

Putting a Spin on the Aharonov-Bohm Oscillations

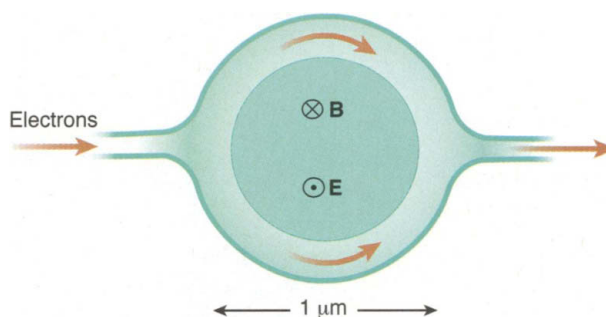
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Of the many fascinating consequences of quantum mechanics, one of the more counterintuitive ones is the Aharonov-Bohm effect: A charged particle can “feel” a magnetic field even when it remains outside the field. In a recent mesoscopic experiment reported in *Physical Review Letters* (1), Yau *et al.* observed an interesting extension of this effect to the spin of the charged particle.

According to classical physics, a charged particle is influenced by a magnetic field only if the particle goes through a region with nonzero magnetic field strength. But according to quantum mechanics, the quantum wave representing the state of a charged particle, such as an electron, can be influenced by the magnetic field even if the particle is nowhere in the region of nonzero field strength. Aharonov and Bohm predicted more than 40 years ago that if the quantum wave is split into two waves that go around a solenoid and interfere, the resulting interference pattern is influenced by the magnetic flux enclosed by the waves (2).

In addition to its charge, the electron has a magnetic moment proportional to its spin. Hence, if the magnetic field strength is nonzero along the electron wave, there are also spin-dependent effects due to the interaction of the magnetic moment with the magnetic field. If an electric field is present, the so-called spin-orbit interaction of the magnetic moment with the electric field (3) further influences the interference pattern (4, 5). All these effects are present in the recent experiment of Yau *et al.* (1).

The experiment is a miniaturized version of the original experiments that confirmed the Aharonov-Bohm effect (6). The apparatus consists of a ring structure with a diameter of $\sim 1 \mu\text{m}$, fabricated inside a GaAs/AlGaAs heterostructure. If such a mesoscopic apparatus made of metals or semiconductors is cooled to about 30 mK, then the conduction electron waves are coherent over the entire structure, because there is no randomization due to inelastic scattering. This leads to interesting quantum effects.



The Aharonov-Bohm effect. Electrons enter and leave the ring structure as indicated by the horizontal arrows. The quantum wave associated with each electron in the entrance region splits into two wave packets that go around the ring, as indicated by the curved arrows, and interfere in the exit region. Homogeneous magnetic field **B** and electric field **E** are applied normal to the plane of the ring. Whether the interference is constructive or destructive, and hence whether the current is maximum or minimum, depends on the values of **B** and **E**. Varying **B** therefore leads to oscillations of the current.

In the experiment of Yau *et al.*, the conduction electrons are like a quantum gas that enters and exits the ring (see the first figure), constituting a current. Homogeneous magnetic and electric fields are applied normal to the plane of the ring structure. The electric field **E** is needed to confine the electrons to this plane.

It has been predicted (7, 8) that the electrical resistance of the current through a mesoscopic ring should vary when the magnetic flux Φ through the ring is varied through changes in the strength of the magnetic field **B**. This magnetoresistance R is an oscillatory function of the magnetic flux with period h/e , where h is Planck's constant and e is the charge of the electron (9). The current is maximum for constructive interference and minimum for destructive interference. This oscillation has been observed in several experiments (10), including the one by Yau *et al.* (see the second figure) (1).

A Fourier transform of R should peak at e/h . Yau

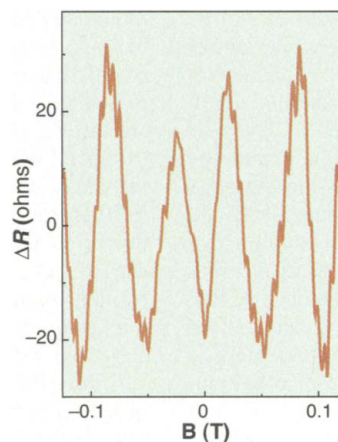
et al. (1) observed this peak in their experiment. But they also found two other smaller peaks on either side of the main peak, suggesting a modulation of the Aharonov-Bohm oscillation of R . These side peaks may be a result of spin-dependent effects. These effects may be obtained by supposing that the magnetic moment of the electron (which is proportional to the spin) interacts with an effective magnetic field (3) $\mathcal{B} = \mathbf{B} - 1/2\mathbf{v} \times \mathbf{E}$, where \mathbf{v} is the velocity of the electron.

