for oligodendrocyte precursor cells (*1*). These increases do not result in growth arrest, apparently because there is a compensatory increase in the expression of positive growth mediators such as Cdk2, Cdk4, and cyclins D1, D3, and E. The indefinite growth observed by the investigators probably reflects a combination of culture components that minimize "stress," including the right hormones and other factors that are able to balance the stresses that do occur. The cultured neural cells remained diploid (that is, they retained both sets of chromosomes) and, in contrast to most established rodent cell lines, their cell cycle checkpoints were activated normally in response to insults such as irradiation or the overexpression of Ras.

It is widely believed that replicative senescence evolved to limit the number of available cell divisions, and that it thus behaves as a brake against the accumulation of the multiple mutations needed for a cell to become malignant. A 70-kg man who lives for 80 years has to be 14,000 times as resistant to developing cancer as a 0.2-kg rat that lives for 2 years: (70 kg ÷ 0.2 kg) × (80 years ÷ 2 years) = 14,000. The results of the two new studies (*1*, *2*) support the notion that a cell's conventional arsenal—which includes DNA repair pathways and antioxidant enzymes—is adequate to protect against the accumulation of mutations and development of cancer during the short life of small organisms. In contrast, larger and longer-lived species had to evolve replicative senescence to ensure that they would have the greatly increased protection that their longevity necessitated (*4*). Thus, although some might interpret the indefinite growth of normal rat oligodendroglial precursor cells and Schwann cells as a feature unique to only specific cell types, we think it more likely that this unfettered growth represents a fundamental biological difference between normal human cells (which count cell divisions) and normal rodent cells (which do not). Appreciating this difference will be essential for designing and interpreting experiments that investigate how replicative senescence, telomeres, and telomerase are involved in aging and cancer.

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PERSPECTIVES: SEMICONDUCTORS

Toward Functional Spintronics

Hideo Ohno

The enormous success of semiconductor electronics we have been witnessing is solely based on the charge carried by electrons. The other key property of the electron, its spin, has been completely ignored in semiconductors but is used in information storage by magnetic materials. Researchers are now investigating ways to use both properties simultaneously in semiconductors (*1*). This field is often called semiconductor spintronics because it is expected to lead to the integration of processing and storage capabilities thus far carried out separately and to quantum information processing that exploits the quantum nature of the spin state (*2*). A key advance has been the synthesis of magnetic semiconductors based on III-V compounds (such as GaAs used in transistors and lasers), which may enable the integration of magnetism into existing semiconductor devices (*3*). However, practical application of spintronics requires room-temperature ferromagnetism in semiconductors. Making such materials represents a substantial challenge for materials science.

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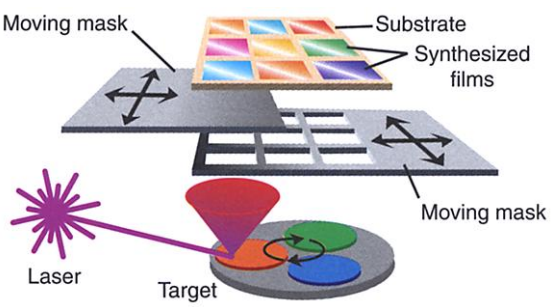

Schematic diagram of the combinatorial laser ablation apparatus used by Matsumoto *et al.* The method allows the formation of a series of thin films with varying elemental composition under virtually identical conditions. Without such methods, one needs to prepare thin films one by one while trying to keep the preparation conditions the same, which is time consuming and difficult.

On page 854 of this issue, Matsumoto *et al.* report the discovery of just such a material (*4*). Their room-temperature ferromagnetic semiconductor is based on anatase, one of the forms of titanium dioxide, doped with a few percent of cobalt. The material is made by laser ablation in high vacuum. Its band gap is wide enough (E_g = 3.2 eV) not to absorb any light at visible wavelengths, and the semiconductor is therefore completely transparent.

