Bose-Einstein Condensate Experiments Lead to Nonlinear Atom Optics and Directional Atom Laser

Through their experiments with the Bose-Einstein condensate, physicists of the Laser Cooling and Trapping Group in the Physics Laboratory at the National Institute of Standards and Technology have recently stepped through a threshold to the field of nonlinear atom optics as well as demonstrated a highly directional atom laser.

To create a Bose-Einstein condensate, the Laser Cooling and Trapping Group, led by Nobel laureate William D. Phillips, created a dense cloud of sodium atoms cooled to very near absolute zero in which all the atoms fell into their lowest possible energy states and became indistinguishable from one another. As described in the March 18 issue of *Nature*, the scientists pulsed beams of laser light with predetermined directions and frequencies onto the condensate, thereby splitting it into three distinct, intense matter waves. Each matter wave had a unique velocity and direction. The scientists applied the same rules governing light to determine the necessary velocities and directions to mix the three matter waves so they would form a fourth. As anticipated, the interaction of these matter waves produced a fourth matter wave with the properties the scientists had predicted.

Phillips said, "Calculations by theorists Paul Julienne, Marek Trippenbach, and Yehuda Band showed it should be easy to do. The theory pushed us in a new direction of investigation. We found a nice agreement between their theory and our experiments. Up until the early 1960s, people thought all properties of light could be explained by the classical theories covering electromagnetic fields. Then researchers began to understand that light could exhibit strange quantum behavior. Nonlinear optics has been key in the development of quantum optics, which explores such behavior. We can now look forward to the analogous development of quantum atom optics." Another possible application is the amplification of matter waves, making a beam of atoms more intense by creating additional atoms that are exact copies of those in the original beam.

In another project, published in the March 12 issue of *Science*, the physicists aimed two optical lasers at the Bose-Einstein condensate (also made of sodium atoms), one from the left side and one from the right. The atoms absorb photons from one laser beam and emit photons into the other laser beam. This process transfers momentum to the atoms and forces them in the direction of one of the laser beams.

In order to select the direction of the atom laser beam, the scientists tune the optical lasers to slightly different frequencies. The atoms preferentially absorb photons from the higher frequency laser and emit them into the lower frequency one. Therefore, they move in a single direction, toward one laser and away from the other.

Although the atoms gain momentum from the laser beams, they are still held in the trap by the magnetic field. In order to free the atoms, the scientists change the atoms' orientation so they are no longer attracted by the magnetic field used to confine them. Reorienting the atoms requires energy, which scientists provide by increasing the difference between the frequencies of the optical lasers.

By pulsing the lasers very quickly, the scientists are able to overlap the small clumps of atoms that are knocked out of the trap with each pulse, effectively making a continuous beam of atoms. By varying the intensity of the laser light, the scientists are able to create atomic laser beams of varying intensities at the chosen direction and speed.

Since this atom laser removes atoms from a Bose-Einstein condensate containing a finite number of atoms, it eventually runs out of atoms. For a continuous atom laser, scientists would have to find a way to replenish the atoms in the Bose-Einstein condensate while removing the atoms that make up the atom laser beam.

This atom laser is very well collimated, that is, the atoms streaming out of the Bose-Einstein condensate remain as a very narrow beam. The atom beam is about 60 μm wide and travels at about 6 cm/s.

Ion-Assisted Deposition Facilitates Copper Metallization of Densely Packed Chips

Othon Monteiro of Lawrence Berkeley National Laboratory has devised a way to inlay copper wires in the semiconductor wafers used to create integrated circuits. In the May/June 1999 issue of the *Journal of Vacuum Science and Technology B*, Monteiro discusses his method of "ion-assisted trench filling," opening the way to more densely packed chips. A National Technology Roadmap issued by the Semiconductor Industry Association predicts that new lithography methods will reduce features of the smallest chips which are already as fine as 250 nm, to 180 nm in 1999 and to 100 nm by 2006, making it possible to pack hundreds of millions more electronic devices on a chip. Many of these microscopic devices must be interconnected by metal wires, which are made by filling tiny trenches in the surface of the semiconductor wafer. Multiple levels are connected by penetrating a layer to make contacts with layers above and below. The standard material of such wires has long been aluminum or aluminum alloys and, in interlayer connectors, tungsten. "As device sizes get smaller, the electrical properties of aluminum will not meet the new requirements," said Monteiro, a materials scientist in the Plasma Applications Group of Berkeley Lab's Accelerator and Fusion Research Division. "We need lower resistivity and greater resistance to electromigration. We also need something that's compatible with lower dielectric-constant materials," which have been introduced by chip manufacturers to improve insulation and reduce circuit delays.

