Atomic motion in ferromagnetic break junctions

To the Editor — Sokolov *et al.*[1] report measurements of the conductance of ferromagnetic point contacts at room temperature as a function of the angle of an applied magnetic field. They find abrupt steps in conductance, of the order of e^2/h in size, at particular field angles, which they ascribe to an intrinsic electronic mechanism associated with the opening and closing of discrete quantum channels in the point contact. Here we show that the angle of an applied magnetic field can have a surprisingly strong effect in causing sudden changes to the configuration of atoms in some nanoscale ferromagnetic contacts, thereby inducing reproducible steps in the electrical conductance as a function of magnetic-field angle. Even at a temperature of 4.2 K the atoms are not always frozen in place. On this basis, we suggest that atomic rearrangements cannot be ruled out as a possible explanation for the results given by Sokolov and colleagues.

We have performed conductance measurements on magnetic point contacts as a function of both field angle and time, at temperatures of 4.2 K and above. The field angle was adjusted using a multiple-coil superconducting magnet. We investigated Ni and permalloy ($Ni_{80}Fe_{20}$) contacts formed by electron-beam lithography and evaporation onto oxidized silicon substrates, followed by controlled electromigration to narrow the contacts to near-atomic cross-sections[2]. In accord with previous experiments on point contacts made from other metals[3,4,5], our measurements of conductance as a function of time reveal two-level conductance fluctuations in all samples at temperatures above several tens of K (and occasionally even at 4.2 K), owing to the motion of atoms or small groups of atoms between metastable arrangements. Magnetic point contacts at room temperature are therefore not static devices, but contain atoms or collections of atoms fluctuating between different positions over a broad range of timescales.

In measurements of conductance as a function of the angle of an applied magnetic field, in approximately 10% of samples we have observed abrupt steps at particular field angles, similar to the results of Sokolov and co-workers. Figure 1a shows an example of a Ni device; we have observed qualitatively similar behaviour in permalloy devices as well. In all cases where we observe these abrupt steps, measurements as a function of time at fixed field angle near the transition point reveal two-level fluctuations with size equal to the conductance step as a function of angle (Fig. 1b). The duty cycle of the time-dependent fluctuations varies continuously from being in the high-conductance state 0% of the time to 100% of the time over a narrow range of field angles in the transition region, demonstrating that the conductance change as a function of angle is a consequence of the atomic motion — if the effects of any pre-existing atomic motion were merely amplified in the transition region by modulating the opening and closing of a discrete quantum channel then the duty cycle would not change. We conclude that, even in magnetic point contacts designed to minimize magnetostriction and magnetostatic forces, the angle of an applied magnetic field can strongly affect the stability of atoms in the contact region and produce abrupt reproducible steps in conductance versus field angle owing to atomic reconfigurations.

The observation of Sokolov *et al.* that their conductance steps occur at slightly different field angles upon repeated measurements is also explained more easily as a consequence of relatively slow atomic motion rather than by an intrinsic electronic mechanism, as thermal fluctuations in the population of electronic states should fluctuate much more quickly than the millisecond timescales of their experiment.

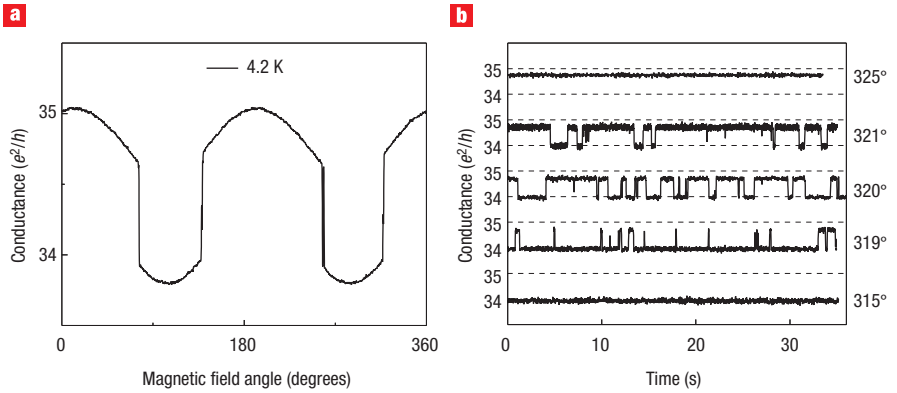

Figure 1 Abrupt conductance changes in a nanoscale Ni contact at 4.2 K. **a**, Conductance as a function of magnetic field angle, for a field magnitude of 800 mT. The field is rotated in the sample plane. **b**, Conductance as a function of time at several fixed field angles, for the same sample as in **a**. At field angles in the vicinity of the conductance steps in **a**, we observe two-level conductance switching owing to atomic motion.

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Authors' response — In their comment[1], Shi and Ralph emphasize that conductance of Ni point contacts produced by an electromigration technique can occasionally exhibit two-level fluctuations (TLF), mimicking the discrete steps in the conductance of the point contacts as a function of the applied magnetic-field direction. They explain the nature of these steps in terms of atomic motion rather than intrinsic electronic effect. We emphasize in this reply that our results[2], obtained on a different magnetic material synthesized by a different method, do not show any data confirming their hypothesis.

Ballistic anisotropic magnetoresistance (BAMR) was observed on Co point contacts electrochemically grown between Au or Ni electrodes. No evidence of

BAMR was found on electrodeposited Ni samples (Fig. S4 in ref. 2). A possible explanation for this discrepancy is the sensitivity of the magnetic properties of Ni at the nanoscale to atomic structure and temperature. Co is expected to be a more magnetically robust material than Ni owing to a larger magnetic moment and stronger exchange interactions. Moreover, Co exhibits larger spin-orbit coupling, a characteristic that is essential for BAMR. Surface atomic motion properties in the electrolyte environment of electroplated junctions are expected to differ significantly from their behaviour in a vacuum environment. In particular, it has been shown that the hydrogen evolution during the fabrication process modifies the transport properties of transition metal nanocontacts through stabilization of atomic configurations[3].

No signature of TLF was observed for several tens of electrodeposited Co samples we investigated. This is evident from the time dependence of the conductance, which always showed an increase during sample growth and a decrease during dissolution of the contact (Figs 1 and S1 in ref. 2). Atomic instabilities should produce stepwise conductance oscillations during sample fabrication, features that we have never detected. We think that the different fabrication methods can result in profoundly different properties of point contact samples. Break junctions obtained by mechanical or electrical means exhibit significant local stress at their weakest point, which controls the conductance. Junctions obtained by electrodeposition techniques involve samples where atoms are added or removed very slowly under electrochemical potential control of the contact surface.

Our magnetoresistance curves (Figs 2, S2 and S3 in ref. 2) clearly show time periodicity matching the angular sweep periodicity with 10–15° dispersion in angles at which the conductance abruptly changes (when repetitive angular sweeps are applied). We have not observed TLFs within this 10–15° angular window in around 2,000 transitions recorded in our experiments, systematically showing a single–step angular change (Fig. S3 in ref. 2). This fact indicates that if TLFs are indeed the origin of the observed angular dispersion in the conductance switching they occur on a much longer timescale than those recorded in Shi and Ralph's experiments. Furthermore, we found no evidence that our measurements were influenced by either the magnitude of the applied saturating magnetic field (Fig. S2 in ref 2) or the gradient of the applied field. If the observed conductance steps were associated with the atomic motion induced at a given magnetic field angle, the magnitude of the field would likely affect the angle at which the conductance change occurs.

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