Ferromagnetic semiconductors such as europium oxide have been known for decades, and III-V– and II-VI–based ferromagnetic semiconductors were reported recently. But all of them are ferromagnetic only below room temperature and have a band gap in the infrared; that is, they are opaque. Initial results about room-temperature ferromagnetism in semiconductors were reported recently by two other groups (*5*, *6*).

The semiconductor reported by Matsumoto *et al.* (*4*) provides considerable flexibility in designing circuits and storage, particularly for devices with displays. Semiconductors can be used to build circuits, but when they are ferromagnetic, they may also be used to build magnetic storage devices called magnetic random access memories (*7*). The working dimension in semiconductor circuits and magnetic storage becomes smaller and smaller as the quest for ever higher speed and density continues. However, we cannot reduce the dimensions of visual user interfaces at the same rate for obvious reasons. The ideal scenario would be the integration of the electronic circuits and magnetic storage with the user interface in a single flat panel display, leading to a truly electronic paper. Especially when the display itself needs thin film transistors to drive individual elements (as is the case in liquid crystal displays, where opaque transistors block some of the fluorescent backlight), the full integration of circuit-storage-display by a transparent semiconductors is highly desirable.

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The method used by Matsumoto *et al.* to synthesize their semiconductor also deserves attention. The authors used a new breed of material preparation called combinatorial synthesis, which is becoming increasingly important for screening the vast range of possible compositions and conditions available to inorganic materials (*8*). In Matsumoto *et al.*'s experiments, intense ultraviolet laser light hits selected targets, giving rise to ablation of the material (see the figure on page 840). The ablated material is deposited on a separate substrate in an oxygen atmosphere, resulting in doped oxide formation. The use of masks leads to a series of thin films with different compositions on a single substrate while keeping other growth conditions virtually constant.

Combinatorial synthesis is critically important for performing efficient searches for materials with specific properties. Promising alternatives such as material design based on first-principle calculations are being developed and have been applied to transition metal–doped zinc oxides (*9*), but the extent to which the method can be applied remains to be seen.

What gives rise to room-temperature ferromagnetism in the new material is not clear yet. The mean field model for carrier-induced ferromagnetism in III-V and II-VI magnetic semiconductors (*10*) does not seem capable of explaining the observations. More investigation is necessary to elucidate the underlying mechanism.

Matsumoto *et al.*'s discovery of a transparent semiconductor with room-temperature ferromagnetism adds a new dimension to the already widespread use of permanent magnets in our everyday life, from refrigerator magnets to mass storage in information technology. Through this transparent material, we get a glimpse of the spintronic devices of the future.