According to Monteiro, copper is much more conductive than aluminum, allowing finer wires with lower resistive losses. Copper is also significantly less vulnerable to electromigration than aluminum and less likely to fracture under stress. Unfortunately, "copper is poisonous to silicon," Monteiro said. "It readily diffuses into silicon and causes deep-level defects."

Less than two years ago the first commercial copper-wired chips were announced by IBM and Motorola. To keep the copper from migrating into the dielectric and poisoning it, a diffusion barrier was used, which lined the trench walls between the copper and the substrate. Motorola used titanium nitride as a barrier. Other possible barrier materials include tantalum, tantalum alloys, and tantalum nitride. IBM and Motorola produced their copper-wired chips by electroplating the copper over the diffusion barrier. Although Monteiro's ion-assisted technique can be used either in conjunction with electroplating or by itself, it has several advantages over electroplating. It can produce thinner, more uniform layers of metals in a variety of architectures. It can be used in narrower trenches with higher depth-to-width aspect ratios. It can fill trenches from the bottom up, automatically eliminating uneven deposition that can lead to voids in the metal lines, or it can produce conformal thin films that mirror the shape of the patterned wafer.

To employ the technique, a substrate wafer etched with trenches is placed under a plasma source. A pulsed-bias voltage is applied to the substrate and can be tuned to accelerate ions toward both the sides and bottom of the trench—in which case a layer builds up evenly—or preferentially to the bottom, filling the trench from the bottom up. The process is terminated when the precise desired thickness of the material has been applied. Films consisting of multiple layers are readily deposited using different cathode materials—copper, tantalum, tantalum nitride, and a variety of other materials can be applied in this way. Copper metallization, for example, may begin by depositing a conformal film of tantalum 20 to 50 nm thick. Ions of copper are then deposited on top of the tantalum layer. The process can be halted when the new material has formed a thin conformal coating, or deposition can be continued until the trench is filled completely.

Another possibility is to use the thin copper layer as a "seed layer" and fill the trench electrochemically. To facilitate closer packing and multilevel connections, trenches are getting proportionally deeper as they get narrower. Monteiro said, "Deep trenches etched into the dielectric must be filled completely, without voids or defects. With current technology, the deeper the trench, the more likely there will be defects."

At present, "dual-Damascene" methods are used to etch the trenches, fill them electrolytically, then mechanically polish away the excess metal using chemically active slurry. Etching and filling narrow structures with high aspect ratios will be especially difficult for dual-Damascene architectures. Multilayer film methods will be essential, but a problem with common vapor-deposition techniques is that material builds up at the top of the trench and closes it off, leaving a void below. In ion-assisted deposition, the highly charged ions drive straight into the trench, dislodging excessive build-up before it accumulates.

Monteiro said, "The challenge is to address narrower paths. Our goal is to get from 250 nm to 100 nm, at a 10:1 aspect ratio. And I'm confident we can go even below that."

Self-Assembled Nanospheres May Enable Controlled Release of Medications

Researchers at Sandia National Laboratories have created self-assembling nanospheres that fit inside each other like Russian dolls. As described in the March 18 issue of *Nature*, the nanospheres—essentially a three-dimensional creation rather than a film or layering of films—have been created by drying liquid droplets blowing through a furnace, rather than evaporation of a liquid layer deposited on a substrate.

