coatings is still in its early stages. Future chapters will focus on the challenge of reducing thermal noise, without degrading optical absorption.

In the years since Advanced LIGO was constructed, new studies have provided better understanding of how tantala bond angles change when doped with titania. According to Harry, it is only recently that "we're starting to understand what's going on and how we get mechanical loss."

Scientists are investigating new materials as well as titanium doping, using different percentages to maintain optical performance while improving thermal noise. If they can achieve a higher refractive index, they could reduce layer thickness. "If we can reduce total thickness, we can reduce loss," Pinard says.

Silica and tantala offer sufficiently low mechanical loss to meet LIGO's current sensitivity requirements. But future designs might involve more than two materials, perhaps using a low absorption stack on top of the mirror and a low mechanical loss substance, such as amorphous silicon, near the bottom. Nanolayered amorphous glassy oxide composites could exhibit better mechanical and optical properties, and use cryo-friendly materials like hafnia and titania.

And while amorphous oxides are conducive to achieving uniform coating over a large surface, "you wouldn't want to go with amorphous [oxides] if you designed a new, low-loss coating from scratch," Harry notes. If a technique could be developed for growing a uniform crystalline coating on unprecedented large surfaces, aluminum gallium arsenide (AlGaAs) is one potential candidate. Macroscopic quantum mechanics experiments that use optical cavities, albeit with sub-mm diameter mirrors, have achieved good results using AlGaAs coatings. The material is now sold for low thermal noise coatings for precision timing experiments.

Another possibility builds on optical filters with dielectric coatings whose refractive index is varied continuously through graded materials, rather than in steps through interfacial layers. "This opens many possibilities in materials science as a means of reducing both scattering and mechanical noise, yet is based on ideas pursued in the past for coatings using techniques other than ion-beam sputtering," Netterfield says.

Future gravitational-wave observatories could use different designs such as silicon test masses or cryogenically cooled optics. Larger interferometers would also increase signal-to-noise ratio for gravity waves; and future detectors could use different lasers, making way for materials with demonstrated optical properties at other wavelengths.

LIGO's next observation run is scheduled for this Fall, and will commence using the same mirrors and coatings as when LIGO made headlines earlier this year. This time, the two US-based interferometers will be joined by the Virgo interferometer in Pisa, Italy, for the first common data-collecting period with all three instruments operating at improved sensitivity levels.

In the longer term, discussions about thermal noise center around mirrors with lower-loss coatings. Because interferometers detect the amplitude of a wave, a factor of two reduction in thermal noise would translate to a factor of eight in detection rate.

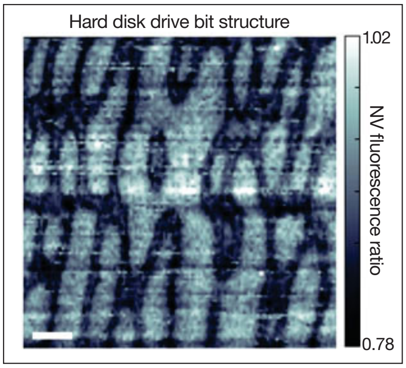
Better understanding of coatings that will not jeopardize optical properties has great potential to improve LIGO sensitivity. "It helps to get the word out about the problem to the materials community," Raab says.

Nano Focus

Researchers take diamond defect to new depths in magnetic imaging

Nitrogen-vacancy (NV) centers are a rising star in the field of high-resolution magnetic imaging. Stable enough to capture condensed-matter phenomena at room temperature, these versatile, atom-sized defects are now soaring to new heights in the magnetism community—and descending to new depths. Research groups led by Ania Jayich from the University of California, Santa Barbara, and Patrick Maletinsky from the University of Basel in Switzerland, have independently developed NV-based sensors that can resolve nano-sized magnetic features at temperatures as low as a few degrees above zero Kelvin. With these sensors, condensed-matter physicists now have access to a wider range of magnetic imaging temperatures.

"There's been a big push toward low-temperature operations because there is a lot of very exciting electronic systems that exist at low temperatures," says Maletinsky, assistant professor of experimental physics. "Graphene, quantum Hall effects, spin Hall effects—there's a big variety." For Maletinsky, who has been pushing the limits of NV-based imaging since his days as a postdoctoral researcher at Harvard University, his group's most recent advance, published in *Nature Nanotechnology* (doi:10.1038/NNANO.2016.63), represents an important technological breakthrough.



