in the halites, corresponding to $^{36}Cl/^{35}Cl \sim 10^{-8}$. But, unfortunately, there is another possible source for the ^{36}Ar, namely the capture of thermal neutrons by ^{35}Cl, which may have occurred during recent cosmic ray exposure in transit to Earth and/or during the time the halite spent on its parent body (*4*, *5*).

With the currently available data, there is no simple unambiguous way to decide between the source of ^{36}Ar, but the observed ratio of ^{36}Ar to ^{35}Cl of about 1×10^{-8} at least provides an upper limit for the ratio $^{36}Cl/^{35}Cl$ at the time of halite formation. More work along the lines pioneered by Whitby *et al.* (*4*) will be required to see how compatible the Ar and Xe data are with each other. The search for neutron effects in other elements may help to determine the origin of ^{36}Ar.

Some of the finer details of I-Xe dating are only now being understood (*7*, *9*). In the Zag halites, the system is disturbed (*4*), as shown by the variation in the $^{129}I/^{127}I$ ratios inferred from different extraction steps, which is larger than can be ascribed to analytical errors of the individual values. This variation may have been caused by shock from the impact that brought together the various meteoritic constituents 4.22 billion years ago. It is clear that halite formation must have occurred very early, but the absolute age and the lessons we think we have learned may have to be taken with a grain of salt.

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PERSPECTIVES: ANTIFERROMAGNETISM

Taking a Very Close Look at Magnetic Structures

Andreas Scholl

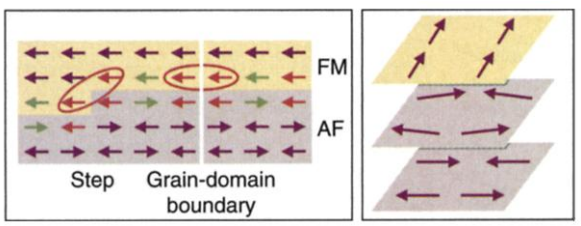
Magnetic materials are key components in today's information technology. Large amounts of data are stored in thin magnetic films on computer hard disks. Magnetic multilayer structures also serve as miniaturized and very sensitive magnetization sensors. Future integrated magnetic elements may even compete with traditional semiconductor technology, for example, as fast nonvolatile random access memory.

To meet the ever-increasing demands on storage density, processing speed, and device complexity, researchers must learn how to control their materials' structure, composition, and magnetic properties on a sub–100-nm scale. This will require advanced tools not only for the fabrication but also for the microscopic characterization of the magnetic structures. On page 1805 of this issue, Heinze *et al.* (*1*) use an innovative scanning probe method to image an antiferromagnetically ordered Mn monolayer with atomic spatial resolution. This is a considerable advance, considering that previous characterizations of antiferromagnetic domains could not go beyond micrometer resolution.

Antiferromagnetic layers are essential components in magneto-electronic devices, because they are insensitive to external magnetic fields. In an antiferromagnetic material, the direction of the magnetic moment alternates from lattice site to lattice site, with no overall macroscopic magnetization. Placed next to a ferromagnet, an antiferromagnet "pins" the ferromagnet's magnetization direction by magnetic exchange forces, causing a shift in the hysteresis loop that is called exchange bias. Modeling studies indicate that exchange bias is caused by a small ferromagnetic moment of the antiferromagnetic surface (see the figure). Imperfections such as domain walls, atomic steps, and grain boundaries are believed to be instrumental for the appearance and size of this moment, because they break the symmetry of the magnetic structure at the surface of the antiferromagnet (*2*). Pure metals such as Cr or Mn, transition metal alloys such as FeMn or IrMn, and transition metal oxides such as Fe_2O_3 (hematite) exhibit antiferromagnetism. Other oxide compounds, like the manganites known for the colossal magneto-resistance effect, can be antiferromagnets or ferromagnets depending on doping and temperature (*3*).