The mixture begins with a homogeneous solution of soluble silica plus surfactant prepared in an ethanol water solvent. In a continuous process that takes about six seconds per particle, the aerosol particles are dried, heated, and collected.

Lead investigator Jeff Brinker said, "We start out with liquid droplets that we pass through a reactor. As liquid starts to evaporate, the rest of the material self-assembles into a completely ordered particle that, when heated, maintains its shape."

The durable silica spheres, which range in size from 2 to 50 nm, form in a few seconds, are small enough to be introduced into the body, and have uniform pores that enable controlled release of drugs. The spheres can absorb organic and inorganic substances, including small particles of iron, which means they can be controlled by magnets and the contents released as needed.

The small porous particles also have characteristics superior to fillers used in encapsulants for weapons and tools. The expansion coefficients of polymers and the metallic devices they cradle usually differ substantially. This means that temperature variations cause the encapsulants to stress the devices they are meant to protect. The induced stresses can decrease longevity of a device. According to the researchers, the nanosphere fillers would occupy the same volume, but because they are porous, can expand and contract with much less stress.

The researchers said that some pore shapes trap materials, while others allow free flow in and out of the spheres. The different kinds of sphere porosity may resemble slits between onion-like layers of silica, or a honeycomb's hexagonal patterns of holes.

Brinker said, "The ability to control these different porosities make them useful for all kinds of applications."

According to the researchers, by sandwiching yielding layers of polymers between hard inorganic layers, this method of self-assembly is an improvement over past methods by increasing toughness and preventing the spreading of cracks.

Materials Research Results Presented at the Centennial APS Meeting

The Centennial Meeting of the American Physical Society held March 21–26 in Atlanta featured areas related to materials research. Some of the materials topics brought to the attention of *MRS Bulletin* included granular materials, scanning probe microscopy, laser and high-energy density plasma, and nanostructures.

Fingering Patterns in Granular Flows May be Due to Surface Tension

By examining the influence that particle segregation plays on the formation of "fingers" at the leading edge of granular flows, previously thought to be caused by irregularly shaped particles, researchers at the University of Illinois have cast serious doubt on the validity of this explanation. Eliot Fried, a professor of theoretical and applied mechanics, said, "Our results show that even when the medium consists of nearly spherical particles, its leading edge may still develop fingers."

Fried and his colleagues—theoretical and applied mechanics professor Sigurdur Thoroddsen and graduate student Amy Shen—performed a series of experiments by rotating an acrylic cylinder containing a small amount of granular material around its horizontal axis of symmetry. For the granular medium, the researchers started with industrial-grade blasting powder, which included tiny, fairly uniform glass beads. The motion of the granules was recorded on videotape with a charge-coupled device camera and then analyzed one frame at a time.

Fried said, "Initially, there is a stick-slip motion of the layer as a whole, as it is dragged up the rising side of the cylinder to a critical angle where it falls back to the bottom. But as the angular velocity is increased, a wave-motion sets in, which creates a span-wise variation in the thickness of the layer—visible as bright and dark bands of light transmitted through the granular material. The frontal patterns resemble fingers."

As reported at the meeting, the researchers next added coarse sand to the glass beads. The resulting fingers and wave patterns did not differ substantially from what had been observed with the beads alone.

"Our results clearly demonstrate that fingers can form at the front of a flowing granular medium even in the absence of segregation induced by coarse, irregularly shaped particles," said Fried. "This suggests that some other mechanism is responsible."

Fried said that because the fingering patterns are similar to those seen in conventional viscous fluids, the explanation may lie in an effective surface tension generated by cohesive forces between grains.

He said, "In fluids, the frontal fingering instability is driven by a competition between viscosity and surface tension. Although granular media are commonly thought to be incapable of sustaining surface tension, we cannot rule out the possibility that the fingering patterns result from a similar competition between the viscosity of the bulk medium and effective surface tension."

Scanning Probe uses Microwaves to Characterize Material Electronic Properties with Submicron Resolution

A thumb-sized microscope that works like a CD-player, only with microwaves rather than visible light, has been invented by researchers at Lawrence Berkeley National Laboratory. Called a Scanning Evanescent Microwave Probe (SEMP), this instrument can be used to simultaneously characterize critical electronic properties along with topography in a wide assortment of materials.

