of the β_2-AR gene correlated with the increased contractility of the heart muscle both in the living animals and in lab tests. Since the animals hadn't been given any adrenaline, the group asked how the receptor alone could increase contractility.

One possibility is that the plethora of receptors was allowing the heart to respond to the animals' existing low levels of adrenaline. But when Lefkowitz and his colleagues gave the mice a drug that blocked the receptors' ability to respond to adrenaline, the heart continued to pump just as hard. So Lefkowitz and his colleagues concluded that a small percentage of the receptors are always sending messages to the cell's interior. Increasing the total number of receptors would therefore mean that the animals would have a greater number of active receptors. "Suppose 2% of the receptors are naturally in the active form and you have a 200-fold increase in total receptors, you have a maximumly stimulated cell," explains Lefkowitz.

Surprisingly, even though the animals' hearts are on permanent overdrive, the mice appear normal. "Intuitively, you would think this couldn't be good for the animals," Lefkowitz says. But "they're happy out to 8 or 9 months—which is as far as we have looked at them."

Lefkowitz's results encourage cardiologist Judith Swain at the University of Pennsylvania Hospital, who is excited about the possibility for cardiac gene therapy. "Because you can dramatically change the contractility of the mouse heart, you can easily see how one could make changes in human heart function using a gene therapy approach," says Swain. Both Swain and Lefkowitz agree, however, that gene therapy is still far in the future.

First, the Lefkowitz group will have to find out if their approach works on animals with diseased hearts. Also, before there is any practical gene therapy for congestive heart disease, researchers will have to overcome such major obstacles as finding a safe and effective way of putting the gene directly into heart muscle cells rather than into early embryos as in the current experiments—a requirement if the method is ever to be applicable to human patients.

Lefkowitz has begun a collaboration with gene therapy pioneer Ronald Crystal at Cornell University Medical College in New York City to achieve just that goal. They plan to explore using a virus to carry the gene to the heart. Alternatively, the gene might be introduced into cardiac muscle cells, which can then be transplanted into hearts (*Science*, 1 April, pp. 31 and 98). If all goes well, Lefkowitz says, it might some day be possible to use therapy with receptor genes to treat heart failure and other illnesses.

–Lisa Seachrist

SOLID-STATE PHYSICS

A New Laser Promises to Put An End to Band Gap Slavery

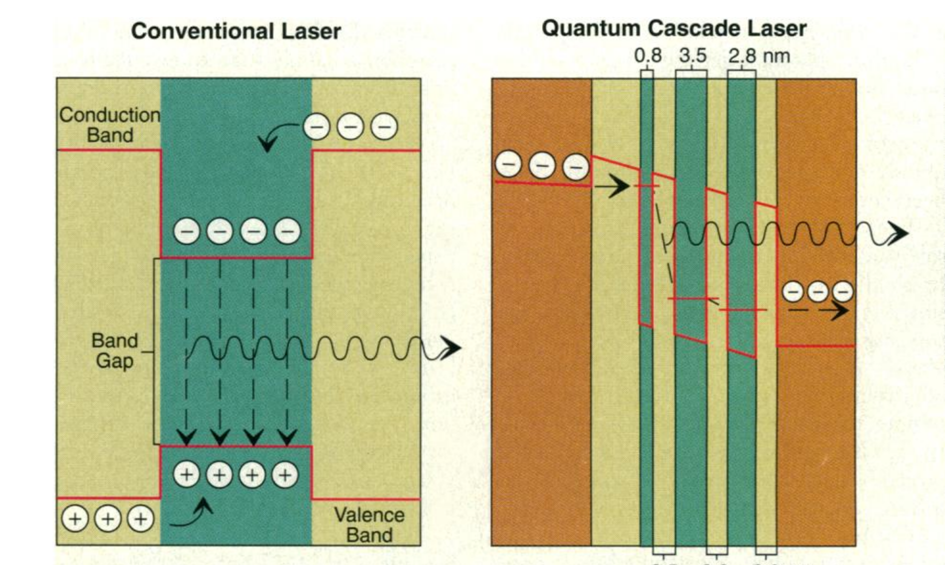
If you are a naturally enthusiastic researcher, one of the few drawbacks to creating a unique new scientific device is the need to restrain your own enthusiasm. For Federico Capasso of AT&T Bell Laboratories—an upbeat man to begin with—and postdoc Jerome Faist, that's a double challenge, because their quantum cascade laser can be viewed both as an advance in laser physics and also as a potential technological coup.