The factor 1/2 distinguishes \mathcal{B} for the electron from the corresponding effective magnetic field experienced by a neutral dipole, such as the neutron, in the combined magnetic and electric fields (4). For an electron in an atom, this difference is traditionally attributed to the semiclassical Thomas precession, that is, the additional relativistic precession of the electron spin due to its acceleration in the electric field of the nucleus (3). The \mathcal{E} experienced by the electron is much larger than the applied electric field. This effect has been shown experimentally and has been attributed to complex band effects in the semiconductor (11). This enhancement enables \mathcal{E} to be observable.

The above combined effect of the electric and magnetic fields on the electrons may also be regarded as arising from

Berry's phase (12), a geometric phase acquired by the wave function when it evolves slowly and returns to the original state. In the present case, \mathcal{B} varies slowly during the motion of the electron along each semicircular ring, and hence the components of the spin state of each electron in the direction of \mathcal{B} remain pinned to this varying direction. However, because \mathcal{B} changes rapidly at the point of entry, the initial directions of \mathcal{B} are different for the two states that go around the semicircular rings and interfere at the point of exit.

But the (noncyclic) Berry phase for each semicircular ring between



Oscillations in the ring. ΔR is the resistance (in ohms, after subtracting a smooth background resistance) in the presence of an externally applied magnetic field **B** (in teslas). As **B** is varied (with the externally applied electric field **E** fixed), ΔR oscillates because of the oscillation of the current. [Adapted from (1)]

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the entry and exit points is well defined. For unpolarized electrons, as in the present experiment, the average of these Berry phase factors may be observed. The phase shifts may also be thought of as a result of the change in kinetic energy of the electrons due to the change in potential energy when they interact with \mathcal{B} , so that the total energy is conserved. This results in a change in wavelength and hence a phase shift.

To obtain the same quantum coherence in a macroscopic conductor, it needs to be superconducting. But in that case the magnetic flux enclosed by the ring is quantized, and hence cannot be freely varied as in the meso-

scopic experiment, which allows the continuous oscillatory dependence of the current on the magnetic flux to be determined.

As the experiment of Yau *et al.* illustrates, mesoscopic experiments enable us to observe directly, in disordered systems, new effects of quantum coherence that could not be observed with macroscopic systems. Also, as the miniaturization of electronics proceeds, there is hope that mesoscopic experiments may prove to be of great practical use. They may, for example, find application in quantum computing, owing to the quantum coherence over the entire mesoscopic apparatus.

References and Notes

1. J.-B. Yau, E. P. De Poortere, M. Shayegan, *Phys. Rev. Lett.* **88**, 146801 (2002).
2. Y. Aharonov, D. Bohm, *Phys. Rev.* **115**, 485 (1959).
3. J. J. Sakurai, in *Modern Quantum Mechanics* (Addison-Wesley, Reading, MA, 1994), pp. 304–305.
4. J. Anandan, *Phys. Lett. A* **138**, 347 (1989).
5. S.-L. Zhu, Z. D. Wang, *Phys. Rev. Lett.* **85**, 1076 (2000).
6. M. Peshkin, A. Tonomura, *The Aharonov-Bohm Effect* (Springer, Berlin, 1989).
7. B. L. Al'tshuler, A. G. Aronov, B. Z. Spivak, *JETP Lett.* **33**, 94 (1981).
8. M. Buttiker, Y. Imry, R. Landauer, *Phys. Lett. A* **96**, 365 (1983).
9. This is a consequence of the fact that the Aharonov-Bohm phase shift is $(2\pi e/h)\Phi$.
10. S. Washburn, R. Webb, *Adv. Phys.* **35**, 375 (1986).
11. Yu. A. Bychkov, E. I. Rashba, *J. Phys. C* **17**, 6039 (1984).
12. M. V. Berry, *Proc. R. Soc. London Ser. A* **392**, 45 (1984).