The investigation of the magnetic structure of antiferromagnets is difficult because of the lack of a macroscopic magnetization. This has hampered attempts to determine the microscopic origins of exchange bias. Large magnetic domains in single-crystal antiferromagnets were imaged by optical methods (*4*) as early as the 1950s. More recently, it has become possible to resolve micrometer-sized antiferromagnetic domains with x-ray spectromicroscopy (*5*), but imaging of domains in technologically important materials with typical grain sizes around 10 nm has remained out of reach (*6*). Heinze *et al.* have now gone a step further, imaging the antiferromagnetic surface structure of a magnetically ordered Mn monolayer with atomic spatial resolution by applying spin-polarized scanning tunneling microscopy (SP-STM), a method pioneered by the authors in the early 1990s (*7*). More than 10 years ago, Blügel *et al.* predicted that such a Mn monolayer would form an ideal two-dimensional antiferromagnet (*8*). But this prediction remained unconfirmed until now, because the magnetic configuration could not be determined by conventional, bulk sensitive techniques like neutron scattering owing to the minute amount of magnetic material contained in a single monolayer.

Unlike conventional magnetic force microscopy, which measures the magnetic dipole force between magnetic sample and



Competing models for the origin of exchange bias at the interface between an antiferromagnet (AF) and a ferromagnet (FM). (**Left**) Coupling by uncompensated moments at steps or grain-domain boundaries generates uncompensated magnetic moments (marked with ovals) on an ideal, completely compensated antiferromagnetic surface. A net coupling results from an imbalance of parallel (red) and antiparallel (green) oriented moments. (**Right**) Spin-flop models assume a 90° angle between the magnetization of the FM and the AF. The moments at the surface of the AF are canted in the direction of the magnetization of the FM (if the coupling between FM and AF is ferromagnetic), leading to the formation of a parallel domain wall. In both models, the ferromagnetic moment at the surface of the AF pins the magnetization direction of the FM, thus causing exchange bias.

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magnetic tip, SP-STM exploits the dependence of the tunneling current on the relative orientation of the magnetization of tip and sample. The magnetic tip acts as a source of spin-polarized electrons, probing the spin-split density of states of the magnetic sample. This technique allows imaging with atomic spatial resolution and, like conventional STM, is mostly sensitive to the topmost atomic layer. The ability to probe topography, crystallography, magnetism, and surface chemistry at the same time renders SP-STM a very powerful tool for the investigation of magnetic surfaces and monolayers. Heinze *et al.* (*1*) now demonstrate that SP-STM can be successfully applied not only to ferromagnetic surfaces (*7*) but also to the compensated surface of antiferromagnets. Using a ferromagnetic tip, the SP-STM image shows a superposition of the crystallographic and the antiferromagnetic structure of the surface. The magnetic contribution even exceeds the effect of the crystallography of the sample. The authors attribute the perhaps unexpected strength of the spin-dependent contrast to the enhanced tunneling intensity of periodic features oscillating with reduced spatial frequency, compared with the lattice periodicity. The larger magnetic unit cell causes a comparatively enlarged tip corrugation, explaining the remarkable sensitivity to the antiferromagnetic structure.

Heinze *et al.*'s approach is generally applicable to the investigation of antiferromagnetic and ferromagnetic conductive surfaces. Its particular strength lies in its unrivaled spatial resolution, allowing the detailed investigation of the magnetic structure inside antiferromagnetic domain walls, at steps, and near impurities or defects. Because of its sensitivity to antiferromagnetic and ferromagnetic order at the same time, SP-STM is an ideal tool for investigating the initial stages of growth of a ferromagnetic material on an antiferromagnetic surface. This may help answer the question whether, and if so how, the magnetic structure of the antiferromagnet is imprinted on the ferromagnet by magnetic exchange coupling, because frustration at the interface between alternating moments in the antiferromagnetic layer and preferably aligned moments in the ferromagnetic layer might cause complex magnetic configurations, e.g., 90° coupling (see the figure) (*9*). The method may also provide valuable information about the role played by steps, surface texture, and surface roughness.