Xiao-Dong Xiang, a physicist with Berkeley Lab's Materials Sciences Division, described how the SEMP uses near-field or nonpropagating microwaves (as opposed to normal far-field microwaves such as radar) to measure the electrical impedance of materials with submicron resolution.

The SEMP's sharp-tipped metal probe is connected to a high quality-factor (Q) microwave resonator equipped with a thin-metal shield. This shielding is specially designed to screen out all but the evanescent microwaves from being generated at the SEMP's tip. As a result, when the tip is scanned over a sample, just above the material's surface, only these evanescent microwaves, with their high spatial resolving power, are free to interact with the sample.

Xiang said, "This feature is crucial for high-resolution quantitative microscopy. If both evanescent and propagating microwaves had to be considered and calculated, as is the case for all other types of microwave probes, the quantitative microscopy would be impossible." The interaction between the evanescent microwaves and the sample surface gives rise to a resonant frequency and quality-factor changes in the resonator that are recorded as signals. Xiang and his colleagues can measure these change signals and translate the results into a measurement of the sample's complex electrical impedance with a spatial resolution of 100 nm.

Xiang said, "We chose the lower range microwave frequencies (a few GHz) because this is the most relevant and best-suited range for most electronic applications."

Photographic Emulsions Used to Track Nuclear Events Produced by Petawatt Laser Pulses

In an on-going project to create an energy source from fusion, researchers from NASA's Marshall Space Flight Center and Lawrence Livermore National Laboratory use photographic emulsions to track nuclear particles produced by the interaction of a petawatt laser pulse with metal targets. In his presentation, Thomas Cowan of Lawrence Livermore described the petawatt laser. He said that it uses a series of mirrors and amplifiers to generate a brief, powerful pulse of light. The amplifier system shortens the laser oscillator pulse to just one-half a picosecond and boosts the power to 1.25 petawatts focused on a gold foil target 1 mm across.

Cowan said that the electrons in the gold atoms hit by the laser are energized enough to produce intense, high-energy gamma rays that knock neutrons from the gold nuclei. Those neutrons cause nuclear fission in the uranium pellet behind the gold target. He said that the high temperatures and electric fields generated by the petawatt flash laser accelerate electrons to as high as 15 MeV, and could be as high as 100 MeV.

Some of the gamma rays produce electrons and positrons by pair production, so the tracks in the emulsion provide a measure of gamma ray production, and intensity, in the blast.

Cowan said, "We don't directly detect the fission products or other nuclear debris with the emulsions. These are captured in the target assembly and we detect them after the laser shot with gamma-ray spectrometers. The electrons and positrons are the particles emanating from the target that we directly measure with the emulsions. In terms of understanding the underlying physics of the laser-plasma interaction, all of these are important, but the electron data are the most direct and most influential of all of our measurements."

Continued on page 8.

Continued from page 7.

The emulsions are strips of photographic film. Each strip is composed of a 500 μm-thick plastic substrate, 1 cm wide and 12 cm long, coated on both sides with a 50 μm-thick emulsion.

Walter Fountain and Mark Christl of NASA and Joy Johnson of the Universities Space Research Association make the emulsions by hand. The film strips are hung inside the chamber where the laser target sits and placed inside three electron spectrometers.

Two low-energy spectrometers are equipped with magnets that make electrons and positrons curve in opposite directions as they enter the spectrometers at close to the speed of light. These spectrometers let scientists measure the relative population of the two particles.

The third spectrometer has magnets to spread the electrons out by energy, like a prism spreading white light into colors, to measure where the energy goes in the by-products of a shot.

Thomas Parnell, who recently retired as the chief of the high-energy astrophysics branch at Marshall, said, "Electronic detectors would be saturated by this flux and the density of particles occurring all at once. But the electrons and positrons leave trails as their passage through the emulsion sensitizes the silver bromide crystals."

