Micro-Magnets plug size / strength gap – Neodymium magnets up to 2 T and up to 100 μm

- Filling the gap in NdFeB magnets between thin films and bulk production
- Small, powerful magnets ~ 50 μm thick, $\mu_0 M_r$ ~ 1.25 T, $\mu_0 H_C$ ~ 2 T
- Reduced material costs
- Reduced RE requirement

Prototype thick film NdFeB magnets currently being produced by the Institut Néel have similar properties to those created by bulk processing of sintered magnets, are capable of fields up to 2 T, but are less than 100 μm thick. Magnets of this size have tremendous potential in small and micro-scale components, systems, devices, and other miniaturisation applications.

Those aren't twigs, they're chains of micro-magnets. And yes, that's an insect.

At the risk of stating the obvious, thick film 'micro-magnets' are manufactured using similar deposition processes to thin film magnets, rather than the compression and temperature-based processes used to manufacture bulk magnets. This enables the creation of magnets smaller than are possible using bulk processes, filling the size / strength gap between deposition and bulk processing and opening up opportunities to use neodymium magnets in applications hitherto thought impossible.

Applications for micro-magnets are many, such as miniature high precision devices with actuator or sensor functions, where a magnet smaller than one possible by 3D printing would be an advantage, such as mobile phone image stabilisation or loudspeakers, or in-motor sensors.

The physical benefits of getting smaller

If a magnet's extrinsic properties are preserved as its physical dimensions are scaled down, the gradient of its external magnetic field gradient is scaled up.

Magnetic interactions can benefit from a scale reduction. Two defining characteristics of a permanent magnet are its coercivity and the strength of its external magnetic field, which is proportional to its remanence. Both coercivity and remanence are extrinsic properties, whose values are determined by the magnet's intrinsic properties and by the magnet's internal structure (size, shape and orientation of main-phase grains, grain boundary phases, etc), dictated by how it is fabricated.

The force of interaction between a magnet and another object is proportional to the gradient of its external magnetic field. If a magnet's extrinsic properties are preserved as its physical dimensions are scaled down, the gradient of its external magnetic field gradient is scaled up. As a result, the magnetic field gradient force per unit volume can be increased by orders of magnitude in micro-scale systems compared to macro-scale systems.

In other words, micro-magnets are relatively much more powerful than bulk manufactured NdFeB, but the effective field is also relatively much closer to the magnet. This could produce a positive spiral effect, where the physically smaller the magnet, the more effect it has, driving a reduction in the physical size of the device.

Other bonuses include the fact that smaller magnets require less material for the same effect, leading to cost reduction in materials and less reliance on RE.

Method of Manufacturing	Thickness (μm)
Thin Film deposition (standard)	up to 0.1
Thin Film deposition (maximum)	up to 10
Thick Film deposition	50 - 100 under investigation at Institut Néel
3D Printing	100 +
Bulk	500 +

Manufacturing methods and achievable magnet thicknesses

Micro-scale manufacturing

Over the years many methods have been developed to make micromagnets, each of which provide good results but also suffers from a moderate or major drawback:

- electroplating of CoPt, screen printing of bonded powders are very well adapted to microfabrication, but the resulting magnetic properties are relatively poor
- sputtering, pulsed laser deposition, low pressure plasma spraying, or direct sintering give excellent magnetic properties, but either the thickness of the deposited layer is too thin or the process is too difficult to adapt to microtechnology and batch fabrication due to high deposition temperature, chemical pollution, slow deposition rate, or small deposition surface.
- machining of sintered NdFeB or SmCo bulk magnets (to a lower limit of a few hundred μm) leads to surface degradation, resulting in a loss of coercivity, and significant material waste, while the manipulation and integration of small free-standing magnets is challenging.

Researchers at Grenoble’s Institut Néel created a breakthrough by using high-rate triode sputtering to lay down NdFeB deposits on a supportive silicon substrate. This produces high coercivity and high remanence NdFeB films of thickness up to 50 μm, on silicon wafers of diameter 100 mm (Fig. 1). These films can be patterned (ie shape the finished micro-magnets) using standard clean-room facilities such as photo-lithographic patterning and deep reactive-ion etching of the substrates prior to deposition of the magnetic layer, wet etching, and chemical mechanical planarisation.

The substrate could be part of the final device, but as the deposition process can involve high temperatures, it could damage temperature-sensitive elements on the substrates. The solution Institut Néel plans to work on is to build films robust enough to transfer from a manufacturing substrate to a final device substrate once cooled.

The size, shape and disposition of the micro-magnets can be adapted to suit specific applications. The fact that they are substrate-mounted greatly facilitates integration into complex micro-devices, and the use of large substrates allows for batch fabrication.