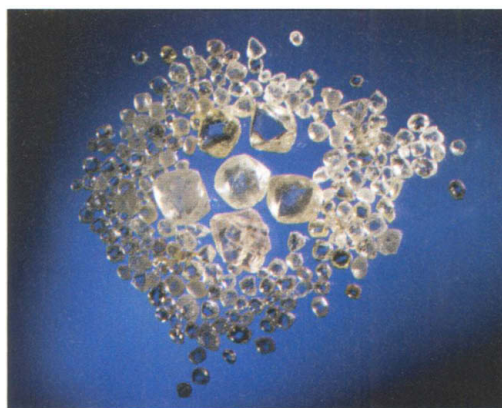
PERSPECTIVES: APPLIED PHYSICS

A Dawn for Carbon Electronics?

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Pure carbon naturally forms two different crystalline materials: diamond, in which all bonds between carbon atoms are the same, and graphite, with two different types of bonds between the atoms. Because diamond is the higher energy form of the two, its natural occurrence is rare compared with that of graphite. In contrast, the lowest energy form of related elements such as silicon (Si) and germanium (Ge) has the same crystal structure as diamond, but no naturally occurring form like graphite.

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Rough natural diamonds. The largest of these diamonds, from a mine in the Orange River area of South Africa, weighs 32 carats. Though extremely valuable as gem stones, they are not pure enough for making electronic devices.

The quirk of nature that makes graphite the lowest energy form of carbon is the main reason it has not been used in electronic devices, in stark contrast to its neighbor in the periodic table, Si. A report by Isberg *et al.* on page 1670 of this issue provides hope that the time has come for diamond electronics (1).

A material suitable for an electronic device must not conduct electrical current in its pure state at room temperature. However, it should be possible to tune its conductivity in a controllable manner by introducing trace amounts of impurity atoms (dopants). Such materials are termed "semiconductors."

Graphitic carbon conducts electricity at room temperature. In contrast, diamond is a semiconductor with physical properties (such as maximum electric field, saturation velocity, thermal conductivity and band-gap) that make it the ideal material for electronic devices (2, 3). The major

barrier to realizing this potential of diamond to date has been the difficulty in synthesizing it in a form that is pure and perfect enough for electronics.

Natural diamonds (see the figure) have too many defects and impurities for use as semiconductors, regardless of the cost associated with their rarity. Only manufactured semiconductor materials are of the appropriate quality for electronics. Crystalline Si wafers used for electronics have impurity and crystalline defect densities that are lower than the atomic density by a factor of 10^{-11} to 10^{-12} . Electronic-grade Si is the purest bulk material known.

The first artificial synthesis of diamond was reported in 1955 (4). It was achieved by subjecting graphite to high pressure and high temperature (HPHT) in the presence of a transition-metal catalyst. This method is

now a standard industrial process. It yields diamonds with submicrometer to submillimeter dimensions that are used as grit in mechanical applications such as polishing. These applications exploit the extremely high hardness and chemical inertness of diamond. But until recently, the impurities and defects in HPHT-synthesized diamonds and their small size precluded their use in electronics.

Alternative methods aimed to synthesize diamond from the vapor phase (5, 6). The first practical method for deposition of diamond from the vapor phase used a hydrocarbon plasma (7). This study heralded a burst of research activity aimed at exploiting the properties of diamond in electronic devices (8).

However, plasma-deposited diamond is not a single crystal. It is made up of many individual crystal grains of 1 to 10 μm in diameter that are oriented differently. Plasma-deposited diamond is polycrystalline when grown on a high-purity noncarbon substrate material, usually a Si wafer. Some success was achieved in growing diamond grains with the same crystal orientation on a different substrate (β -SiC), and the resulting films showed promising electronic properties (9). But β -SiC is also difficult to synthesize, and general progress was impaired by not having available diamond of the required quality.

Over the past 2 years there have been renewed grounds for cautious optimism. High-quality HPHT diamonds in polished form with dimensions of many millimeters have become available, forming suitable substrates on which ultrapure diamond can be grown with a hydrocarbon plasma source (10). The fusion of the two methods for synthesizing diamond artificially has led to the demonstration of single-crystal diamond layers that approach the quality required for electronic devices (11–13). Importantly, it has also been possible to control the con-