SEMICONDUCTOR LASERS

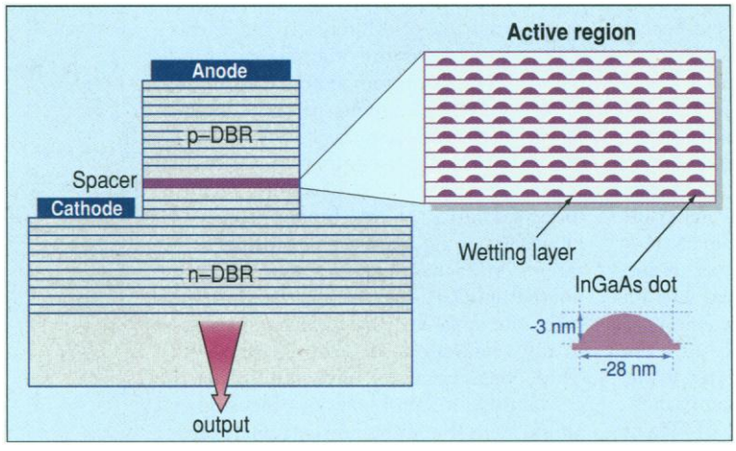
Fast, Cheap, and Very Bright

Gerhard Fasol

Saito *et al.* (*1*) recently reported room temperature operation of a quantum dot (QD) vertical-cavity surface-emitting laser (VCSEL) powered by current injection. This work combines recent advances in self-organized crystal growth of highly homogeneous multiple layers of quantum dots with the development of high-performance VCSELs. Cheap high-performance lasers have revolutionized data communications and many other fields. As this breakthrough demonstrates, the progress of laser development and data communications is anything but slowing down.

The infrared VCSEL was invented by Iga and co-workers (*2*) in the late 1970s. Schneider and co-workers achieved laser emission at red wavelengths 1993, and in 1994 Motorola commercialized infrared VCSELs (*3*). In VCSELs, the laser cavity is vertical to the crystal substrate and much shorter (usually one-half of the wavelength of light in the material) than that in conventional edge-emitting lasers. Modern VCSELs use epitaxially grown multilayer distributed Bragg reflectors (DBRs) as mirrors, which are doped to serve an additional role as current contacts. Gain is provided by an active layer of one or more quantum wells at the antinode of the longitudinal electromagnetic eigenmode of the cavity. VCSELs were a revolutionary concept, and it took almost 20 years, but they have now reached commercial application in gigabit-rate optical fiber communication systems (*4*). VCSELs have many advantages over edge-emitting lasers: lower fabrication costs, lower testing costs, lower threshold current, superior bandwidth, and the capability to be fabricated into large arrays in a single fabrication sequence (*3*). Therefore, they have the potential to become the most important type of commercial laser soon.

The VCSEL allows many interesting design variations: The electromagnetic VCSEL-cavity modes can be designed to minimize the spontaneous emission noise, and other new device concepts are possible. In a particularly advanced proposal (*5*), the whole VCSEL laser cavity, including the DBR mirrors, is constructed as a three-dimensional photonic–band gap macrocrystal, incorporating a phase-shift layer between the mirrors, which promises refined performance.



Quantum dot vertical-cavity surface-emitting laser of Saito *et al.* (*1*), which operates at room temperature. The laser cavity consists of two AlAs/GaAs distributed Bragg reflectors (DBRs), which act as mirrors at the laser wavelength. The active region consists of 10 layers of self-assembled $In_{0.5}Ga_{0.5}As$ quantum dots.

The use of quantum dots as the active medium in VCSELs may lead to lasers with even greater performance. To the best of my knowledge, Saito *et al.* (*1*) are the first to report such a current injection QD-VCSEL working at room temperature.

