$\tilde{M} = (\delta_N\rho_N/\delta_F\rho_F)(1-\alpha_F^2)$ (ref. 8), where α_F is the polarization of bulk permalloy. Although no current flows in F2 in an open-circuit voltmeter measurement, a 'mismatch' is also invoked at the Cu–Py2 interface, and the model proposed by Jedema *et al.* for ΔR (for dimensions $<\delta_N$) differs from that given in equation (1) by the factors $\tilde{M}^{-1}(\tilde{M}+1)^{-1}\approx 10^{-3}$.

However, this assertion relies on the erroneous assumption that the intrinsic interface resistance, R_i, is perfect, $R_i = 0$. In theory[3,8], an F–N interface is characterized[9] by $r_N = (\delta_N\rho_N)$ and $r_F = (\delta_F\rho_F)$, relative to R_i. A 'resistance mismatch' is important only if $R_i << r_N$, r_F. This issue is analogous with spin injection at an F-semiconductor interface[10]. Efficient spin injection is achieved when a barrier, with resistance as small as r_S or r_F, mediates transport. For F–N interfaces, a contact resistance, R_C, exists at metal–metal interfaces that are formed by lift-off processes, regardless of ion-mill cleansing. R_C dominates interfacial transport, $R_C = R_i \geqslant r_f \approx 10^{-11}$ Ω-cm², and the interface parameter η, rather than α, characterizes spin injection.

I therefore question the validity of the model proposed by Jedema *et al.*. If the data are related to spin accumulation, the discrepancy between theory and experiment is derived from a misapplication of one-dimensional Valet–Fert theory to a two-dimensional system, errors that are independent of F–N interface contact resistance. First, the resistance per square of copper is much less than that of the permalloy, $R_{(sq,Cu)} = 0.3\ \Omega << R_{(sq,Py)} = 2.0\ \Omega$, and the copper wire that spans Py1 shunts the imposed bias current. The current density injected across the F1–N interface is one-seventh of the modelled value.

Second, the film Py2 supposedly measures a signal that is related to "...densities of the spin-up and spin-down electrons in the centre of the cross..."[1], which I question. Spin detection is an interfacial effect[3,8] and depends on the spin densities at the N–F2 interface. Detection is averaged over the width of Py2 and ΔR is diminished by roughly half.

Third, spin diffusion in the copper is isotropic. Only half of $\tilde{\mathbf{M}}$ diffuses towards the centre of the cross, and one-third of this population diffuses down each of the remaining arms. For $L < \delta_N$, the spin density near Py2 is diminished by a factor of one-sixth. Together, these errors give factors of 10–100 that vary with L, a fact that undermines the analysis of Jedema *et al.*

The observed variations in $\Delta R/R$ of 0.1–5.0% are extremely small. As the model of Jedema *et al.* is sensitive to ρ_F, and ΔR is proportional to ρ_F^2, it cannot distinguish between anisotropic magneto resistance, $\delta\rho_F/\rho_F = 2.5\%$, and spin injection. Anisotropic magneto resistance can be measured by determining the angular symmetry of R as an external field is rotated in the sample plane. For the example shown in Fig. 1b, the coercivities of F1 and F2 of the spin-transistor sample[5,6] are $\mathbf{H}_{C,1} = 10$ Oe and $\mathbf{H}_{C,2} = 21$ Oe. After applying a field $\mathbf{H} = 100$ Oe at $\Theta = 0°$, $\mathbf{H}$ is reduced to $\mathbf{H}_{C,1} < \mathbf{H} = 15$ Oe $< \mathbf{H}_{C,2}$, such that $\mathbf{M}_2$ remains oriented along $\Theta = 0°$, but $\mathbf{M}_1$ can follow $\mathbf{H}$ through a 360° rotation. Referring to the lower trace (left axis), $R = V_S/I$ is minimum after $\Theta \approx 180°$ when $\mathbf{M}_1$ and $\mathbf{M}_2$ are antiparallel, and maximum near $\Theta \approx 0°$ when $\mathbf{M}_1$ and $\mathbf{M}_2$ are parallel. This $\cos\Theta$ symmetry is characteristic of spin accumulation. Next, $\mathbf{H} = 100$ Oe is applied and then reduced to $\mathbf{H}_{C,1} < \mathbf{H}_{C,2} < \mathbf{H} = 40$ Oe, so $\mathbf{M}_1$ and $\mathbf{M}_2$ are always roughly parallel and V_S (upper trace, right axis) is roughly constant. By contrast, anisotropic magneto resistance has two maxima in a 360° rotation (Fig. 1c).

