picosecond or femtosecond electron pulses for use in diffraction experiments. If the incident pulse contains too few electrons, the number of diffracted electrons is too small to obtain a high-quality diffraction pattern.

Siwick *et al*. overcome this difficulty by using a carefully designed electron "gun" (the device that produces the electron pulses). They demonstrate the power of this accomplishment by obtaining the complete structural record of a material undergoing a laser-induced transition from the ordered crystalline solid phase to the disordered liquid phase.

The diffraction pattern measured before the arrival of the laser pulse reveals the well-known structure of aluminum metal. The atoms are arranged in a regular array called a face-centered cubic lattice, in which each atom is surrounded by 12 neighbors. When the laser energy is deposited in the material, this order is maintained for a little more than a picosecond. The atoms then begin to oscillate violently around their equilibrium position as a result of the rapid heating caused by the laser pulse. The data reveal that during the initial picosecond, the temperature of the solid material greatly exceeds the normal equilibrium melting temperature, a rare phenomenon called superheating. During the next few picoseconds, the regular atomic order collapses completely, and a structure characteristic of the liquid state emerges.

The study of Siwick *et al*. (*1*) significantly extends the scope of time-resolved structural investigations. The rapid progress in this field will have a great impact on many areas of science, and both electron and x-ray diffraction are likely to play an important role. Time-resolved electron diffraction is particularly well suited for surface studies, such as the investigation of surface chemical reactions. This could lead, for example, to further progress in understanding the mechanisms of surface catalysis.

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PHYSICS

Marriage of Two Device Concepts

Alessandro Tredicucci

Recent advances in semiconductor growth and processing techniques are providing unprecedented possibilities for creating artificial crystal structures with new properties. Scientists are exploiting this ability to realize innovative devices—from diodes and transistors to lasers and modulators—with specifically designed functionalities and performances.

The latest milestone in this area is reported by Colombelli *et al.* on page 1374 of this issue (*1*). The authors have produced a "metamaterial" in which the electronic band structure and the electromagnetic field dispersion are tailored and matched to create a unipolar injection laser capable of vertical emission. The device combines two concepts that are enjoying vast success in fundamental and applied solid-state science: quantum cascade lasers (*2*, *3*) and photonic crystals (*4*, *5*).

In a quantum cascade laser, radiation is generated by electronic transitions in a structure consisting of alternating layers of two semiconductor materials. The energy levels of the crystal electrons can be tuned by controlling the thickness, periodicity, and composition of the layers. Quantum confinement splits the bulk conduction band into subbands and minibands, which determine electrical transport and enable new optical transitions. When a bias voltage is applied across the material, a periodic cascade of such intersubband transitions is established. The population inversion necessary for lasing is then achieved through electrical injection (*2*, *3*).

Because the properties of the above gain material can be controlled through design, quantum cascade lasers are highly versatile (*6*, *7*). However, their most striking feature is their frequency adaptability (see the figure, left panel): Quantum cascade lasers are the only solid-state lasers that can operate in a broad wavelength range from 3 to about 150 μm. Applications include chemical recognition and sensing [for example, for environmental monitoring, inspection of production processes, and security controls (*3*)], biomedical or industrial imaging, and DNA diagnostics.

One characteristic, however, is shared by all quantum cascade lasers. Because the translational invariance of the crystal is broken only in the growth direction, radiation is emitted mainly in the plane orthogonal to this direction. This feature prevents the realization of vertical-cavity surface-emitting devices, which, in contrast, are widely used for conventional interband semiconductor lasers because they simplify coupling with optical fibers, are more efficient, and allow massive parallelization.

Colombelli *et al.* elegantly circumvent this limitation by using a two-dimensional photonic crystal structure (*1*). In a photonic crystal, the refractive index is periodically modulated, so that only a restricted range of wave vectors (called the Brillouin zone) is available for light propagation. This results in the creation of photonic bands (*4*, *5*), similar to electronic bands in a solid. Photonic crystals offer new opportunities for manipulating light, for example, by confining it to length scales comparable to its wavelength, preventing its propagation (*4*, 5), or even causing negative refraction (*8*). Applications include specialty fibers (*9*) and planar waveguides for on-chip optical interconnects and photonic circuits (*10*).

Colombelli *et al.* (*1*) use lithography to create a two-dimensional photonic crystal within the planar quantum cascade waveguide. In their structure, optical modes of appropriate frequency ω are created with wave vector $k_{xy} < \omega/c$ (where c is the speed of light), as a result of the formation of photonic bands (see the figure, right panel). This condition ensures that light can radiate vertically in the direction orthogonal to the waveguide plane. Furthermore, some of the low k_{xy} modes so created possess zero dispersion; these planar stationary waves in the *x-y* plane provide the necessary feedback for laser action on the intersubband transition. Beyond vertical emission, this solution enables miniaturization of the device size down basically to the laser wavelength. The two properties are very appealing for parallel integration of many quantum cascade lasers on the same chip.

