

would then become comparable, within a factor of 10, to microdisks or micropillars.

This unique combination of properties opens several promising avenues for solid-state CQED. For example, in microcavity lasers, the lasing threshold is reached when, on average, one photon occupies the resonant mode. The extremely long photon trapping times (~ 40 ns) observed by Armani *et al.* for toroid microcavities is especially attractive for developing very low threshold lasers. As with microspheres⁵, doping silica toroids with rare-earth ions could lead to optically pumped lasers with a sub-microwatt lasing threshold. Provided this can be done on a semiconductor substrate, such as GaAs, toroid microcavities could also be used to build a fully integrated electrically pumped laser by coupling the resonator to a nearby semiconductor emitter, such as a collection of quantum dots. Simple estimates show that lasing could be achieved at room temperature with a much smaller threshold current (perhaps only 10 nA) than that achieved¹⁰ by the best vertical-cavity surface emitting lasers (30 μ A). Such sources would be very interesting for remote optical sensing, especially in an environmental or biomedical context. Low-threshold lasing and non-linear effects could also revive studies into optical computers, which were halted because the power required to operate elementary logic gates could not be scaled down.

At a more fundamental level, single quantum-dot lasing is now also within reach, provided temperatures typically lower than 50 K are used (at higher temperatures the quantum dot emission broadens spectrally, which reduces its coupling to the mode). Such a laser could display an even lower threshold

current, in the picoampere range¹¹, together with other unusual effects, such as self-quenching and blinking. At temperatures as low as a few kelvin, single quantum dots could enter into a strong coupling regime, in which the emitted photon is trapped for such a long time in the cavity that it can be reabsorbed and reemitted by the quantum dot. Thanks to their small V , semiconductor microcavities¹² and microspheres, coupled to quantum dots, are close to demonstrating the strong-coupling regime, although they have various problems to overcome. Small toroidal microcavities in the 10 μ m diameter range would represent a much better compromise between Q and V figures of merit to address this issue. Observing a strong coupling regime for single quantum dots would be a significant breakthrough in the field of quantum information processing. For example, potential quantum computers using quantum dots as qubits could use resonant coupling to a cavity mode to mediate interactions between distant quantum dots, and realize the two-qubit gates necessary for their operation¹³.

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SHAPE-MEMORY ALLOYS

Combinatorial high jinks

A new strategy for mapping the mechanical and magnetic properties of thin films has been used to discover ferromagnetic shape-memory alloys with previously unknown compositions. The results provide new insight into an underlying composition–structure–property relationship of the Ni–Mn–Ga system.

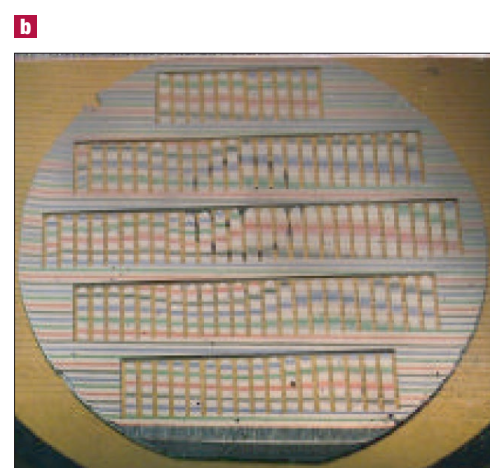
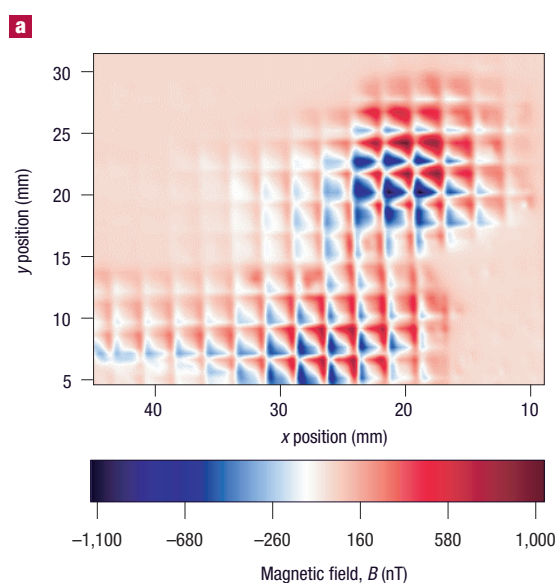
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Combinatorial materials science¹ — the systematic study of material properties as a function of composition — was first introduced systematically in the search for new pharmaceutical drugs. Since 1995, it has also been applied successfully to a range of