For a long time it appeared impossible to fabricate quantum wires and dots of sufficient quality, and many attempts have failed. Etching and lithography did not succeed. One fundamental difficulty is that the lower the dimensionality, the more unfavorable the surface/volume ratio becomes; therefore, surface quality requirements rise dramatically as the dimensionality is decreased from quantum wells to wires and to dots.

Recently, however, impressive self-organized crystal growth of highly regular arrays of homogeneous quantum dots has been achieved. Under certain conditions, the free energy of an array of strain-relaxed pyramids can be lower than that of a continuous strained film grown onto a substrate with a different equilibrium lattice constant. This effect was proposed in 1985 for the growth of InAs quantum dots onto GaAs (*6*). When a thin layer of InAs or InGaAs is grown onto GaAs, a complicated interplay between growth kinetics, surface energy, and strain energy arises. Crystal growth shows a striking sequence of events: initially, a continuous strained InAs or InGaAs layer grows onto GaAs. However, when a critical thickness of a few monolayers is exceeded, the strained film breaks up. The pyramids and their edges create a strain field in the underlying substrate material and interact by means of it (*7*). The result can be a surprisingly regular periodic array of quantum pyramids of very regular size. These striking self-organization effects have been experimentally discovered in various systems (*8*). When such self-organized dots are over-grown with a barrier layer and a new layer of self-organized dots is grown onto the next barrier layer above, the strain field causes the upper array of dots to align with the dots of the layers below. As subsequent layers are grown vertically, they interact through the strain field (*9*), and the upper layers of quantum dots show increasing perfection: both quantum-dot size and spacing grow more uniform (*10*) as the number of layers increases. This vertical self-assembly effect might explain why Saito and co-workers' multilayer quantum dot array VCSEL seems to show intrinsically higher performance than QD-VCSELs incorporating only a single layer of quantum dots.

The active layer of the room temperature current-injection QD-VCSEL (*1*) (see figure) consists of 10 superimposed layers of quantum dot arrays. The laser emission is at a wavelength of 960 nm, the threshold current is about 30 mA (corresponding to a threshold current density of about 820 A/cm^2), and the light output power is typically 1.5 mW. These characteristics show that the QD-VCSEL is not very far from commercial application. The flexibility of this design approach promises much scope for optimization of parameters.

The impact of the data communication revolution on our daily life is great, and behind this revolution are developments such as the discovery of cheap and superior lasers. Further developments arising from the combination of VCSELs with self-organized crystal growth driven by complex strain fields may thus be quite important. Of course, much research in this area still remains to be

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done: optimizing VCSEL cavity design, understanding and improving self-assembled quantum dot growth, or solving the long-standing problems of polarization control and emission-mode stabilization in VCSELs, for example. Gallium nitrides are now providing another dimension, with the discovery (*11*) that laser emission in the most recent InGaN lasers is probably from self-organized dots.

References

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METEORITICS

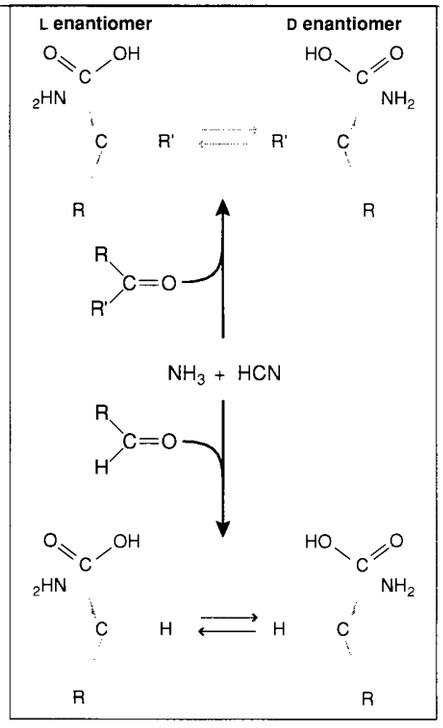
Extraterrestrial Handedness?

