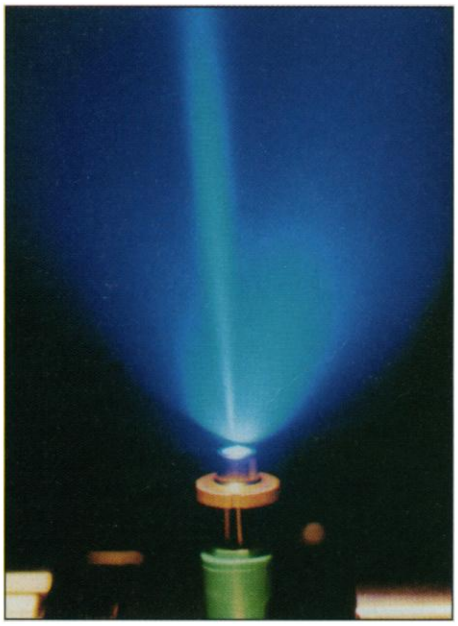
Room-Temperature Blue Gallium Nitride Laser Diode

G. Fasol

Nakamura *et al.* recently reported the fabrication of very bright blue, green, and yellow light-emitting diodes (LEDs) (*1*) and of room-temperature, pulsed current-injection blue laser diodes (*2*, *3*) from gallium nitride (GaN) and related materials. Their employer, Nichia Chemical Industries (Anan, Tokushima-ken, Japan), announced commercial blue GaN LEDs in November 1993 and green LEDs in September 1995. These are stunning developments on the forefront of applied physics, but even more importantly, they have come from a medium-sized company with modest resources and staff. It is a case that may offer some lessons for new ways of doing research in the future.

The discoveries at Nichia have propelled the previously little-noticed GaN materials into the mainstream of solid-state research. This has created new branches of the optoelectronic industry with strong growth potential and many new applications in preparation. These new industries already employ several hundred people and will employ many more in the future. These discoveries may also eventually replace vacuum tube lighting technologies, namely light bulbs and fluorescent tubes, by solid-state devices, analogous to the replacement of electronic vacuum tubes by transistors. Light-emitting diodes, including the new blue LEDs, are in commercial service today in large outdoor displays. The replacement of light bulbs by LEDs in traffic signals is presently being tested on a large scale in different climatic areas of Japan: LEDs use only about one-quarter of the electricity, and it is expected that they will only have to be replaced once every 10 years, whereas light bulbs in traffic signals are routinely changed once a year in Japan, for safety reasons, at great cost.

For at least 25 years there has been a race to develop blue and green semiconductor light emitters. Such light emitters are expected to have very large commercial markets in a wide range of applications, including lighting, signaling, flat-panel computer and television displays, color copiers, color scanners, optical data storage, and medicine. Most electronic industry giants and many government laboratories and universities competed in this race, but almost all of the groups worked on II-VI compounds (such as ZnS, ZnSe, and ZnMgSS). These have not yet yielded any commercial products, despite the expenditure of enormous research resources. The reason is that II-VI compounds are rather fragile and are grown at comparatively low temperatures. Defect propagation and other problems limit the lifetimes to only a few hours, far below the 10-year minimum lifetime necessary for most commercial electronic products. Recently there has been some improvement in lifetimes and control of defect creation.



New blue light. Blue laser light emission from a GaN-based electrical carrier injection laser diode. [Photo: Nichia Chemical Industries]

Gallium nitride electroluminescent diodes were demonstrated at RCA Laboratories in the 1970s (*4*), and research on the GaNs has continued on a small scale ever since. At least three major problems had to be solved for GaNs to succeed: (i) the lack of suitable lattice-matched epitaxial substrates, (ii) thermal convection problems due to the very high growth temperatures (about 1000°C), and (iii) the failure of *p*-type doping.

