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

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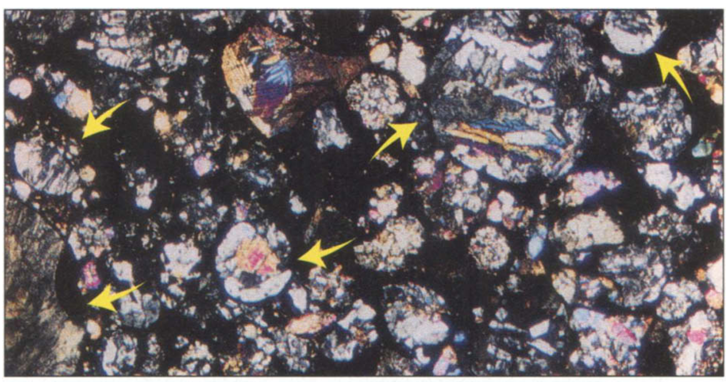
Studies of star-forming regions have provided striking pictures of accretion disks and energetic outflows, yielding insights into how molecular clouds evolve to form main-sequence stars. But the processes corresponding to the formation of the inner regions of our solar system—where Earth resides—cannot 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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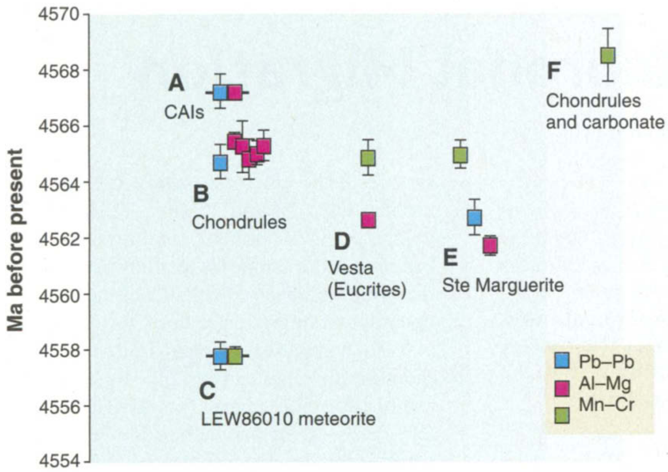

Early solar system chronology. Dashed lines indicate calibrations between chronometers; calibration errors are not propagated. **(A)** When the decay of ^{26}Al is calibrated against the Pb-Pb time scale for CAIs (*1*), chondrule Pb-Pb (*1*) and Al-Mg (*11*) ages **(B)** agree well. **(C)** The Mn-Cr chronometer is calibrated against Pb-Pb using the rapidly cooled meteorite LEW86010 (*12*). **(D)** The Mn-Cr age of Vesta (proposed parent body of the eucrite meteorites) records core-mantle separation, whereas the Al-Mg age records cooling of a basalt (*13*). **(E)** The meteorite Ste Marguerite records processes on an asteroid. The Mn-Cr age predates the phosphate Pb-Pb ages, while the Al-Mg age was reset later in feldspar (*9*) (see text). **(F)** Anomalously early Mn-Cr ages for chondrules may record formation of precursors (*14*), but carbonate from the meteorite Kaidun (*10*) appears to predate CAIs.

by stellar nucleosynthesis. It formed as energetic particles from the early Sun broke up stable nuclei in the accretion disk, and models suggest that this could also be the source of some of the other short-lived radionuclides (*3*). This casts the assumption of homogeneity, and hence the use of some short-lived radioisotopes as chronometers, into doubt.

Primitive meteorites are samples of asteroids that formed in the early solar system and survived relatively unscathed until an impact led to their transport to Earth. Among other things, they contain chondrules and calcium-aluminum–rich inclusions (CAIs) (see the first figure). Chondrules are millimeter-sized spherical droplets believed to have been produced when grain assemblages were flash heated and quickly cooled, although the heating mechanism is still uncertain. CAIs are typically centimeter-sized and consist of the first minerals to condense at equilibrium from a gas of solar composition. They were clearly exposed to an energetic particle flux because they contained live ^{10}Be when they formed (*2*). CAIs appear to have cooled rapidly, and it is thought that they formed when material close to the early Sun was recycled into the accretion disk by a stellar wind from the early Sun (*4*).

The distribution of $^{26}Al/^{27}Al$ ratios in CAIs at their time of formation shows a sharp peak at 5×10^{-5} (*5*). The highest $^{26}Al/^{27}Al$ ratios found in chondrules are $\sim 1.5 \times 10^{-5}$ (*1*). This corresponds to an interval of about 2 to 3 My between CAI formation and chondrule formation—if variations in $^{26}Al/^{27}Al$ ratios can be interpreted chronologically. Until the work of Amelin *et al.* (*1*), data were insufficiently precise to allow comparison of this interval with the Pb-Pb chronometer. By refining the absolute age of the CAI and defining the formation age of chondrules, they show that the Pb-Pb system (which cannot have been influenced by the process that formed ^{10}Be) agrees with the Al-Mg system. The conclusion that ^{26}Al was not produced in the early solar system is reinforced by the identification of ^{10}Be excesses in unusual inclusions that lack excess ^{26}Al (*6*).

More surprising, perhaps, is the demonstration that chondrules formed over a relatively short time, imposing a significant constraint on the mysterious heating mechanism involved in their formation. Proposed heat sources range from lightning or transit through shock fronts in the nebula—the cloud of dust and gas from which the Sun and planets were forming—to processes associated with collisions between planetesimals. If chondrules indeed formed in a nebular environment, the proponents of the various models must now explain why their favored heating mechanism was restricted to less than 1 My of the life of a nebula that lasted at least 2 to 3 My (the interval between chondrule and CAI formation).

Even though each of the short-lived chronometers now seems to yield reliable times between events, it remains difficult to deduce a unified system of absolute ages. In a chronometer based on a long-lived radioisotope, the system today can be used as a common zero. This option is not available when short-lived isotopes are used, so we must rely on calibrations of the systems against one another and against the Pb-Pb chronometer. Confidence in this procedure is increased when the chronometers in question can be shown to have recorded the same interval between the events being dated. There is evidence of consistency between the Mn-Cr and I-Xe systems (*7*, *8*). The new results, combined with analyses of feldspar from another chondritic meteorite (*9*), show similar consistency between the Al-Mg and Pb-Pb systems.

The second figure shows a compilation of dates from the short-lived radioisotope chronometers (*8*), modified and simplified in light of the results of Amelin *et al.* The Al-Mg and Pb-Pb systems agree where tested, as do the I-Xe and Mn-Cr systems. However, when the two groups of chronometers are combined, some inconsistency remains. When applied to the meteorite Ste Marguerite, the ^{26}Al system agrees most closely with the Pb-Pb age of phosphate grains, whereas the ^{53}Mn (and linked ^{129}I) systems record significantly earlier events. Perhaps this reflects varying closure conditions for the chronometers. There are also some uncomfortably early ages in the linked Mn-Cr and I-Xe systems, notably the Mn-Cr age of carbonates from the meteorite Kaidun (*10*).

Even when two chronometers are applied to the same mineral, there is no guarantee that their clocks were stopped at the same time. Especially in samples that cooled slowly, different chronometers passed through their different closure temperatures at significantly different times. Despite these remaining uncertainties, a picture is emerging in which the first solids evolved to asteroids with diameters of ~100 km or more in 2 to 3 My.

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