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Turning on a Dime

Ulrike K. Müller and David Lentink

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calized at the interfaces between semiconductors but are free to move in lateral directions (the two-dimensional electron gas). Murakami *et al*. (*9*) considered empty states (holes) in the valence band. The latter system is more complicated, but its phenomenology fits the simple picture sketched above.

In the present work (*4*), Kato *et al.* focus on the spin accumulation in thin films of doped GaAs and strained and doped InGaAs layers in the presence of an electric current. They observe a component of the spin accumulation that is normal to the film and strongly localized at the edges (see the figure, right panel). The data provide strong evidence for the existence of the spin Hall effect. The spin Hall current is blocked at the edges, where the spins accumulate. The same impurities that create the spin Hall current dissipate the spin accumulation that diffuses back into the film (*7*), on a length scale that can be estimated by inspecting the image of the spin accumulation (*4*).

The results for the two semiconductors are very different, highlighting the importance of differences in band structure and strain field. The direct proof for an internal field in the strained InGaAs film makes this material a candidate for the intrinsic spin Hall effect. Nevertheless, Kato *et al*. suggest that it is extrinsic, because the effect is small and no dependence on crystal direction is observed. Hence, in the present samples, the intrinsic Hall effect appears to be suppressed by the the scattering from impurities and defects.

The experiments reported by Kato *et al* (*2*–*4*) provide an unprecedented glimpse into a new magnetic effect, but many open questions remain. For instance, there is no consensus among theoreticians about the resilience of the intrinsic spin Hall effect to defect scattering (*14*), and some voice doubts about the concept of a spin current in the presence of spin-orbit interactions.

It should be very interesting to repeat the present experiments on hole-doped samples with a larger internal magnetic field. Such experiments may confirm the observation of the intrinsic spin Hall effect in the two-dimensional hole gas (*15*) or test theories that predict a more robust effect in the valence band (*16*). Another big challenge also remains: To fulfill the promises of spintronics, scientists must transform the novel spin accumulation and spin currents into voltage differences and charge currents in micro- or nanoelectronic circuits.

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PHYSIOLOGY

Turning on a Dime

Ulrike K. Müller and David Lentink

Scientists may think that insects are the masters of unconventional lift (*1*–*4*), but it seems that birds have caught on to the same trick, using it to outsmart their insect prey. On page 1960 of this issue, Videler *et al.* (*5*) report how swifts—agile aerial hunters that catch insects on the wing—produce unconventional lift: They use their wings to generate a so-called leading-edge vortex. Biologists first caught on to this vortex in 1996 when trying to explain how insects fly (*1*). Since then, this vortex has been observed again and again in flying insects (*2*–*4*). The new study reveals that a bird's wing also can generate this type of vortex (*5*).

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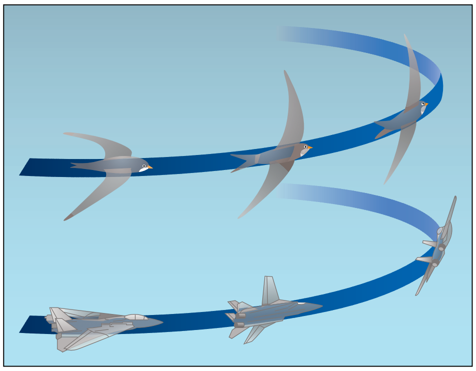
A leading-edge vortex forms on the top of a wing when the angle between the wing and the oncoming air flow is large. The flow then separates from the wing at the leading edge and rolls up into a vortex. To form a leading-edge vortex at lower angles of attack, some wings have a sharp rather than blunt leading edge. To exploit this vortex, the flying animal needs to keep the vortex close to its wing. Insects and swifts have found different solutions to this problem. To stabilize the vortex, flying insects beat their wings rapidly (*1*), whereas gliding swifts sweep their wings backward (*5*). The leading-edge vortex spirals out toward the tip of the wing, adopting the shape of a tornado. Like a tornado, the air pressure in the core of the vortex is low, sucking the wing upward and sometimes forward (during flapping).

Swifts have scythe-shaped wings that consist of a long curved hand-wing, which is attached to the body by a short arm-wing. The hand-wing is composed of primary feathers, which form a sharp and swept-back leading edge. Both features help to generate and stabilize a leading-edge vortex. Videler *et al.* cast a model of a single swift wing in fast gliding posture and recorded the flow fields around the wing in a water tunnel using digital particle image velocimetry. (Flow patterns in water are the same as in air as long as the same Reynolds number is used.) They observed that a vortex forms on top of the wing close behind the wing's leading edge. This leading-edge vortex is robust against changes in flow speed and angle of attack—observations that agree well with those of other biologists studying the leading-edge vortices of insects. However, surprisingly, the swift wing produces such a vortex at angles of attack as small as 5°, compared with 25° to 45° typical for insects (*6*, *7*).



On the wing. Swifts are aerial hunters, catching flying insects on the wing. To outmaneuver their agile prey, swifts are able to fly fast and to make very tight turns. To maximize flight speed as well as maneuverability, evolution and aeronautic engineering converged on the same solution—variable wing sweep. Swifts (**top**) and the Tomcat jet fighter (**bottom**) keep their wings swept back to reach high flight speeds. To execute tight turns, both flyers reduce their wing sweep.

The achievements of aerospace engineers have inspired biologists to study the aerodynamics of flying animals. Engineers first discovered the extraordinary amount of lift that leading-edge vortices produce when they solved the problem of how to land supersonic fighter jets and passenger aircraft like the Concorde. Swept-back wings not

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only make supersonic flight possible, but also generate stable leading-edge vortices at high angles of attack. The resulting extra lift enables delta-wing aircraft to land safely despite their small wings, which are much smaller than those of conventional aircraft.