functional materials, with luminescent, superconducting or dielectric properties². Usually, many small samples, differing slightly in composition, are deposited by an automatic computer-controlled method and then characterized, again by an automated method. (An alternative name for this approach is ‘high-throughput screening.’) For screening of physical properties and to determine ternary phase diagrams, thin films deposited by sputtering in ultra-pure argon are generally preferred. Mechanical properties have also been studied,

Figure 1 The novel screening techniques used by Takeuchi *et al.*⁴ to study the magnetic and shape-memory properties of the Ni–Mn–Ga composition spreads. **a**, Scanning SQUID image of a part of a Ni–Mn–Ni₂Ga₃ spread wafer. The spread is patterned into arrays of 2 × 2 mm square grids so that variation of magnetization in in-plane magnetized samples can be detected. **b**, A photograph of a Ni–Mn–Ni₂Ga₃ spread deposited on a micromachined cantilever library. The lines are a reflection by the cantilevers of an image with coloured lines. The martensitic transition can be detected by a shift in the position of the lines as the local curvature of each cantilever changes.



but hitherto only with massive samples prepared by interdiffusion³. In a remarkable study published on page 180 of this issue⁴, the thin-film approach has been used to measure both the mechanical behaviour and ferromagnetic properties of a range of ternary alloys in the Ni–Mn–Ga system.

The Ni–Mn–Ga alloys examined in this study are ‘multiferroic’. A ferroic material is one that can switch between two conditions, such as ferromagnetic and paramagnetic or deformed and undeformed. A multi-ferroic material shows two or more such properties, linked causally. The Ni–Mn–Ga alloys are shape-memory alloys (SMAs): materials that can be substantially deformed by a localized stress-induced phase transformation (the martensitic transition), and then returned to their original shape by heating. The so-called Heusler composition, Ni₂MnGa, is a well-known SMA that is also ferromagnetic. When an SMA is ferromagnetic, shape-memory effects can sometimes be induced by an applied field, and this offers the prospect of novel applications.

Takeuchi and co-workers wished to discover how many other compositions in the Ni–Mn–Ga system — aside from Ni₂MnGa — showed both ferromagnetic and shape-memory properties. To achieve this without extravagant investment of time and money, high-throughput screening methods capable of accurately measuring the relevant properties in very small specimens (of the order of 1 mm²) had to be found. Takeuchi and co-workers have done this twice over. They have developed rapid characterization techniques to measure both the magnetic and mechanical properties of their Ni–Mn–Ga thin films (Fig. 1). Their results show that these two properties are highly correlated across a large region of the phase diagram.

First, they used a scanning SQUID (superconducting quantum interference device) microscope recently described by Fleet *et al.*⁵. This allows accurate measurement of the magnetic field (and thus local magnetization) at the surface of a single 2 × 2 mm sample in a combinatorial array. Second, the authors

used an ingenious technique to detect a structural phase transition in the thin films⁶. Here, a ‘spread’ of compositions is deposited in the form of thin films on tiny silicon cantilevers, which are then progressively heated while under observation. When the SMA undergoes a phase transition from the martensitic to the austenitic form, the cantilever bends. Because the cantilever with the deposited metallic film acts as a concave mirror, the phase transition can be simply detected by a sudden change in reflection resulting from the changing radius of curvature of the ‘mirror’. This method permits simultaneous measurement of the martensitic transformation temperatures of an entire array of Ni–Mn–Ga compositions.