After a shot, the emulsions are removed from the spectrometers and measured. The emulsions are developed at very low temperatures to protect the thick emulsions and ensure even development so the electron tracks appear as tiny dark strips in the emulsion.

Parnell said, "Most of the electron counting is done visually, by eye, with a standard analytical microscope."

Cowan said, "The emulsion technique... was the key difference in being able to distinguish the high energy electrons and very rare positrons from the flood of other intense radiation coming from the laser-target interaction. Other techniques that use more conventional electronic detectors were blinded by the radiation flash and required much more care and development to function reliably."

Nanoharp and Nanomagnets Fabricated

Researchers from Cornell University's Nanofabrication Facility reported both the development of a nanoharp to be used to study the physics of vibrating systems and the test results of nanomagnets to be used as magnetic data disks. Graduate student Dustin Carr presented both projects that were supervised by Harold Craighead, a professor of applied and engineering physics.

The nanoharp, carved out of a single crystal of silicon, consists of two endpieces, one square and one triangular, with several "strings" made of silicon rods 50 nm in diameter, ranging from about 1000 to 8000 nm long. Carr said that they built the device using electron-beam lithography and "released silicon" technology, which refers to nanostructures that have been undercut to be freely suspended in

Continued on page 9.

Continued from page 8.

space. The nanodevices operate in a vacuum where their vibrations can be transmitted through the silicon base.

The researchers make the silicon rods vibrate by applying a radio frequency voltage signal through the silicon base. They then measure the resulting vibrations by bouncing laser light off the strings and observing the reflected light with an interferometer.

The researchers have measured vibrations at frequencies from 15 MHz up to 380 MHz. Carr said, "The system can detect a motion of as little as one nanometer, or possibly less."

Physics professor Jeevak Parpia said that the group plans to examine the behavior of these oscillators at very low temperatures: "When you drive a mechanical oscillator, the oscillation increases in amplitude with the amplitude of the drive, but at very low temperatures the relationship becomes nonlinear. The intent is to take these very small oscillators and see if they behave differently than the larger devices we've worked with in the past."

In another project, the researchers fabricated nanomagnets as small as 25 nm long. Postdoctoral associate Stephane Evoy said that magnets less than 100 nm wide, when magnetized, form magnetic fields in which all of the atoms are aligned, whereas in larger magnets, many smaller domains form in which groups of atoms align in various directions. Evoy said that the single-domain magnets could be used for data storage.

In this project, the researchers deposited rows of tiny cobalt dots on silicon surfaces using techniques originally designed to make electronic circuits. In various experiments, they created dots ranging from 25 nm to 100 nm wide, in several different arrangements. Most were about 80 nm wide, 140 nm long, and ~20 nm thick.

Carr reported that, by reading the orientation of individual magnets using a magnetic force microscope, they found much interaction between the magnets. Sometimes, a whole row lined up one way, with adjacent rows in the opposite orientation. Sometimes changing the polarity of a single magnet affected other magnets in its immediate vicinity, in all directions. This was particularly so when the spacing between the magnets was less than 400 nm.

To study the magnetic properties of large arrays of these nanomagnets, and the properties of silicon itself, Carr and graduate student Lidija Sekaric built silicon oscillators consisting of small paddles ~2–5 μm wide, suspended at the ends by rods 50–100 nm thick. By applying an alternating-current electric field, they caused the suspended surfaces to oscillate. They said that with arrays of nanomagnets deposited on the paddles, they will apply an external magnetic field and look for any change of the behavior of the paddle, which will provide information about the magnetic properties of the nanomagnet array.

Sekaric said that the approach used to make these tiny oscillators could be used to make very sensitive magnetometers for the study of other magnetic systems.

Introduction of Jellyfish DNA into Silkworms Creates Green Fluorescent Silk Fibers

In the March 1 issue of *Genes & Development*, Hajime Mori and colleagues at the Kyoto Institute of Technology in Japan report that they have developed a technique to produce genetically altered, green fluorescent silk fibers that are spun by the silkworm. The development of an insect system to produce foreign proteins has potential applications for silk or other economically important proteins.