I question the general validity of 'resistance mismatch' at F–N interfaces; the one-dimensional model is probably incorrect, and the results of Jedema *et al.*[1] may require a new interpretation.

Mark Johnson
Naval Research Laboratory,
Washington DC 20375, USA
e-mail: mjbooj@anvil.nrl.navy.mil

1. Jedema, F. J., Filip, A. T. & van Wees, B. J. *Nature* **410,** 345–348 (2001).
2. Johnson, M. & Silsbee, R. H. *Phys. Rev. Lett.* **55,** 1790–1793 (1985).
3. Johnson, M. & Silsbee, R. H. *Phys. Rev. B* **37,** 5312–5325 (1988).
4. Silsbee, R. H. *Bull. Mag. Res.* **2,** 284–285 (1980).
5. Johnson, M. *J. Appl. Phys.* **75,** 6714–6719 (1994).
6. Johnson, M. *Phys. Rev. Lett.* **70,** 2142–2145 (1993).
7. Soulen, R. J. *et al. Science* **282,** 85–88 (1998).
8. Johnson, M. & Silsbee, R. H. *Phys. Rev. B* **35,** 4959–4972 (1987).
9. Johnson, M. & Silsbee, R. H. *Phys. Rev. Lett.* **60,** 377 (1988).
10. Rashba, E. I. *Phys. Rev. B* **62,** 16267–16270 (2000).

Jedema et al. *reply* — Johnson suggests that our results[1] are not due to spin transport but rather are caused by spurious effects, in particular the anisotropic magneto resistance of the ferromagnetic contacts. However, our experiment was designed explicitly to eliminate any magneto-resistance effects that might arise from the ferromagnetic contacts.

We used the well known principle of four-terminal measurement. No current flows through the ferromagnetic detector contact, so its (magneto) resistance does not affect the measurement. Similarly, the (magneto) resistance of the ferromagnetic injector contact is not relevant, because any voltage that develops across it will not affect the current that is sent through it. The only region that could then possibly give rise to a (magneto) resistance is the central part of the copper cross, but explicit measurements confirm that this region does not produce any magneto resistance. So, having eliminated all other possible contributions, the only mechanism left that can give rise to a signal is spin accumulation. In view of this, and of the consistency of our measurements and analysis[1,2], the suggestion that we cannot distinguish between spin accumulation and anisotropic magneto resistance is unjustified.

Johnson also points out that if we have observed spin accumulation, then our conclusion that the spin polarization of the current is low (1–2%) must be wrong — claiming that it should be considerably higher (around 40%). Our detailed theoretical model[2] reveals that our conclusion does not crucially depend on specific details of the injection mechanism. Moreover, we did not invoke conductivity mismatch[3]. It is an integral part of the description, in which the boundary conditions imposed by the contacts are included in a straightforward way.

Consistent treatment of the injector and detector contacts[4,5] is missing from Johnson's description, which therefore cannot be applied directly to the case of transparent contacts. Moreover, we did not observe any interface resistance between ferromagnetic and non-magnetic regions, as Johnson suggests, which could be distinguished from the bulk diffusive resistance. There is also no physical reason why there should be such a large resistance at a (disordered) interface between metals.

Our experiments enabled us to observe spin accumulation in its purest form, without any contribution from spurious effects. The low spin polarization of the injected current can be explained by proper modelling of the entire system, including the contacts.

F. J. Jedema, A. T. Filip, B. J van Wees
Department of Applied Physics and Materials Science Centre, University of Groningen, 9747 AG Groningen, The Netherlands
e-mail: b.j.van.wees@phys.rug.nl

1. Jedema, F. J., Filip, A. T. & van Wees, B. J. *Nature* **410,** 345–348 (2001).
2. Jedema, F. J., Nijboer, M. S., Filip, A. T. & van Wees, B. J. *J. Supercond.* **15,** 27–35 (2002).
3. Schmidt, G., Ferrand, D., Molenkamp, L., Filip, A. T. & van Wees, B. J. *Phys. Rev. B* **62,** R4790 (2000).
4. Fert, A. & Lee, S. F. *Phys. Rev. B* **53,** 6554–6565 (1996).
5. Herschenfield, S., & Zhao, L. Z. *Phys. Rev. B* **56,** 3296–3305 (1997).