ning in 1994 (*Science*, 30 September 1994, p. 2014).

The IBM team manufactured a ring from three separate crystal grains of a high-temperature superconductor known as yttrium-barium-copper-oxide (YBCO). The three grains were arranged so there were three boundaries in the ring at which the direction of the crystal lattice changed. These direction changes meant that, if paired electrons racing around the ring were d-wave, their phase should change one or three times, producing a net phase change around the ring. Researchers can detect this change as a small amount of magnetic current, or flux, spontaneously generated through the center of the ring. There would be no such flux if the pairing was s-wave.

The IBM team duly detected the flux using a scanning magnetic probe. But s-wave proponents were quick to note that complexities in YBCO's structure complicate the picture. YBCO conducts current in two closely stacked copper oxide layers, and some theorists suggested that two s-wave pairs, one in each layer, traveling in perpendicular directions and out of phase, could mimic phase changes similar to a d-wave pair. YBCO also has "chains" of copper and oxygen atoms near the copper oxide layer, which make movement in one lattice direction easier than in the perpendicular direction; this means that the observed flux in the ring could be explained by more complex pairing wave functions, known as s+d or s+g. "The question is, 'is the [phase] change really due to the superconductivity, and not the crystal structure?'" says theorist James Annett of the University of Bristol in the United Kingdom.

So last year, with the help of colleagues from the State University of New York, Buffalo, the IBM team manufactured a ring made from a different high-temperature superconductor, thallium-barium-copper-oxide. Although harder to coax into the required three-grain shape, its crystal structure within each grain is much simpler: only a single copper oxide layer and no copper chains. "It kills two birds with one stone," says Tsuei.

And sure enough, the researchers again found flux in the ring. "It is an important result. It's the first time any of these experiments have been done on a material other than YBCO," says Leggett. "The simplest phonon theories really are dead," says Philip Anderson of Princeton University in New Jersey, a veteran of the field.

There are still some experimental results keeping s-wave alive, however. In particular, there is work from a group led by Robert Dynes of the University of California (UC), San Diego, in which they observed current perpendicular to the copper oxide planes—which is forbidden by d-wave—in YBCO. And according to results yet to be published, researchers at UC Berkeley—working with the San Diego team—have duplicated their results. "These provide strong evidence of s-wave pairing in YBCO," says Klemm.

Similarly, Praveen Chaudhari, also of IBM Yorktown Heights, has been looking for a d-wave phase change for several years using a different method than Tsuei and Kirtley. "We're trying hard to look for d-wave, but not succeeding," he says, adding "I'm still sitting on the fence myself."

So while d-wave proponents seem to be winning most of the battles, they have not yet won the war. Klemm is philosophical: "Now more people do favor d-wave, but science has its own truth; it's not a democracy."

–Daniel Clery

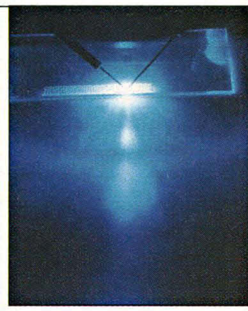
MATERIALS SCIENCE

Blue Laser Race Turns Red-Hot

In the race to make the first blue-light semiconductor lasers, the lead horse has come up slightly lame. Chip-based lasers that emit blue beams of light are expected to be an instant commercial hit, because the short blue wavelengths can be used to pack a lot of data in a very small space. But experimental lasers based on zinc-selenide (ZnSe), the one semiconductor material that's been capable of emitting a blue laser beam, have been hobbled by quick burnout. Now, however, a highly touted entry has finally stepped onto the track, ready to give the leader a run for the money.

In the 15 January issue of the Japanese *Journal of Applied Physics*, a team from Nichia Chemical Industries in Tokushima, Japan, reports making the first electrically powered laser—in this case violet in color—from a robust semiconductor alloy known as gallium nitride (GaN). The report has sent a ripple of excitement through the laser research community. "It's a very significant milestone," says J. J. Song, a physicist who heads the laser center at Oklahoma State University in Stillwater. "The whole world has been trying to make a GaN laser diode. This shows it can be done."

Although the performance of the new GaN lasers still lags behind that of those made from ZnSe—indeed, they also suffer from burnout problems—this gap could narrow rapidly, because GaN is inherently more durable, says Cammy Abernathy, a gallium nitride expert at the University of Florida, Gainesville. What's more, GaN is already used to produce other light emitters, known as light-emitting diodes (LEDs). This pre-existing research infrastructure is likely to push a GaN laser to the head of the field, where it could quadruple the storage capacity of devices that currently use longer wavelength red lasers, such as optical computer discs and audio compact discs.



NICHIA CHEMICAL INDUSTRIES

New blues. A semiconductor laser made from gallium nitride shines a blue light bright with promise.

The Nichia team was, in fact, the first to make commercial nitride-based blue LEDs (*Science*, 22 April 1994, p. 510), and—led by materials scientist Shuji Nakamura—they built on this technique to make lasers. Both semiconductor LEDs and lasers generate light when electrons and holes are injected into the device from electrodes placed on opposite sides. A series of sandwichlike layers of different semiconductor alloys then funnels these charges to one or more "quantum wells" in the center of the device, where the charges combine to give off photons of light. In LEDs, these photons fly out in random directions, but lasers incorporate a pair of mirrors that reflect and amplify the photons, turning them into a coherent beam.

The Nichia group's initial success at making blue LEDs stemmed from the ability to lay down these sandwichlike semiconductor layers, a hard task because they tend to develop a lot of defects. Nichia's GaN layers were also riddled with tiny cracks—but to the researchers' surprise the cracks didn't prevent the LEDs from functioning. GaN is very tolerant of defects.

Cracks, however, are bad for lasers, as photons ricochet off them in all directions. To prevent the cracks from forming, Nakamura and his colleagues added an extra semiconductor layer near the bottom of their sandwichlike devices. Unlike the hard and brittle layers that sit on top, the new layer, made from an alloy of indium-gallium-nitride, is relatively soft. This layer acts as a kind of expansion joint, relieving the strain between the atomic lattices of adjoining semiconductor layers that would otherwise lead to cracking.

The device still has one drawback: It can only handle short electrical pulses; continuous streams overheat it, causing it to burn out. ZnSe lasers, in fact, last longer, yet because GaN can handle thousands of times more defects than ZnSe without trouble, researchers expect that the growing research effort on GaN will quickly close the performance gap. "There's still a window of opportunity for [ZnSe] lasers," says Anis Husain, who directs research funding for semiconductor optics at the U.S. Defense Department's Advanced Research Projects Agency. "But that window is closing very rapidly."

–Robert F. Service