Most work today makes use of sapphire substrates, which have a lattice mismatch of about 15% with respect to GaN. Akasaki at Nagoya University and Nakamura at Nichia both developed very similar buffer-layer technologies to achieve GaN epitaxial growth with appropriate defect density (*5*). Both Akasaki and Nakamura use metal-organic chemical vapor deposition methods. The substrate temperature is more than 1000°C during growth. This temperature is exceptionally high and causes convection problems, which were addressed by one of Nakamura's inventions. He developed a dual-flow reactor (*6*), where an auxiliary stream of gas blows perpendicularly to the substrate, pushing the primary stream of reactants toward the substrate and improving the growth.

A long-standing problem was the failure to achieve *p*-type doping in GaN materials. Akasaki showed that a solution existed: He discovered by accident that the low-level electron beam irradiation in an electron microscope could yield *p*-type GaN (*7*). However, it was Nakamura who solved the problem of *p*-type doping fully. He found (*8*) that all previous GaN researchers had annealed their samples in ammonia (NH_3). Ammonia dissociates above ~500°C, releasing atomic hydrogen, which passivates the acceptors. Therefore, Nakamura switched to annealing in a clean nitrogen (N_2) atmosphere and thereby invented a reliable method to achieve high-quality *p*-type GaN materials. These discoveries led him to the development of commercial blue GaN LEDs (*1*), which are about 200 times as bright as previously available blue LEDs.

The next race is to develop the first commercial GaN-based blue laser diode, which has, to the best of my knowledge, not been settled yet. The first trophy in this race was won again by Nakamura: on 12 December 1995, Nichia Chemical Industries announced the first room-temperature electrically pumped blue GaN semiconductor laser diode (*2*); however, it is not commercially viable yet.

Whereas luminescence in the LEDs is still extrinsic (owing to implanted impurity atoms), laser emission seems to result from band-to-band transitions in the active layer consisting of 26 periods of an $In_{0.2}Ga_{0.8}N$/$In_{0.05}Ga_{0.95}N$ multi-quantum-well structure. Nakamura has recently reduced the number of layers, which lowers the laser threshold current and voltage.

A further problem, which Nakamura seems to have solved, is the difficulty of cleaving GaN-based layers grown on sapphire. Nakamura reports (*2*) the fabrication of mirror cavity faces by reactive ion etching, and very recently, he also achieved lasing in cleaved laser structures (*3*).

Electrically induced laser emission at room temperature is a very important result because laser action in new material systems is usually reported for pulsed optical excita-

The author is in the Department of Electrical and Electronic Engineering, Institute of Industrial Science, University of Tokyo, 7-22-1 Roppongi, Minato-ku, Tokyo 106, Japan, and the Sakigake 21 program of the Research Development Corporation of Japan (JRDC). E-mail: fasol@cc.iis.u-tokyo.ac.jp

tion or at very low temperatures. However, the initially announced current threshold (1.7 A) and the voltage (on the order of 35 V) at the operating point are still far too high for immediate commercial application. Nakamura tested the experimental laser structures for 2 hours under pulsed current injection at room temperature and found no degradation. The research priority at the moment is to achieve continuous emission. Recently, Nakamura decreased the threshold voltage to 20 V and the threshold current to below 200 mA and increased the lifetime to 24 hours with a pulsed-current duty cycle of 0.1 to 0.2%. With a 20% duty cycle, the lifetime is as short as 20 min. This rapid progress during the last few months is, of course, very encouraging; therefore, there is much hope that commercial blue GaN-based lasers will be announced in the not-too-distant future.

One application for blue lasers is in CD-ROM and magneto-optical data storage: the data density will be about four times higher because of the shorter wavelength of blue laser light. Other important applications are in displays, medicine, lighting, and more.