Jeffrey L. Bada

Asymmetry in the handedness of molecules that arise through biosynthesis is perhaps one of the more unique features of life on Earth. A well-known example is that only L amino acids are incorporated into proteins during transcription even though amino acids with a chiral or asymmetric carbon atom can exist as two chemically equivalent optical isomers, the L and D enantiomers. How this L amino acid handedness, or homochirality, originated in terrestrial life has been an area of considerable discussion (*1*). Prebiotic syntheses of amino acids either on Earth or elsewhere would be expected to produce racemic mixtures (equal amounts of the L and D enantiomers, or D/L = 1.0). Therefore, an enantiomeric selection process was required at some stage in the origin or evolution of life on Earth. Because there is no apparent biochemical reason why L amino acids would be selected over D amino acids, the homochirality has been considered to be simply a matter of chance.

Analyses of carbonaceous chondritic meteorites have been of central importance in the debate about the origins of homochirality. The discovery in 1970 that the Murchison meteorite contained endogenous amino acids (*2*), some of which play an essential role in biochemistry as we know it, provided the first conclusive evidence that amino acids have been produced by abiotic cosmochemical reactions either somewhere in the solar system or in extrasolar environments. However, because those amino acids processing a chiral carbon were found to be racemic within the limits of the measurements, there appeared to be no evidence that the exclusive use of L amino acids in terrestrial biochemistry was preordained. Subsequent analyses of Murchison made more than a decade after the original reports indicated that some protein amino acids showed an apparent enrichment in the L enantiomers, but this excess was considered to be due to terrestrial contamination rather than the result of some sort of abiotic enantiomeric resolution or enrichment process (*3*). However, as reported by Cronin and Pizzarello on page 951 of this issue (*4*), some unusual amino acids present in the Murchison meteorite apparently do have small excesses of the L enantiomers (that is, D/L < 1.0). These measurements have minimized the contamination problem by focusing on amino acids that either are extremely rare or have never been reported in terrestrial organisms or the geosphere.

Four α-dialkyl amino acids—α-methylisoleucine and α-methylalloisoleucine (2-amino-2,3-dimethylpentanoic acid), α-methylnorvaline (2-amino-2-methylpentanoic acid), and isovaline (2-amino-2-methylbutanoic acid)—are reported to have an L enantiomeric excess of 2 to 9% (*4*). Only isovaline has been reported in some microbial peptides, where it is present as either the L or D enantiomer (*5*). The α-hydrogen analogs of two of these α-dialkyl amino acids, norvaline and α-amino-n-butamoic acid, are racemic, suggesting that enantiomeric excess is only preserved in amino acids that are resistant to racemization (see figure). The analyses were carefully carried out, and there is no obvious reason to believe that the enantiomeric excesses are analytical artifacts, although confirmation with other analytical methodologies, and the detection of similar excesses in other carbonaceous chondrites, are certainly required. Assuming that the enantiomeric excesses are indeed real, how were they generated and do they have anything to do with the L amino acid homochirality found in life on Earth?



α–Amino acids in carbonaceous chondrites are thought to have been formed by the Strecker synthesis reaction in aqueous solutions. The reaction of HCN with aldehydes and ammonia generates amino acids with an α hydrogen (lower branch), which can racemize. The similar reaction with ketones produces α-dialkyl amino acids (upper branch), in which racemization is prevented because of the absence of an α hydrogen.

α–Amino acids in carbonaceous chondrites are generally thought to have been generated by the reaction of aldehydes, ketones, ammonia, and hydrogen cyanide (the Strecker reaction shown in the figure) in aqueous fluids on the meteorite parent body (*6*). This synthetic pathway would produce racemic mixtures of amino acids with a chiral α carbon because the starting aldehydes are achiral (that is, they lack an asymmetric carbon); at chiral β carbons, racemic mixtures would also be expected, unless the starting chiral ketones were already enriched in one enantiomer by some process. The finding of L enantiomeric excesses in both α-methylisoleucine and α-methylalloisoleucine,

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