Figure 1a shows an image constructed from measurements with the SQUID device, together with a colour calibration that indicates the magnitude of the magnetization in each sample in the spread. The Curie temperature of each sample was also determined and found to be proportional to the strength of magnetization. Figure 1b shows a number of coated silicon cantilevers together with a reflected optical image (in the form of an array of coloured lines), showing a gradual increase in bending angle (and thus a change in martensitic transformation temperature) from one side of the array to the other.

Using these novel measurement methods, the authors covered a large portion of the ternary phase diagram and found that the strongest magnetization and highest phase transition temperatures (implying the most pronounced SMA function) were both found well away from the traditional Heusler composition, Ni₂MnGa. Moreover, the authors found a linear relationship between the martensitic transition temperature and room-temperature magnetization — the higher the magnetization, the lower the transition temperature. This behaviour shows that there is a strong coupling between SMA behaviour and ferromagnetism over a large range of compositions.

From an applications point of view, the goal in the search for novel ferromagnetic SMAs is to find

compositions with both a high Curie temperature (and thus increased room-temperature magnetization) and a high martensitic transition temperature. This study clearly shows that there must be a trade-off between these two properties, and moreover, that the Heusler composition does not necessarily provide the optimum combination of properties. The highly ingenious characterization methods developed for this study constitute the most important aspect of the work, and open the way to further combinatorial studies of other alloy systems.

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MATERIAL WITNESS KEEPING ART ALIVE

Field for the British Isles, by contemporary artist Antony Gormley, which I saw recently, is a wonderful sculpture: accessible, resonant and poignantly

beautiful. But it must be a curator's nightmare. All those thousands of little terracotta figures, as brittle as prehistoric pots — how many relocations will they survive?

At least museums and galleries have plenty of experience with terracotta. Gormley, like many modern sculptors, has often been experimental with his materials, throwing up challenges that never faced the conservators of stone and bronze statuary.

Take his early work *Natural Selection* (1981). Here are 24 objects, some natural, some man-made, each encased in lead. There is a pea, a banana, a goose egg, a grenade, a light bulb, a coconut. Lined up in ascending size, they present a study in the evolution of form and the relationship of natural to artificial.

Why lead? “It is the best possible material”, Gormley has said, “It’s the most female metal, the most malleable and the densest.” (Wait till he gets hold of osmium!) But although Gormley also likes lead’s “impenetrability”, his casings proved not quite as impermeable as he’d hoped.

The objects containing fruits and vegetables soon started leaking, forcing Gormley to unsolder the seams and dry the organic contents before resealing them. The goose egg started emitting the unpleasant rotten odour of hydrogen sulphide. The casing was cut apart and the eggshell cleaned.

As the sculpture’s conservators pointed out, Gormley’s prized impenetrability of lead prevented them from using X-rays to study the state of the casings’ contents non-destructively. The coconut was a particular problem: its organic acids were corroding the metal, and the conservators at the Tate Gallery in London were compelled to seek safety advice from the Natural History and Science Museums.

The coconut proved to have produced a thick layer of basic lead carbonate inside its casing. The shell was carefully sawn in half, cleaned and chemically treated. (All concerned were determined that the original objects should not be replaced by new ones.) The pitted lead was filled with polyester resin coloured with graphite. When not on display, the work is now stored in a sealed, desiccated container.

The issues that arise in conserving modern sculptures like this are quite different from those for older works. “No-one knows what an ancient sculpture looked like when first made”, conservator Jackie Heuman points out. Moreover, ageing of old materials, like the patination of bronze, may be aesthetically pleasing, as well as providing a record of the history of the work.

Restoration of modern works is often much more radical. Sometimes they are entirely remade, as was the case for Naum Gabo’s *Linear Construction No. 2*, made from strung nylon threads that slackened when the work was rehung in 1970. Gabo, one of the first to use plastics in his sculpture, accepted such problems as the price of innovation. “The genesis of a sculpture is determined by its material”, he said, adding “there is no limit to the variety of materials suitable for sculpture.”

PHILIP BALL