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PERSPECTIVES: CHEMISTRY

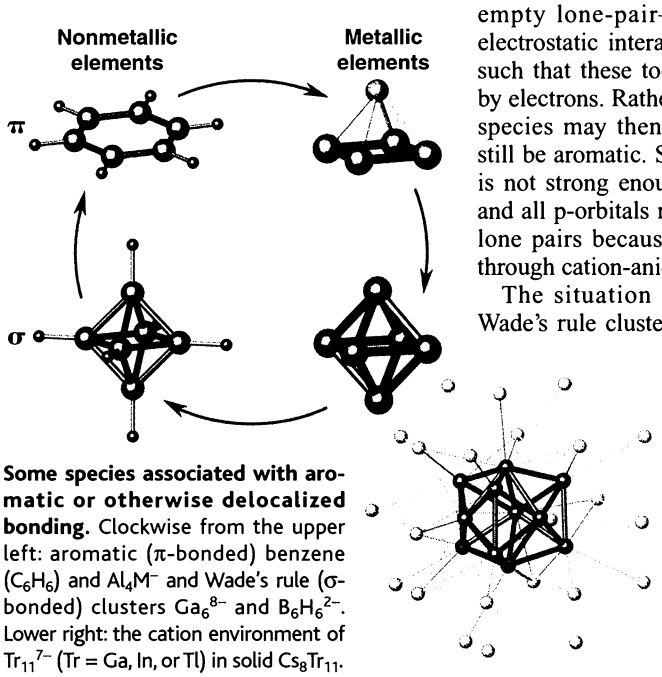
Aromatic Metal Clusters

Dong-Kyun Seo and John D. Corbett

Why certain molecules are more stable than others is not always easy to understand, not least because nature's diversity does not permit a unified answer for all classes of compounds. Among the useful concepts is aromaticity, the simplest and yet most successful description of the particular stability of unsaturated cyclic hydrocarbons with 2, 6, 10, ... $(4n + 2)$ electrons delocalized in π-orbitals perpendicular to the ring plane. A similar concept, Wade's rules for closed shell deltahedra (*1*), describes delocalized σ-bonding among gas-phase and solid-state cluster compounds, including those of the electron-poor elements Ga, In, and Tl (*2*, *3*). But stability based on aromaticity has not been confirmed unambiguously for any molecular moiety other than the hydrocarbons and related compounds (*4*).

On page 859 of this issue, Li *et al.* (*5*) report the most convincing evidence to date for aromaticity in an all-metal system. The authors have created through laser vaporization a series of bimetallic clusters consisting of a square planar Al_4^{2-} anion face-capped by an M^+ cation (M = Li, Na, Cu) (see the figure). Photoelectron spectroscopic measurements and ab initio calculations show that the anions have two electrons in the π-bonding highest occupied molecular orbital (HOMO) on Al_4^{2-}. The results have important implications for related polyanions in the solid state.

In considering the electronic structures of clusters without externally bound atoms, it is customary to fill lone-pair molecular orbitals (MOs—orbitals delocalized over three or more atoms), which are regarded as nonbonding, with two electrons. This is also consistent with the electronic structure schemes for hydrogen-terminated carbon or boron clusters. It is therefore tempting to assume that an aromatic Al_4 cluster should have six negative charges and should be isoelectronic with the analogous $C_4H_4^{2+}$. In contrast, Li *et al.*'s novel aluminum tetramer has only two negative charges and yet exhibits one filled π-HOMO because two of the four lone-pair–like MOs lie higher in energy and are empty, whether an M^+ ion is attached or not. The expected instability of Al_4^{2-} toward the loss of an electron ($Al_4^{2-} \rightarrow Al_4^- + e^-$) is eliminated by the substantial coulombic (and covalent) energy, around 200 kcal/mol, that is gained upon capping the square with M^+ to form Al_4M^+ (*6*). This is reminiscent of the importance of cation-aromatic ring interactions in organic and biological systems (*7*).



Some species associated with aromatic or otherwise delocalized bonding. Clockwise from the upper left: aromatic (π-bonded) benzene (C_6H_6) and Al_4M^- and Wade's rule (σ-bonded) clusters Ga_6^{8-} and $B_6H_6^{2-}$. Lower right: the cation environment of Tr_{11}^{7-} (Tr = Ga, In, or Tl) in solid Cs_8Tr_{11}.

Will this π-bonding be preserved in an equivalent Al_4^{2-} unit when the tetramer is surrounded by cations in a solid? Probably not, for the following reasons. First, the surrounding cations will probably stabilize empty lone-pair–like orbitals through electrostatic interactions and polarization, such that these too will need to be filled by electrons. Rather than M_2Al_4, the stable species may then be M_6Al_4, which may still be aromatic. Second, if the π-bonding is not strong enough, it may break down and all p-orbitals may be filled to become lone pairs because of the energy gained through cation-anion interactions.

The situation is rather different for Wade's rule clusters. Their polyhedral geometries (see the figure) allow the formation of only skeletal σ-orbitals, in addition to lower lying lone pairs (or B–H bonds in the case of the boranes) that are always filled. There is no evidence that stabilization of lone pairs by cations drastically alters the electronic

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