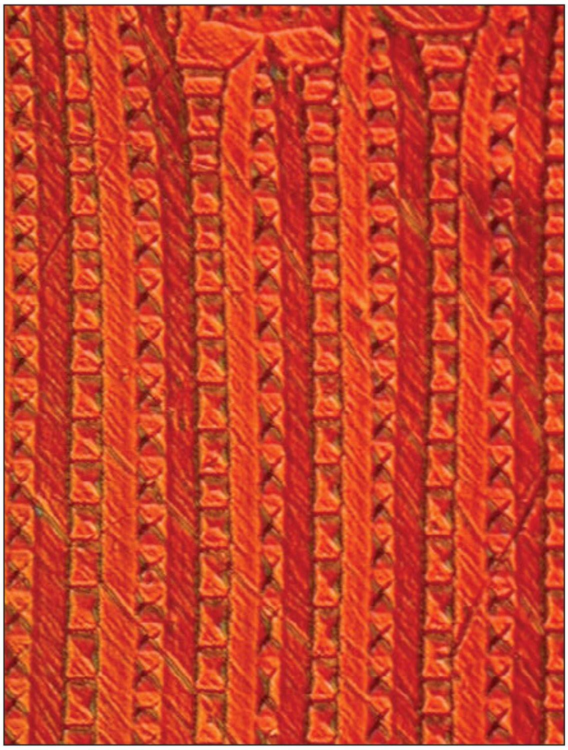
Non-Joulian magnetostriction revealed in Fe-Ga alloy

Large non-volume conserving magnetostriction has been discovered in iron-gallium magnets. This paradigm-shifting discovery was made by Harsh Deep Chopra at Temple University and his collaborator Manfred Wuttig at the University of Maryland, and published in the May 21 issue of *Nature* (DOI:10.1038/nature14459; p. 340). The researchers have termed this "non-Joulian magnetostriction" to distinguish it from the volume-conserving "Joule" magnetostriction discovered by Joule in 1841.

When a magnetic field is applied to a conventional ferromagnet, the internal magnetic domains rotate to align themselves along the direction of the field. This re-magnetization process also causes the dimensions of the magnet to change while conserving its volume. Thus, while the magnet expands along one direction, it simultaneously contracts along transverse directions. This phenomenon—which is known as Joule magnetostriction—is responsible for the humming sound of transformers and, importantly, is the basis of many actuators, ultrasonic devices, sonars, medical, and defense applications. The uniaxial extension of Joule magnetostriction also implies that simultaneous actuation in mutually perpendicular directions requires complicated stacked composites.

Chopra and Wuttig were studying the magnetostrictive behavior of recently discovered Fe-Ga alloys using disk-shaped single crystals when they observed that the magnets did not seem to be contracting along any direction. Their investigation showed that the magnetic alloys had several other anomalous features—linear and non-dissipative magnetization, unconventional directions of easy magnetization, and a unique magnetic domain structure. As shown in the Figure, the crystals have alternating parallel bands of highly periodic domains that are divided into regular rectangular cells. Significantly, each cell behaves as an autonomous magnetic and elastic entity and does not contribute to any long-range magnetic or elastic effects. This is different from the domain structure ordinarily present in ferromagnets, and the researchers have labeled these cells "autarkic."

"Our findings fundamentally change the way we think about a certain type of magnetism that has been in place since 1841. We have discovered a new class of magnets, which we call 'non-Joulian magnets,' that show a large volume change in magnetic fields," Chopra said in a communication to *MRS Bulletin*.



Cellular domains in non-Joulian Fe-Ga magnets. Figure courtesy of Harsh Deep Chopra/Temple University.

With this unusual domain structure the researchers could explain all the observed magnetostrictive effects in Fe-Ga alloys using a simple "rule of mixture for cells." A given cell can only be along one of two mutually perpendicular crystallographic directions (x and y). When the field is along one of these directions (say x), all the cells are aligned parallel to it, leading to a large magnetostriction along this direction. The autarkic nature of the cells means that each cell can orient itself independently of its neighbors. Thus, when the field is along a mixed direction, some cells that were initially along the x direction abruptly switch to the y direction causing the domain structure to be a mixture of perpendicular cells. Maximum magnetostriction therefore occurs only along these specific "easy" directions, which is opposite to what is observed in other ferromagnets. The abrupt non-rotational alignment of the cells with the unusually low anisotropy energies leads to magnetization curves that are non-hysteretic and direction-independent. The autarkic cell structure along with the rule of mixture of cells therefore accounts for all the anomalous features of non-Joulian magnetostriction.

Siva Guruswamy of The University of Utah, whose team developed the Fe-Ga alloys that form the basis of this discovery, called this work "groundbreaking." In a communication with *MRS Bulletin*, he further said that "against conventional wisdom, Professors Chopra and Wuttig demonstrate the existence of a significant volume change due to magnetization and accompanying magnetostriction in these alloys, contrary to the Joule magnetostriction model used for well over a century."

Jayasimha Atulasimha of Virginia Commonwealth University remarked on the "simple and elegant explanation for the hysteresis-free and linearly reversible behavior of these alloys." Richard James of the University of Minnesota wrote in an accompanying editorial in *Nature* that "this may help unravel the mystery of the phenomena of magnetic hysteresis." Given that magnets are the main components of electric motors, generators, energy harvesting, and power distribution systems, this result might prove to be a very important milestone.

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