The swept wing of a swift generates a stable leading-edge vortex. Yet the exact role of this vortex in the swift's flight performance can only be inferred from observations of their flight. Swifts in flight turn on a dime while catching insects, a spectacular aerobatic display. Anybody observing swifts circling in a yard will notice that the birds hold their wings swept back during fast flight and swiftly change the wing sweep to execute tight turns (see the figure). Aerospace engineers converged on the same solution for their military aircraft, which have to perform optimally both during supersonic and subsonic flight (*8*). Pilots of fighter jets such as the F-14 Tomcat and the Tornado can choose between different wing sweeps for maximal dogfight and cruise performance (see the figure).

The gliding flight of storks inspired the first airplane designs of Otto Lilienthal in the late 19th century. The benevolent flight characteristics of these slow and stately gliders invested airplane pioneers with the confidence to take to the skies. Swifts are radically different gliders from storks: They are nimble and fast. These attributes require the ability not only to generate large aerodynamic forces from unsteady lift mechanisms, but also to exercise exquisite control over these forces. The next challenge for Videler and his team is to elucidate how swifts use their variable wing sweep to gain direct control over leading-edge vortices in order to increase their flight performance. In the future, the swift's flight control might inspire a new generation of engineers to develop morphing microrobotic vehicles that can fly with the agility, efficiency, and short take-off and landing capabilities of insects and birds.

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PHYSICS

Superconductivity in Thin Films

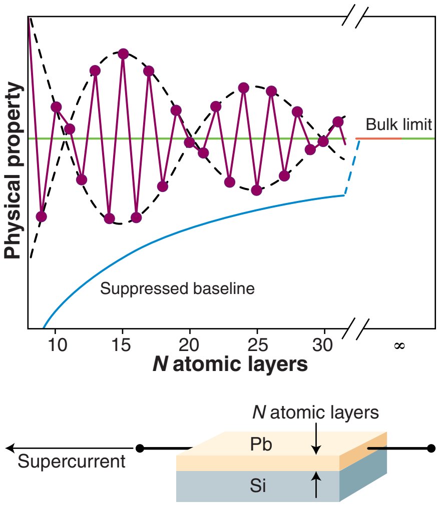
Tai-Chang Chiang

Since the 1960s (*1*), researchers have explored the possibility that the superconducting properties of thin films may be superior to, or at least different from, those of bulk materials. Guo *et al.* now demonstrate on page 1915 of this issue (*2*) that film thickness can indeed affect superconducting behavior. Their data show convincingly that the superconducting transition temperature (T_c) of thin lead films oscillates with film thickness.

As the thickness of a film is reduced to the nanometer scale, the film's surface and interface confine the motions of the electrons, leading to the formation of discrete electronic states known as quantum well states (*3*). This quantum size effect changes the overall electronic structure of the film. At small thicknesses, physical properties are thus expected to vary, often dramatically, with thickness.

Recent experimental studies have demonstrated such variations with film thickness for properties such as the electronic density of states, electron-phonon coupling, surface energy, and thermal stability (*4*–*8*). The variations are expected to follow a damped oscillatory curve that is superimposed on a $\pm N^{-\gamma}$ baseline (where N is the number of atomic layers in the film and the exponent γ is often close to 1).

The superconducting transition temperature for a metal such as lead depends on the density of states and on electron-phonon coupling. It should thus also vary with film thickness. Early work generally showed a reduction in T_c for small film thicknesses, in qualitative agreement with a $N^{-\gamma}$ dependence. However, in most cases, structural defects were probably the main reason for the reduction (*9*).



Quantum oscillations in thin films. (Top) Schematic variations in physical properties (including the superconducting transition temperature T_c) of lead films as a function of atomic layers (N) in the film, assuming a flat baseline (green). The dashed curves are envelope functions. Also shown is a different baseline (blue), suppressed at small film thicknesses, which corresponds qualitatively to the data reported in (*2*). **(Bottom)** Schematic drawing for an experiment that tests the superconducting properties of such films.

An oscillatory dependence of T_c on film thickness is a far more convincing proof for quantum size effects. Some prior studies suggested such oscillatory behavior (*7*, *8*), but the report by Guo *et al.* (*2*) is the first definitive and quantitative demonstration. Using atomically uniform films of lead with exactly known numbers of atomic layers deposited on a silicon (111) surface (see the figure), the authors observed oscillations in T_c that correlated well with the confined electronic structure. Their work has elevated this type of measurement to a new level of precision and sophistication.

Quantum oscillations can be understood by analogy to the systematic property variations of chemical elements. The number of confined electrons in a film increases as the film gets thicker. These electrons fill quantum well states, just as the electrons in atoms fill successive shells. However, in contrast to the spherical geometry of atoms, the films are planar. The properties therefore vary with film thickness. The period at which they do so is fixed for each system and equals one-half of the bulk Fermi wavelength (which is related to the average electron density and the crystal structure) (*4*).

For lead films on silicon (111) surfaces, the period of variation is 2.2 atomic layers. Because this is close to 2 atomic layers, physical properties (including T_c) should oscillate between films with even and odd numbers of layers. However, the slight difference between 2.2 and 2 layers leads to a beating effect (see the figure, where a flat baseline is assumed).

The atoms at each surface or interface of a film amount to $1/N$ of the total number of atoms in the film. These atoms are perturbed by the surface or interface much more than the rest of the film is. The effect

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