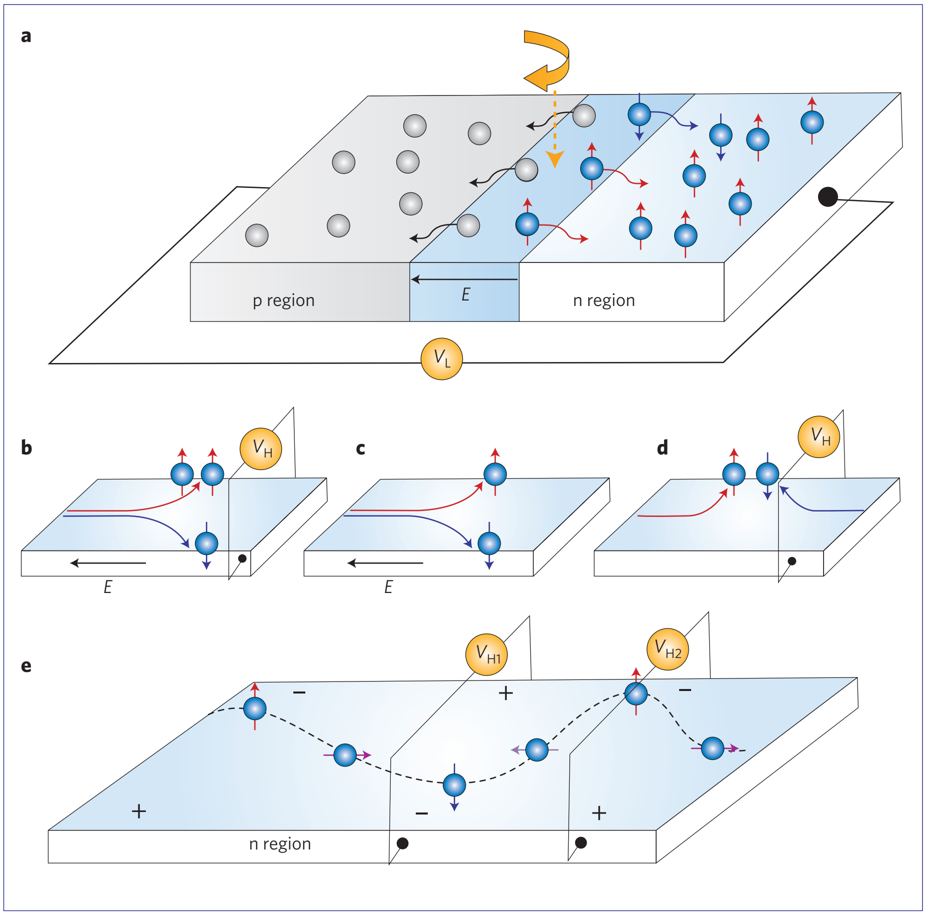

Figure 1 | Photovoltaic and spin-dependent Hall effects. **a**, A spin-polarized solar cell[3]. Circularly polarized light creates electron–hole pairs, and a built-in field, *E*, separates carriers of opposite charge and yields the longitudinal voltage V_L. Owing to very strong spin–orbit coupling, holes (grey circles) lose spin imbalance immediately[2], whereas the spin imbalance of electrons (blue circles) depends on the circular polarization of the incident light. **b**, The AHE combines the net spin polarization of carriers with their spin-dependent deflection. In the transverse direction, both a charge imbalance (manifesting as the Hall voltage, V_H) and a spin imbalance are present. **c**, The spin Hall effect involves no initial spin polarization and leads to a transverse spin imbalance but no V_H, as the number of the deflected carriers with opposite spins is the same. **d**, The inverse spin Hall effect yields no charge but only a pure spin current. This could result from a diffusive process, so no electric field is needed. A spin-dependent deflection leads to a transverse charge imbalance and thus V_H. With an equal number of opposite spins there is no spin imbalance. **e**, The spin-injection Hall effect is closely related to the AHE. A net spin polarization of carriers is created away from the regions of measurement. A spatial evolution of a single spin shows an interplay of spin-dependent deflection and spin precession arising from an effective magnetic field due to spin–orbit coupling. The measured signal, an average over many electron spin trajectories, still preserves the depicted spatially changing transverse spin imbalance and V_H, which can even change sign.