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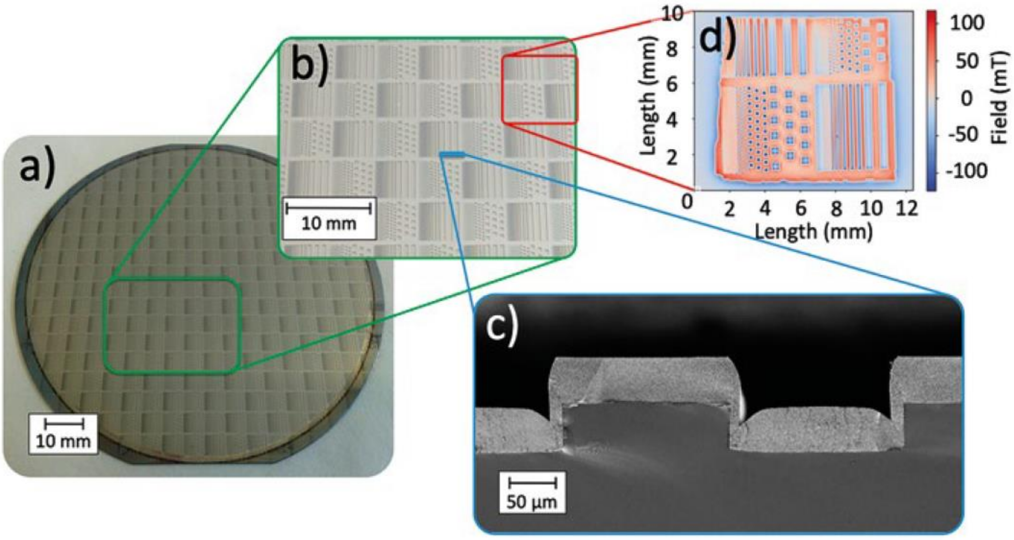

(a, b) Plane-view optical images of a 50 µm thick NdFeB film deposited on a pre-patterned 100 mm Si substrate together with (c) a cross-sectional scanning electron microscope image of a few micro-magnets and (d) a Magneto-Optical image of the stray magnetic field produced by a part of the film.

Current applications & magnetic functions offering potential applications

Small scale magnets are already well established in commercial products such as HDD read heads, fluxgates, transmission coils, ABS sensors, etc. However, only a handful of thick film magnet laboratory-developed prototypes have been developed, including RF microswitches for mobile phones, read/write heads and micropositioners, matrixes of optical microcommutators for fibre optic networks, micromotors for noninvasive surgery and microrobotics, micropumps and microvalves for lab-on-chip and micro-fluidic devices, electrical microgenerators for autonomous power supplies, micromirrors for adaptive optics, magnetic suspensions for hard disk drives, etc.

The physical properties of thick film magnets already mentioned offer many commercial benefits and opportunities:

- **Permanent Forces—Bistability Suspensions**

  Permanent magnets provide constant magnetic fields. This means that simple or bistable permanent latching forces can maintain a system in a given configuration without the need for energy consumption. As well as energy savings, this offers excellent safety guarantee in the case of power failure.

  Such permanent forces can also be implemented into passive magnetic suspensions / bearings, providing frictionless support.

- **Long-Range Actuation**

  Magnetic fields and gradients can be effective over long distances relative to the size of the magnet, allowing for example large-throw and / or wide-angular actuators.

- **Contactless Remote Actuation**

  Contactless magnetic interaction allows remote actuation through sealed interfaces. This not only enables wireless actuation but also allows vacuum packaging of resonant systems. It also means a magnet can be added to a system without needing to be integrated within the system, simplifying fabrication. Finally, interaction from within a sealed component makes magnetic actuators very well suited to harsh environments.

- **High Actuation Speeds**

  Because of their reduced size, most micro-actuators are characterized by very high speeds. In actuation mode, for a given force, acceleration is proportional to the mass of the mobile element. Thus micro-actuators have very fast response times, often in the range of 1 to 100 μs.

  In physical terms, maximum admissible rotational speeds are limited by the radius of the rotating element and by the material's mechanical strength. Operational speeds in the range 10^5 - 10^6 r/min are commonly achieved in MEMS.

  Inductances and electrical energy levels involved are very low. This means that in electronics, very high frequency control circuits can be built.

- **Exotic modes of actuation**
  - thermal demagnetisation of a thermomagnetic material can be very fast in microsystems;
  - magnetic "reprogramming" of semi-hard materials by demagnetisation and remagnetisation;
  - strain-induced modulation of the magnetization of a magnetostrictive material by hybridisation with a voltage actuated piezoelectric element.

Institut Néel's technology is proven – it has been used in a range of bio-medical applications, in the framework of collaborations with various laboratories, and the team have already developed prototypes with a company under commercial confidentiality. They're currently working with collaborators on demonstrators they can show publicly by summer 2021. These will be energy harvesting devices, one using thermal management and the other mechanical vibrations to generate electricity.

They are also working on a "maturation" project with the local technology transfer incubator SATT - Linksium to explore the market potential and find new industrial partners and clients of a future start-up.

As the global drive for smaller, more capable devices continues, Institut Neel's micro-magnet technologies and capabilities are well placed to provide the key component and fill the manufacturing gap in magnet size / strength.

For more information

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Reference

"Magnetic Micro-Actuators and Systems (MAGMAS)", IEEE TRANSACTIONS ON MAGNETICS, VOL. 39, NO. 5, NOVEMBER 2003, Orphée Cugat, Jérôme Delamare, and Gilbert Reyne (PDF Link)

About the UK Magnetics Society

People involved with the UK Magnetics Society believe that magnetism in all its forms is an amazing force, and that by understanding and harnessing it people can deliver amazing things. We are called the UK Magnetics Society, but only because we started there. There are no limits to members, delegates, events or content – as our resources allow, we always have and always will engage worldwide, supporting magnetics professionals in all fields or countries, and in industry, government and academia.

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