Faced with these prospects, Capasso oscillates between expansiveness and caution. "It's really a nitty-gritty technical advance" with implications that could be "quite mind-boggling," Capasso, head of Bell Labs' quantum phenomena and device research department, says in an unguarded moment. Then, swinging to caution, he adds that it would be a mistake to "toot the technological thing" because it could take years for the laser to become practical. So he settles for calling it "a very significant research achievement." Most other researchers who know of the work, described on page 533 of this issue of *Science*, echo that judgment.

What Faist and Capasso have built, in collaboration with Alfred Cho, Deborah Sivco, Carlo Sirtori, and Albert Hutchinson, is the first semiconductor laser whose wavelength is set entirely by an artificially created physical structure—dozens of atoms-thick sandwiches of semiconductor known as quantum wells—rather than by the laser's chemical composition. Whereas a conventional semiconductor laser generates light when excited electrons drop across a material's intrinsic "band gap" into the ground state, the new AT&T device extracts light from electrons cascading down energy steps created by the quantum wells. Because those stair steps, unlike a band gap, can be tailored at will by changing the thickness of the wells, the laser should open up regions of the infrared spectrum that are critical for monitoring pollutants or detecting objects through the atmosphere, but are now difficult to reach with semiconductor lasers.

Before that can happen, say other physicists, Faist and his colleagues must prove that the laser can emit light continuously (so far it fires only in pulses) and can operate efficiently at temperatures above that of liquid nitrogen. But even if the quantum cascade laser doesn't turn out to be a technologically useful device, says Dan Botez of the University of Wisconsin, it will stand as a tour de force of physics. University of California, Berkeley, physicist Charles Townes, who shared the Nobel Prize in 1964 for the invention of the laser, agrees, calling the quantum cascade laser "a beautiful piece of solid-state and laser physics."

What impresses Townes is the sharp departure from conventional laser design. Conventional semiconductor lasers fire when electrons in the semiconductor are excited from their ground states—known as the valence band—across the band gap into states



Tripping the light. In a conventional semiconductor laser, a material's intrinsic band gap sets the wavelength. In a quantum cascade laser, it's the result of energy levels *(red)* created by a series of sandwich-like quantum wells. The diagram shows one of the laser's 25 active regions.

known as the conduction band. The result is a "population inversion" of excited electrons sitting in the conduction band above positively charged vacancies, or "holes," in the valence band. When one of the excited electrons drops back into the valence band, it combines with a hole and releases a photon. That photon prompts more electrons to drop and emit photons, and so it goes as the photons, all at about the same wavelength and phase, bounce back and forth between cleaved crystalline planes of the semiconductor, which serve as mirrors. The photon flux grows until it reaches a threshold and the laser erupts with a burst of coherent, monochromatic radiation.

As early as 1959, however, Benjamin Lax of the Massachusetts Institute of Technology proposed a different kind of laser, one that would generate light from electrons only, as they jumped down energy levels artificially created within the conduction band by a magnetic field. In 1971, two Soviet physicists, Rudy Kazarinov and Robert Suris, proposed a more practical way to create such a laser—by relying on quantum wells. Proposed the year before by Leo Esaki and Raphael Tsu, then at IBM, these sandwiches of semiconductor are so thin that they can accommodate only certain electron wavelengths, or energies. Because the exact energies depend on the wells' thickness, Kazarinov and Suris proposed that wells arranged in a series could emit laser light at a chosen wavelength. Electrons "tunneling" sequentially from well to well, they argued, would drop from higher to lower energy levels and emit photons corresponding to the energy difference.

Fine tailoring. Kazarinov's and Suris' idea was one element of the quantum cascade laser. But building it also required technological finesse, in the form of molecular beam epitaxy (MBE), a technique for depositing semiconductors atom-by-atom that Cho pioneered in the 1960s. By the mid-1980s, Cho had refined MBE to the point where it allowed what Michael Newkirk of MIT's Lincoln Laboratories calls "amazing feats of molecular control." One of those feats was the building by Cho and Capasso of an assemblage of 35 quantum wells. Their 1986 experiment demonstrated sequential tunneling of electrons through the wells' energy levels—just as Kazarinov and Suris had proposed—but it failed to produce light. Capasso, however, calls it "a good failure," since it prompted him to launch the all-out effort that has now paid off.