Nitrogen-vacancy (NV) magnetometry image of the bits of a hard disk at $T = 6$ K. Dark features correspond to the 5.3 G magnetic field contours (2892 MHz RF field). Scale bar, 100 nm. Credit: *Nature Nanotechnology.*

NV centers are naturally occurring defects in diamond that consist of a substitutional nitrogen atom and a neighboring lattice vacancy. In the laboratory, NV centers are created by ion implanting nitrogen atoms in a piece of diamond, knocking carbon atoms out of place in the lattice. Each implanted nitrogen atom and associated vacancy together behave as a single quantum spin. This allows scientists to track the energetic signature of an individual NV center (indicated optically by fluorescence) in response to a magnetic field across a sample. The atomic size and quantum behavior of NV centers have allowed scientists like Maletinsky to measure magnetic fields with nanoscale resolution. And because this sensitivity is preserved under ambient conditions, NV centers can be used to detect tiny magnetic fields in materials ranging from high-temperature superconductors to living cells—materials closed off to cold-temperature technologies such as superconducting quantum interference devices (or SQUIDs) and magnetic resonance force microscopes.

At cryogenic temperatures, however, the tables are turned. NV-based sensors have never been shown to operate under such cold conditions.

Maletinsky's team addressed this problem by immersing their room-temperature NV sensor in a liquid-helium cryostat, allowing them to plunge to an operating temperature of about 4 K. The low tendency of helium to boil, Maletinsky says, allows their system to be very "quiet," a key priority when the sensor is a single quantum spin nestled in a diamond nanopillar welded to the tip of an atomic force microscope.

With this system, the research team could quantitatively image the stray field emanating from magnetic vortices across a sample of $YBa_2Cu_3O_{7-\delta}$, a high-temperature superconductor known to form these quantum defects when cooled below its transition temperature (about 89 K) under an applied magnetic field. More importantly, the research team was able to extract a notoriously elusive measure known as the London penetration depth, which describes how far a magnetic field penetrates into a superconductor.

The key to making such highly sensitive, high-resolution measurements, Maletinsky says, is how close the delicate NV sensor can be brought to a sample surface. "Tip-to-sample distance is the crucial figure of merit in these experiments."

Ania Jayich would agree.

An assistant professor in the Physics Department, Jayich leads a group who published their own work on cryogenic NV-based sensing concurrently with Maletinsky's team in *Nature Nanotechnology* (doi:10.1038/NNANO.2016.68).

"High spatial resolution is possible because our sensor is so small," Jayich says. "But the sensor is ultimately limited by the distance to the sample, not its size."

And herein lies a significant challenge for researchers like Jayich and Maletinsky. A shorter tip-to-sample distance should mean higher sensitivity. But because one quantum phenomenon is being used to detect another, at short distances, sample surface effects can compromise the "quantumness" of a NV center, as Jayich puts it. "It's a problem that plagues almost all quantum technologies," she says. "Quantum behavior is very delicate and very sensitive to its environment."

Within these limits, however, Jayich's group resolved magnetic domains smaller than 100 nm in a hard disk using their NV-sensing system, which is unlike that developed by Maletinsky's team.

Instead of a single diamond pillar, Jayich's group glues an entire array of pillars to their scanning tip, producing a micro-hairbrush structure. This arrangement makes it difficult to precisely control how close a NV center on a single bristle reaches a sample surface. However, it allows the researchers to produce several NV centers at once and choose the brightest and most stable one for imaging. The structure also holds promise for conducting wide-field experiments in which multiple NV centers can be optically addressed to quickly scan across large areas. But this and other improvements to NV-based imaging, some argue, may not come until much later.

Eli Zeldov, a professor at the Weizmann Institute of Science in Rehovot, Israel, acknowledges that NV-based sensors have made significant progress within the last few years, with a performance ceiling on par with that of the nanoSQUID imaging technology he has helped pioneer. Nevertheless, he argues that NV-based sensing currently remains a relatively slow and complicated technique, both in fabrication and in operation.

"It requires microwaves, it requires optics, it requires very delicate equipment," Zeldov says. "It's tricky. This can improve with time, but there's still quite a lot of room for improvement."

But for NV researchers like Jayich and Maletinsky , there may be no time like the present.

"We have established this system that already has really good sensitivity, excellent spatial resolution, and is quantitative," Maletinsky says. "I think now we're in a position where we can demonstrate very meaningful applications with the performance we already have."

Omar Fabian

Kirigami honeycomb material exhibits a "Poisson's switch"

The ancient Japanese art of origami that uses strategic folding has found many interesting technological applications such as the Miura-Ori method for folding/unfolding antennas in satellites. Perhaps less known is kirigami where, in addition to folding, cutting is also allowed. Kirigami has also been a subject of intense scientific investigation, not least because several natural systems such as bird wings have periodic polyhedral designs that could easily be reproduced using kirigami techniques.

Robin Neville, Fabrizio Scarpa, and Alberto Pirrera, from the University of Bristol, UK, report how a class of kirigami cellular materials show large shape and volume deformations that could find potential applications in many shape-morphing materials. The researchers start with a flat sheet of poly ether ether ketone—a thermoplastic polymer. A pattern of slits is cut into the sheet, which is then corrugated and folded repeatedly to give a honeycomb architecture. The ease of this method allows the process to be applied to many starting materials and to be automated. By varying a small number of initial parameters such as the