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 mesoscopic 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.

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PERSPECTIVES: APPLIED PHYSICS

A Dawn for Carbon Electronics?

Gehan A. J. Amaratunga

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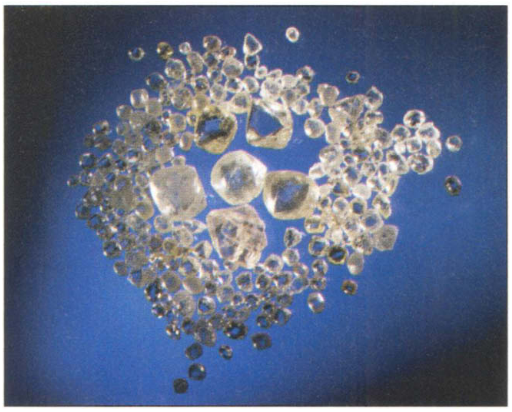
The quirk of nature that makes graphite the lowest energy form of carbon is the main reason it has not been used in electronic devices, in stark contrast to its neighbor in the periodic table, Si. A report by Isberg *et al.* on page 1670 of this issue provides hope that the time has come for diamond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



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.

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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-

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The author is in the Engineering Department, Cambridge University, Cambridge CB2 1PZ, UK. E-mail: ga@eng.cam.ac.uk

THE LATEST MOBILITIES OF DIAMOND IN COMPARISON TO OTHER SEMICONDUCTORS

Semiconductor	Mobility	Maximum electric field	Band-gap
	cm^2 V^{-1} s^{-1} (μ)	V cm^{-1} (E_m)	eV (E_g)
Diamond (C)	4500 (electron) 3800 (hole)	10^7	5.5
Silicon carbide (SiC)	700 (electron)	3.0×10^6	3.26
Gallium nitride (GaN)	2000 (electron)	3.0×10^6	3.0
Gallium arsenide (GaAs)	8500 (electron)	4.0×10^5	1.42
Silicon (Si)	1500 (electron) 450 (hole)	3.7×10^5	1.12
Ge	3900 (electron) 1900 (hole)	2.0×10^5	0.66

ductivity of diamond layers by incorporating boron during plasma growth. Therefore, two of the key elements required from a semiconductor material suitable for electronic devices—a high-quality crystal that can be doped—are now achievable in diamond.

The results reported by Isberg *et al.* (*1*) could be a watershed for carbon electronics. The authors have artificially synthesized diamond with electronic properties that surpass those expected from theory or measurements hitherto. In particular, they have measured the mobility μ of holes and electrons in their very high quality diamond. The mobility is a constant of proportionality that links the velocity **v** that a mobile charge carrier—an electron (−) or a hole (+)—achieves in a solid subjected to an electric force field **E** ($\mathbf{v} = \mu\mathbf{E}$).

Isberg *et al.* have measured mobility values for low electric fields of 4500 cm^2 V^{-1} s^{-1} for electrons and 3800 cm^2 V^{-1} s^{-1} for holes in plasma-grown diamond. These are the highest values of mobility ever measured in diamond. The hole mobility measured in diamond is significantly greater than the electron mobility measured in SiC and GaN (see the table), two other wide-band-gap semiconductors currently explored for high-frequency (>10 GHz) and high-power density applications (*14*, *15*).

At present, the controlled change in the conductivity of diamond can only be achieved through increase of the hole concentration through boron doping. The results suggest that hole-conducting (p-type) diamond devices may be a practical and better option than electron-conducting (n-type) SiC or GaN for high-frequency and high-power electronic devices.

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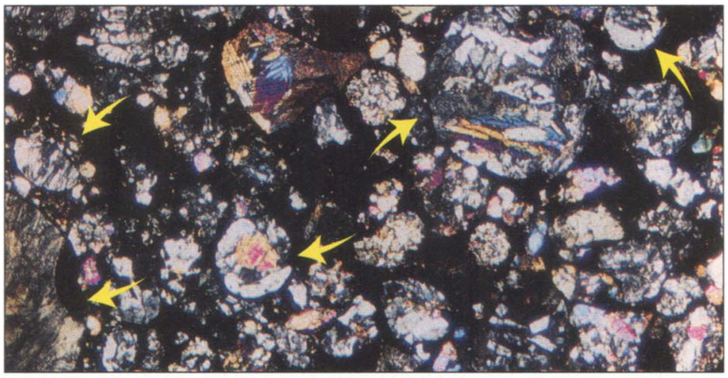
PERSPECTIVES: GEOCHEMISTRY

The Solar System's First Clocks

Jamie Gilmour

Studies of star-forming regions have provided striking pictures of accretion disks and energetic outflows, yielding insights into how molecular clouds evolve to form main-sequence stars. But the processes corresponding to the formation of the inner regions of our solar system—where Earth resides—cannot yet be resolved around other stars. For glimpses of a solar system's early days, researchers must therefore turn to primitive meteorites. On page 1678 of this issue, Amelin *et al.* (*1*) present an important breakthrough in this area: They report the absolute ages for two key events in the formation of solid bodies in our solar system.



"Clocks" in meteorites. A thin section of the meteorite Tieschitz—some chondrules are indicated.

Our solar system formed about 4560 million years ago (Ma). To establish the relative timing of events during this formation process, which lasted some 10 million years (My), scientists rely on measurements of the decay of radioactive isotopes. The daughter products of radioactive decay are chemically different from their parents and tend to equilibrate with their surroundings. However, during certain events—for example, when a mineral crystallizes from a melt and cools—the daughter products of radioactive decay can no longer equilibrate, preserving a record of the state of the system. By measuring the relative concentrations of parent and daughter isotopes today, we can determine when this "isotopic closure" occurred.

Only the Pb-Pb chronometer, based on the decays of the long-lived uranium isotopes ^{235}U and ^{238}U to lead isotopes, is sufficiently precise to resolve the absolute ages of discrete events during the formation of the solar system. Information on the intervals between events might also be gained from the decay of short-lived radioisotopes, notably ^{26}Al-^{26}Mg (half-life 0.73 My), ^{53}Mn-^{53}Cr (3.7 My), and ^{129}I-^{129}Xe (16 My), which were present in the early solar system. But the short half-lives that make these systems potentially useful can lead to problems. Some are so short-lived that they must have been produced shortly before the solar system formed. A radioactive decay can only be interpreted as a chronometer if the parent was homogeneously distributed across the region of application—a condition less likely to be met by a radioisotope that was produced shortly before the events being dated.

The short-lived radioisotopes were long assumed to have been produced by stellar nucleosynthesis close to the formation region of the solar system. However, McKeegan *et al.* showed recently that ^{10}Be was also present (*2*). ^{10}Be is not produced

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The author is in the Department of Earth Sciences, University of Manchester, Manchester M13 9PL, UK. E-mail: jamie.gilmour@man.ac.uk