But what directs homing of IEL progenitors to the gut mucosa? A leading candidate is the $\alpha_4\beta_7$ integrin. Recent observations suggest that CD8$\alpha\beta$ (or CD4) and CD8$\alpha\alpha$ IEL progenitors do not express the $\alpha_4\beta_7$ integrin at the same time during development. Colonization of lymph nodes and Peyer's patches by naïve SP T cells is random. These cells begin to express $\alpha_4\beta_7$ integrin only when stimulated by peptide-bearing dendritic cells originating specifically in the gut mucosa. After circulating through lymph and blood, these stimulated T cells return to the gut-associated lymphoid tissue and to the gut epithelium itself as CD8$\alpha\beta^+$ (or CD4) IELs (13). In contrast, CD8$\alpha\alpha$

IEL progenitors may acquire their preference for the gut mucosa much earlier while they are still in the thymus. Thymocytes that are TCR$\alpha\beta^+$ DN or weakly CD8$\alpha\alpha^+$ are a very small population in the adult thymus, but some of these cells express $\alpha_4\beta_7$ integrin or contain ζ and FcϵR1 γ chains, or display both features, none of which is observed in DP thymocytes (14).

Contrary to popular belief, the double life of IELs in the gut mucosa has been hidden behind a DP birth in the thymus. But what is the $ROR\gamma t$ orphan gene doing in the middle of the $\alpha\beta$ T cell differentiation pathway when typically it is involved in formation of lymphoid tissues? We should

probably brace ourselves for more bizarre ontogenic twists in the lives of thymus-born immune cells—don't expect an orphan to hold only one secret.

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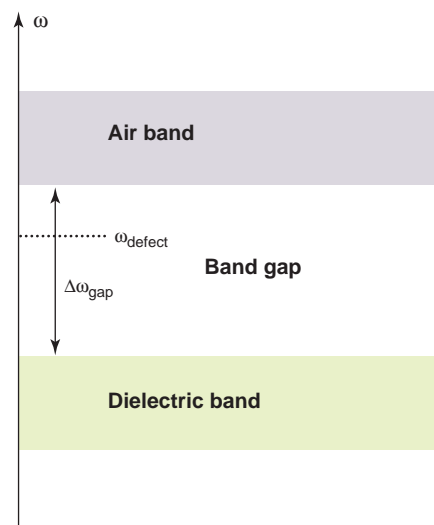14. D. Guy-Grand, P. Vassalli, unpublished data.

PHYSICS

Woodpiles for Photons

Reinald Hillebrand and Ulrich Gösele

In 1987 John (1) and Yablonovitch (2) independently published seminal papers that reported exciting new optical properties for artificially created periodic structures of dielectric objects. Properly designed, these so-called "photonic crystals" feature a band gap, which means that photons having an energy within this range are not transmitted through the photonic crystal. It was also predicted that point defects in these photonic crystals could act as microcavities or microresonators, and linear defects could act as waveguides. Point defects should lead to localized additional energy levels within the photonic band gap. The report by Ogawa *et al.* (3) on page 227 of this issue deals with the realization and subsequent optical characterization of point defects in a specific three-dimensional (3D) photonic crystal, termed a "woodpile" structure, because of its resemblance to a stacked woodpile. The woodpile of the given size provides a band gap at the near-infrared wavelengths used in optical communications (see the figure). In this device, a quantum-well structure is introduced as a light source. The light emission is suppressed within the band gap, but it can take place at the embedded defect cavities.

For the study of photonic crystals, it is helpful to remember the basics of condensed matter physics, in particular the theory of electronic band structures for periodic crystalline matter (see the figure). Electrons (or photons in the case of pho-

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Photonic band gap. Schematic band structure of photon energies ω in a photonic crystal. For an appropriate periodic design of the dielectric structure, a complete band gap $\Delta\omega_{gap}$ between the air band (upper shaded area) and the dielectric band (lower shaded area) arises. The additional state ω_{defect} inside the band gap is caused by a local defect. Only photons with energies inside a band, or locally at a defect state, can propagate in such a structure.

tonic crystals) are transmitted in bands of allowed states. Because there are no states in a band gap, no propagation is possible. Point defects, or intentionally arranged rows of point defects, can guide the light through the photonic crystal by offering localized states with frequencies within the gap.

Two-dimensional photonic crystals (that is, periodic arrays of rods or pores on a micrometer or submicrometer scale) al-

low a relatively easy incorporation of waveguides and point defects by conventional lithography and etching techniques. But they lack the full potential of photonic crystals; in particular, 2D band gaps are not sufficient for full reflection and a complete suppression of spontaneous emission of in-gap frequencies. In addition, photon leakage at waveguide bends can hardly be avoided.

Many 3D photonic crystal structures have been suggested, often in analogy to cells and lattices of classical crystallography (4). Some of these approaches could also be realized experimentally, such as inverted opals (5), electrochemically etched structures, or spiral architectures by special deposition techniques (6). Silicon-based photonic crystals of optimized geometry can reach a band gap size of more than 25% relative to the mid-gap frequency. Unfortunately, most of the growth techniques do not allow point defects or waveguides to be introduced. Combining holographic lithography (7) and laser direct writing in photosensitive media allows flexible fabrication of 3D photonic crystals, and efforts are under way to achieve controlled incorporation of defects.