The key strength of Heinze *et al.*'s approach, its extreme surface sensitivity, may also be its only weakness with regard to the investigation of coupling phenomena, because the STM signal primarily originates from the topmost atomic layer. Possible changes in the magnetic configuration of buried layers therefore are hidden from the eye of the observer. It is thus a complementary technique to x-ray spectro-microscopy techniques (*5*, *6*), which because of their elemental specificity and relatively long probing depth (3 to 5 nm) excel at the investigation of layered systems at more modest spatial resolution. However, SP-STM is clearly unrivaled for the investigation of the antiferromagnetic structure of magnetic monolayers, surfaces, or surface alloys, as Heinze *et al.* have compellingly demonstrated.

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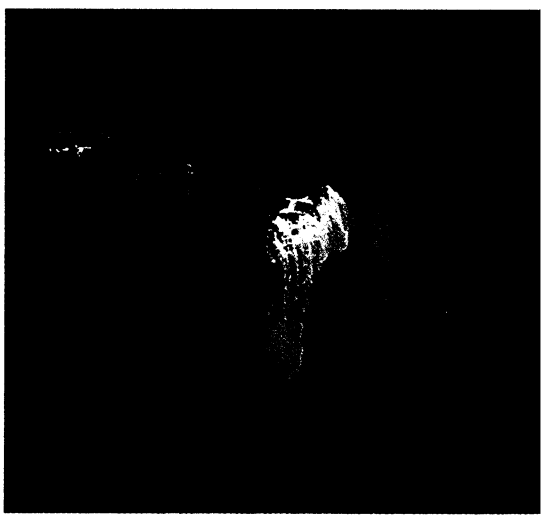
PERSPECTIVES: ENVIRONMENTAL POLICY

Counting the Cost of Deforestation

Robert Bonnie, Stephan Schwartzman, Michael Oppenheimer, Janine Bloomfield

The free market is generally not thought of as an ally of forest conservation. Although societies value forests in myriad ways, traditionally the marketplace has assigned a high value to wood products and nonforest uses of forestland such as agriculture. The marketplace often fails to value the "ecosystem services" that forests provide, such as watershed protection, biodiversity conservation, carbon sequestration and the consequent reduction in greenhouse gas (GHG) emissions. These ecosystem services have enormous value to society (*1*), yet forests continue to be degraded or lost at alarming rates. Currently, 14×10^6 ha of tropical forests are lost annually worldwide (*2*).

Increasingly, forest conservationists have sought to use market economics to protect natural forests from liquidation and conversion to nonforest uses. Examples include ecotourism, certification of wood products from sustainably managed forests, and selling nontimber forest products such as Brazil nuts and mushrooms. In response to global efforts to address climate change, there is increased interest in the benefits of carbon sequestration that accompany forest conservation. Successful marketing of the carbon benefits provided by forest conservation will depend on instigation of international GHG emissions targets such as those contained in the Kyoto Protocol (a treaty of the United Nations Framework Convention on Climate Change). Although such targets have yet to enter into force, investments have already been made in forest conservation projects by energy companies and other industries seeking to secure "credits" for reducing GHG emissions. For example, American Electric Power, PacifiCorp, and BP-Amoco have invested nearly $10 million in the Noel Kempff Mercado Climate Action Project, covering some 600,000 ha of Bolivian rainforest (see the figure). Efforts such as this are a valuable supplement to decreasing fossil fuel consumption, an essential step in the reduction of GHG emissions.



Amazonian rainforest in Bolivia's Noel Kempff National Park.

On page 1828 of this issue, Kremen *et al.* (*3*) demonstrate that the formal adoption of forest carbon markets (as proposed under the Kyoto Protocol) by the international community could dramatically increase incentives for developing nations to protect forests. Using a case study in Madagascar, the authors analyze the costs and benefits associated with preserving a 33,000-ha area of tropical forest (Masaola National Park and surrounding buffer zone) or, alternatively, authorizing large-scale industrial logging. From the standpoint of the local inhabitants and the global community, the financial benefits from designation of the park outweigh those provided by logging. In contrast, at the na-

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