Silkworms, or more precisely, the larvae of the moth *Bombyx mori*, spin silk to form a cocoon in which they will develop into moths. Mori's group infected the silkworm larvae with a genetically engineered insect virus that carried an altered version of a silk protein. They fused the gene encoding the light chain of the fibroin protein—a major protein component of silk—to the gene encoding the green fluorescent protein from jellyfish. After the virus infects the larval cells, the virus embeds itself into the silkworm's DNA.

Through a process called homologous recombination, the silkworm's natural fibroin gene was replaced with the new altered version. When ultraviolet light is shone on the silk glands of these infected larvae, the glands glow with a green color. The development of this technique opens the door for genetic researchers to engineer silk proteins and reintroduce them into moths that can, in turn, produce genetically altered silk.

Theoretically, such a protein-producing insect could be used to produce important proteins, such as the spider silk protein spidroin, which has potential industrial uses ranging from the fibers in bullet-proof vests to parachutes.

X-Ray Studies Indicate Ordering of Liquid Layers at Solid Surfaces

Researchers at Northwestern University have directly observed that molecules of liquid close to a solid surface organize into layered structures much like a solid. Professor of physics and astronomy Pulak Dutta, who led the study, said, "In a confined geometry, like in a filter, a pore, or between two plates, there has been evidence that liquids don't behave like bulk liquids, and that their properties are different. The liquid isn't changing its chemical composition, so it must be changing how the molecules are arranged.

As reported in the March 15 issue of *Physical Review Letters*, Dutta and his coworkers bounced extremely brilliant x-rays off of a thin film of tetrakis(2-ethylhexoxy)silane, TEHOS, which had been applied to a solid surface of silicon. The reflected x-rays formed an "interference pattern" similar to the checkerboard light patterns created by shining light through a grating. With x-rays, such behavior indicates a molecular solid, and analysis of the pattern showed that the TEHOS molecules, which were used for the study because they are nearly spherical, were forming three solid-like layers, each one-molecule thick.

The layered TEHOS molecules were in an intermediate physical state between a bulk liquid and a solid, according to graduate student Chungjong Yu. He said that the physical state can be deduced from the shape of the reflectivity curve.

Yu said, "A very shallow ripple indicates a liquid, and sharp peaks indicate a solid. These are broad humps."

In regards to past research, Dutta said, "The question was, if you take a typical, garden-variety liquid, perfectly disordered, then when it starts flowing against a surface or being squeezed through pores, is it still a liquid? What we've now shown is no. It's one of these intermediate structures—the molecules are somewhat ordered—they're neither perfectly ordered nor disordered."

By using synchrotron radiation in this study, Dutta said, "This is a new application of synchrotron radiation. It's a first step to making rigorous measurements of how liquids organize near solid surfaces." As more studies are completed, he said, "we can use this body of knowledge to learn how to design molecules that would make better lubricants, to understand why lubricants behave the way they do, why they fail and how to prevent them from failing."

He said that the findings are also of interest from a theoretical standpoint, "There has been an enormous amount of work on the free surface of liquids, the liquid-air interface. Scientists worked for years to see if there is layering on the free surface. Well, there isn't. If you have a cup of a liquid, on the top layer, the air-liquid interface, it's a liquid." □

Advertisers in This Issue

	Page No.
Bede Scientific, Inc.	Inside back cover
Chemat Technology, Inc.	54
EDAX, Inc.	4,5
Fischione Instruments	48
High Voltage Engineering	Inside front cover
Huntington Mechanical Laboratories, Inc.	Outside back cover
KLA Tencor	8
Materials Research Society	78
RBD Enterprises, Inc.	9
Saint-Gobain Industrial Ceramics, Inc.	3
Solartron	36
Thermionics Vacuum Products	6
Virginia Semiconductor, Inc.	10
VLSI Standards	29

For free information about the products and services offered in this issue, check **www.mrs.org/publications/bulletin/advertisers** or fill out and mail the Reader Service Card, or FAX it to 312-922-3165.