How will these new possibilities impact quantum cascade research and technology? For mid- to far-infrared quantum cascade lasers, they do not seem to offer great advantages, especially because surface emission and miniaturization are achieved—at least in this first implementation—at the expense of more relevant performance characteristics such as output power and threshold. However, the regular and controllable beam profiles of photon-

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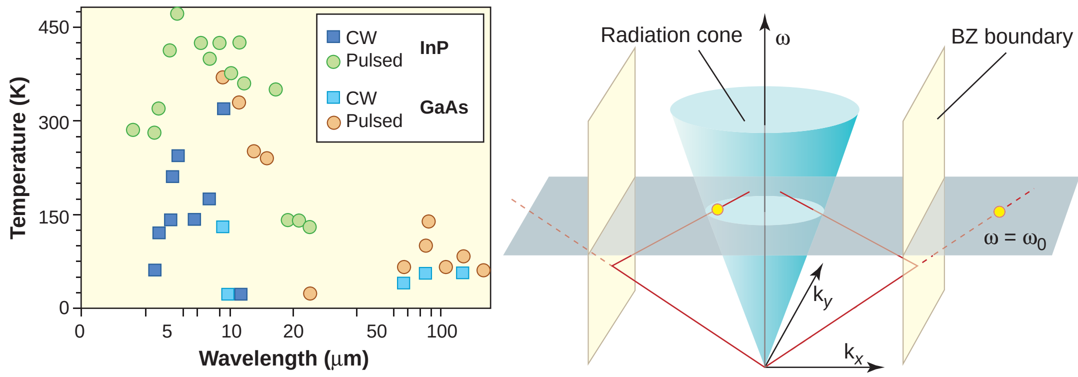
ic crystal quantum cascade lasers are likely to be very desirable, for example, in imaging applications. More importantly, substantial efforts are currently invested in pursuing the realization of quantum cascade lasers at near-infrared telecommunication wavelengths. Their property of being easily modulated at very high speed would be very useful in high-throughput data transmission. In this respect, device integration and vertical coupling of the light would be as essential as for conventional interband lasers.



Quantum cascade successes. **(Left)** Maximum operating temperatures of the best existing quantum cascade lasers as a function of their emission wavelength. **(Right)** Frequency ω of a representative waveguide mode (red line) as a function of its wave vector k_{xy}. The photonic crystal structure restricts the allowed wave vectors to the Brillouin zone (BZ), whose extension depends on the crystal periodicity. The portion of the $\omega(k_{xy})$ curve that, in the absence of the photonic crystal, would be outside the BZ (dashed line) is "reflected" into the BZ, creating a photonic band. With this trick, a guided mode of frequency ω_0 (yellow dot), which would otherwise have a large wave vector, can instead be formed inside the cone $\omega > ck_{xy}$ (the "radiation cone"). This is necessary for obtaining radiation orthogonal to the *x*-*y* plane.

Finally, photonic crystals could serve as waveguides in future cascade lasers realized in structures with lower dimensionality, such as nanowhiskers (*11*), which should provide better threshold and temperature performances.

One should also ask the reverse question: What can quantum cascade lasers give to photonic crystal science? They may provide the ideal laboratory system for developing new physics and device concepts. Because only electrons are involved, they do not suffer from surface recombination, and injection photonic crystal devices are easily made. Furthermore, they can operate at long wavelengths, greatly simplifying fabrication technology. And, as we can see from (*1*), their mainly planar emission is a perfect match for simple two-dimensional configurations.

But quantum cascade lasers offer even more. As Colombelli *et al.* show (*1*), they can operate using surface-plasmon waves. Surface-plasmon photonic crystals may enable the miniaturization of photonic circuits, with great promise for subwavelength optics, data storage, and microscopy (*12*). The availability of sources emitting in surface-plasmon photonic crystal modes will further fuel this area of research.

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STRUCTURAL BIOLOGY

Learning to Speak the Language of Proteins

David T. Jones

Understanding the folding of proteins can be likened to learning to speak a new language. Learning a language can be a long and difficult process. For both young children and travelers in foreign countries, the first breakthrough in learning a language is the ability to speak a few important phrases, such as "I'm hungry!" or "Where is the railway station?" and to be clearly understood. Eventually, by uttering more and more of these phrases and listening to the resulting replies, the learner develops basic conversational skills. Finally, after a great deal of practice, the learner begins to understand the actual syntax of the language, and the process is almost complete. Applying this analogy to the report on page 1364 of this issue, we can say that Kuhlman *et al.* (*1*) have spoken a new sentence in the complex language of protein folding and have been understood perfectly.

These investigators have successfully created a new protein from scratch. Using an iterative computer program that optimizes both sequence design and structure prediction, they have created a 93-residue α/β protein that they call Top7, which has a unique, as yet unobserved, topology. Then, they synthesized their new protein and analyzed its unique folded structure by nuclear magnetic resonance spectroscopy and x-ray crystallography. The final x-ray structure of the protein turned out to be an almost exact copy of the structure modeled by the computer. The Kuhlman *et al.* work is a clear demonstration that structural biologists have mastered the first stage of learning the language of protein folding.

As with most languages, the language of proteins is based on a relatively simple alphabet. In the case of most naturally occurring proteins, an alphabet of just 20 letters corresponding to 20 amino acids is enough to construct an astonishing variety of protein structures that carry out a staggering array of biochemical processes. The so-called protein-folding problem that has preoccupied structural biologists for more than four decades can be most simply explained as the problem of discovering how simple strings of 20 amino acids can encode the complex three-dimensional (3D) folded structures of proteins. Solving the protein-folding problem implies that we

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