In mid-January, after numerous blind alleys and years of what Capasso calls "very systematic work, hundreds of MBE runs, hundreds of wafers gone," the team came up with a working quantum cascade laser. "It's such a complex design," says Faist, "so many things that could have gone wrong, that I almost couldn't believe my eyes" when it worked.

At its heart are 25 active regions—the steps in the energy staircase. Each active region is in turn made up of three quantum wells—nanometer-thick quantum sandwiches in which insulating layers of aluminum indium arsenide flank a center of indium gallium arsenide. The wells differ in thickness, hence in energy level. When electrons flow through this structure, Faist explains, they tunnel from the first well to the second, drop down to a lower energy level, and emit photons. To maintain a population inversion, essential for laser action, this lower level must remain empty, and that's the role of the third quantum well in the active region. That well's insulating barrier is so thin that it "siphons" electrons from the second well, allowing the device to keep emitting light. From the third well, the electrons pass to the next active region—the next step in the cascade—and so on through the structure. The photons emitted along the way ricochet between two cleaved planes, and the flux is amplified many times, as in a conventional laser.

Elaborate as this many-layered parfait is, there's no doubt that it works. As Faist and his colleagues turned up the current across the structure, the emitted light suddenly turned coherent and its intensity increased nearly 100-fold. The change, says Capasso, is "like a phase transition, bingo, you get into a new state of light." Simultaneously, the light suddenly became monochromatic. "If the spectrum narrows dramatically above a threshold, you have it," says Capasso.

Perhaps the most significant virtue of the new laser, says Capasso, is that the designer can control the wavelength of the emitted light simply by varying the thickness of the quantum wells. That should open the way to generating light in the mid-to-far infrared spectrum, which includes wavelengths to which the atmosphere is transparent. Lasers that operate at these wavelengths could be used for pollution monitoring—probing the chemicals in smokestack plumes or automobile emissions—or for collision avoidance radars in automobiles.

Band gap freedom. Because conventional semiconductor lasers are, as Capasso puts it, "slaves of the band gap," reaching the mid-to-far infrared now requires materials with small band gaps. And suitable materials, such as mercury cadmium telluride, tend to be hard to process, very temperature-sensitive, and subject to defects. "By controlling the wavelength by changing the layer thickness," says Capasso, "we can use materials of much wider band gap, which are more technologically mature and easier to process." In that respect, agrees Townes, the quantum cascade laser "can fill a very important gap."

Faist and Capasso also see advantages in the fact that the energy levels in a quantum well are sharply defined rather than broad, like those in a conventional semiconductor laser. That should give the quantum cascade laser a narrower spectrum than its conventional counterparts—"another beauty of our laser," Faist calls it. He adds, however, that "we haven't been able to prove it experimentally, but we are sure about it." The precise energy levels should also protect the quantum cascade laser from changes in temperature, which tend to smear out the distribution of electrons and holes, broadening the spectrum and lowering the gain of conventional semiconductor lasers.

AT&T

Proud parents. Clockwise from left, the Bell Labs team: Capasso, Cho, Hutchinson, Sivco, Faist, and Sirtori.

On the other hand, the quantum cascade laser has been tested only at temperatures too low for some practical applications—at the time the paper went to press, no higher than 90 degrees Kelvin, 13 degrees above the temperature of liquid nitrogen. What restricts the laser to low temperatures is its inefficiency. The current needed to drive the device is so large that it would overheat if operated near room temperature or made to produce anything more than pulses of light. Given these drawbacks, says Botez, "at the present time, the device appears impractical. A conceptual, *i.e.*, not technological, breakthrough is needed to make this device efficient and thus of practical use."

Faist is cautious as well, but he notes that since submitting the paper, he and his colleagues have created lasers that produce 10 times more power and operate at up to 125 K. In any case, the technology is only 3 months old—and further developments are surely possible. The quantum cascade laser, says Faist, "is clearly extremely different from anything that's been done before. Whether or not you can call it revolutionary will still depend on what the future holds." And if that future is as promising as many think, the time will come when he and Capasso won't need to curb their enthusiasm any longer.

–Gary Taubes