Transverse voltages such as this were first seen in the nineteenth century. In the ordinary Hall effect, charges of different signs are deflected in opposite directions by applied electric and magnetic fields. This deflection happens irrespective of the spin, and the ordinary Hall effect is not accompanied by an imbalance in the spin on either side of the device. However, there are also several spin-dependent Hall effects that directly rely on spin–orbit coupling (Fig. 1b–e). The oldest, the anomalous Hall effect (AHE; Fig. 1b), was discovered in 1880 and remained a theoretical puzzle for nearly a century[4]. An imbalance of carrier spins and the spin–orbit coupling lead to an asymmetry in scattering: carriers of opposite spins are deflected in opposite directions transverse to the charge current. Both a transverse (Hall) voltage, V_H, and a transverse spin imbalance are present. In contrast, the spin Hall effect (Fig. 1c), predicted in 1971[4] but only recently measured[5,6], starts from an initial spin balance and yields no V_H, only a transverse spin imbalance. There is yet another phenomenon, the inverse spin Hall effect (Fig. 1d)[4,7]. For electrons of opposite spin moving with equal but opposite velocities there is no net charge current but we talk of pure spin current[2]. From the scattering asymmetry, we expect a V_H but no transverse spin imbalance.

How should we refer to the Hall voltage measured by Wunderlich *et al.*[1] (Fig. 1e)? There is clearly a connection to the AHE: both V_H and the transverse spin imbalance are present. However, unlike most AHE measurements, there is no magnetic material nor an applied magnetic field. To make things more complicated, even the experts cannot always agree on nomenclature. For example, one 25-year-old experiment[8] is referred to as both the inverse spin Hall effect[4] and the AHE[9] in different places. To avoid taking sides and to emphasize the spatial separation between the creation (injection) of a spin imbalance and V_H measurements, Wunderlich *et al.* term their observation the "spin-injection Hall effect".

With one stroke they have accomplished several important goals. A surprisingly large V_H, comparable to the values known for the AHE in ferromagnets, and measured in a completely non-magnetic structure, offers a means of looking more closely into still-puzzling spin-dependent Hall effects. A factor in generating a large V_H was the clever use of two-dimensional carrier confinement in a p–n junction and the choice of the growth direction of the planar structure to tailor the spin–orbit coupling and spin transport[10,11]. The degree of circularly polarized light is directly proportional to the transverse signal. In a p–n junction, V_H, rather than a longitudinal signal, which requires a magnetic region[12,13], thus provides an effective conversion of light polarization into an electrical signal. A simple polarization reversal reverses both the spin up/spin down imbalance and V_H.

What could be next? This particular p–n junction is limited by the fact that it loses its built-in *E* field before reaching room temperature. The next batch of p–n junctions will probably resolve this issue. Theoretically, we could ask what materials choice and what boundary conditions[14] at the side contacts would increase V_H and transverse spin accumulation. A transverse output of a p–n junction could be input into other devices, offering intriguing paths to spin optoelectronics and spin-controlled signal amplification[2]. Adding a pair of electrodes to the top and bottom of a planar p–n junction would alter the electric field and, in turn, through spin–orbit coupling, control the spin precession[2]. Perhaps the word 'photo' will be removed from the title: a transverse signal in a p–n junction could be a versatile tool for spin detection not only in GaAs and other optical materials. Spin can be electrically injected from a magnet[2] and detected even in Si–Ge junctions, which are not amenable to light and standard optical methods[15]. Although such junctions would have a smaller spin–orbit coupling, a smaller V_H may decay slowly enough to be detected at distances one hundred times greater[16] than in the present geometry. Even with less light, the future seems bright. ❐

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