The fabrication of the woodpile photonic crystals by Ogawa *et al.* (3) is based on wafer bonding, also termed wafer fusion or wafer direct bonding, which is a well-established technique for microelectronic mechanical system applications and for the fabrication of so-called silicon-on-insulator wafers (8). The fabrication involves (i) structuring of the surface of a wafer in terms of a regular array of grooves by lithographic techniques; (ii) proper etching; and then (iii) bonding of two wafers under a twist angle of 90°. Back etching one of the wafers to the woodpile-layer height, and then repeating the bonding procedure with high-precision alignment, allows construction of woodpile structures with five, nine, or even more individual layers. The

wafer bonding approach allows point defects and potentially also waveguides to be introduced parallel to the layers by proper lithography. In addition, wafer bonding can incorporate a layer that acts as a light source (if optically pumped). In the specific fabrication approach of Ogawa *et al*. (*3*), the woodpile structure consists of a GaAs photonic crystal with point defects and an InGaAsP multi–quantum-well structure as light emitter. The measured photoluminescence spectra clearly prove the photonic band gap. In addition, they show in-gap defect modes depending on the defect size, as expected from theory. The authors succeeded in mapping the defect by the in-gap frequency of 1.55 µm.

What are the technological implications? In principle, the combination of lithography, etching, and wafer bonding could be extended to more complex photonic circuits with desirable properties. To

take full advantage of the 3D properties of photonic crystals, the number of layers has to be increased. The real question is whether wafer bonding may offer an economically and technologically feasible fabrication approach for complex and functional 3D photonic crystals containing waveguides and microresonators. Based on present knowledge, for economical fabrication the problem of wafer scale alignment has to be solved. Another problem is the cost to etch down all the wafers to woodpile-layer thickness, a process that might be too time-consuming for mass production. The fabrication of silicon-based structures would be attractive. In this case, the optically pumped active layer could be SiO_2, doped with silicon nanocrystals and erbium, emitting around 1.5 µm wavelength. The required alignment of silicon woodpiles appears to be more difficult than in the case of GaAs,

owing to the lower electronic band gap of silicon.

Ogawa *et al*. (*3*) have described the fabrication of 3D photonic crystals of woodpile type including point defects and a multi–quantum-well structure. They report on photoluminescence measurements of corresponding microresonator states within the band gap. This is a major step forward in the direction of desirable complex photonic circuits as integrated "semiconductors for light."

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MOLECULAR BIOLOGY

Unraveling DNA Condensation with Optical Tweezers

Xiaowei Zhuang

Since the invention of optical tweezers by Ashkin, Chu, and co-workers almost 20 years ago (*1*), this technique has been applied to a variety of biological systems. It has yielded a wealth of information, such as how biopolymers behave under stress (*2*), how DNA-interacting enzymes decode or digest DNA (*3–6*), how motor proteins walk along molecular tracks (*7*, *8*), and how RNA and protein molecules fold and unfold (*9–11*). By allowing the manipulation of individual molecules, optical tweezers reveal how these biological systems work at the molecular level. On page 222 of this issue, Case *et al*. (*12*) demonstrate yet another elegant application of this technique: unraveling the mystery of how proteins called condensins make DNA take on a compact form.

In essence, optical tweezers use a tightly focused laser beam to trap a particle in three dimensions and, through redirection of the beam, manipulate the particles (*1*). Focused light exerts two forces on the particle. The gradient force draws the particle toward the focus of the beam where the

light field is the strongest. The scattering force arises from the radiation pressure exerted on the particle by absorbed or scattered photons, which blow the particle down the optical axis like a wind. When balanced, these two forces hold the particle just slightly downstream of the light focus.

Perhaps the most fascinating applications of optical tweezers are in biology. Because biological molecules are often too small to be manipulated directly by optical tweezers, a micrometer-sized dielectric sphere is often attached to the molecule of interest to serve as a handle (see the figure, panel A). This allows one to manipulate the position of the attached biomolecule and to exert a well-defined force. Both parameters can be determined with great accuracy: The position of the microsphere can be measured to within 1 nm, and the force to within 1 pN. Optical tweezers, therefore, allow exquisite control over the manipulation of biomolecules.

Using this technique, Case *et al*. have discovered that bacterial condensins compact DNA in an orderly fashion. DNA condensation is essential for cell division because compact DNA is much easier to split between two daughter cells than DNA in its expanded form. The chromosomal DNA of bacteria is compacted into a nucleoid (*13*), and eukaryotic cells employ an elaborate

mitotic machinery to achieve chromosome compaction (*14*). In both worlds, SMC (Structural Maintenance of Chromosomes) proteins are crucial players in the process of DNA condensation (*13*, *14*).

Case and co-workers concentrated on the *Escherichia coli* condensin MukBEF, which consists of an SMC dimer (MukB) and two non-SMC subunits (MukE and MukF) (see the figure, panel A). In their setup, polystyrene beads were attached to the two ends of a piece of double-stranded DNA. One bead was held by an optical trap and the other by a micropipette (panel A). By moving the micropipette away from the optical beam, the investigators obtained a force-versus-extension curve for the DNA. In a previous study, this group had used a similar method to examine the mechanical properties of DNA. However, when they applied their trick to DNA in the presence of MukBEF and ATP, they were caught by surprise.

First, they found that the force-extension curve increased more quickly than observed for naked DNA (see the figure, panel B). This is perhaps not so surprising considering that MukBEF condenses DNA. A very interesting phenomenon, however, occurred as the force reached 17 pN: A sawtooth pattern became superimposed on an otherwise flat region of the curve, indicating that the DNA-MukBEF complex underwent a phase transition consisting of individual decondensation events (see the figure, panel B). As the force was relaxed, the DNA returned to its original condensed form. Amazingly, when the applied force was less than but still close to 17 pN, recondensation was so slow that individual condensation steps of

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