An important point is that GaN LEDs convert electric energy into light with an efficiency lower than that of fluorescent light tubes; lasers, on the other hand, already have a differential efficiency of the order of 35% per facet, which is much higher than that of fluorescent tubes. Therefore, there is some hope that GaN lasers might also have important large-scale lighting applications. In this context, it is important to realize that the blue LEDs (and lasers when they become available) fill the gap in the spectrum of available semiconductor light emitters, which so far has prevented the creation of white lighting and full-color displays with semiconductor emitters.

Although there has been a considerable amount of work on the development and study of GaNs for many years, particularly by Akasaki, it was only through Nakamura's research that GaNs moved from a potentially promising material to the actual commercially viable solution of the unsolved problem of a practical blue-light emitter. Nakamura and Nichia's chairman, Nobuo Ogawa, insist very strongly that there is no collaboration with other companies or universities at this time, and Nichia is proud that it received no government support.

How is a medium-sized company—Nichia Chemical Industries—leading this field against all major multinationals? In fact, it is no accident that this breakthrough was achieved at Nichia. There is much concern at present about the health of physics research (9), and perhaps Nichia teaches us something new about how research can be done. How did a single researcher, until recently without a Ph.D. degree or publications, win this race, and how is he still leading the field against competing multinationals with larger resources? In my view, there are several reasons. One reason is corporate emphasis on simplicity: Ogawa, also Nichia's founder, grew up in a farming family and became a pharmacist during the Second World War. During the hardships following the war, he founded Nichia by borrowing family money to develop his first materials. He therefore learned to bring products to market quickly with limited resources. Nichia today has about a quarter of the world market of phosphors for television monitors and fluorescent tubes. So actually, blue diodes are not Nichia's first success story.

Nichia's management structure for the blue LED and laser development consists of Nakamura and Ogawa. There is no additional hierarchy, no committees, no politics, no advisers, no national program, no international center, and no government support. Such structures tend to minimize risk by favoring mainstream research done by many groups in parallel. Ogawa decided on the GaN project knowing that it was a risky gamble, and he gave Nakamura full support to do the project. A large organization, on the other hand, is unlikely to give several millions of dollars for a high-risk project to a researcher without a Ph.D. and without research publications 10 years after having earned his master's degree—which is precisely what happened in Nakamura's case. One could say that the GaN project started at Nichia and has made such rapid progress because Shuji Nakamura fell in love with GaN.

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Receptor Tails Unlock Developmental Checkpoints for B Lymphocytes

Patricia E. Roth and Anthony L. DeFranco

The immune system consists of many specialized cell types with diverse functions. This diversity results, in part, from the development of distinct lymphocyte cell types. As they mature, lymphocytes pass through discrete stages, their progress directed by specific molecules. Two new papers (*1*, *2*), including a report in this issue of *Science*, reveal two novel checkpoints in the developmental program of antibody-producing B lymphocytes. The molecular triggers for these checkpoints are well-known receptor molecules expressed by B cells that have now acquired new regulatory roles.

During their development, B cells pass through a series of regulated stages in which the functional genes are formed that encode both the secreted and membrane forms of immunoglobulin (Ig). Membrane Ig complexes with a heterodimer of the accessory proteins Ig-α and Ig-β to form the B cell antigen receptor (BCR). The Ig-α and Ig-β proteins each contain a single NH_2-terminal, extracellular Ig-like domain, a transmembrane domain, and a short cytoplasmic domain. The signal-transducing components of the receptor reside in a two-tyrosine–containing motif in the cytoplasmic domains of both Ig-α and Ig-β. This receptor plays a critical role in the activation of B cells during an immune response. The cytoplasmic tails of the T cell antigen receptor and of various Fc receptors also contain this signaling motif, the immunoreceptor tyrosine-based activation motif (ITAM). The two papers describe the effects on B cell development of gene knockout experiments in which the expression of the entire Ig-β molecule was ablated (*1*) or the final 40 amino acids of the Ig-α cytoplasmic domain, including its ITAM, were removed (*2*).

After hematopoietic stem cells in the bone marrow commit to the B cell lineage, they undergo a stereotypical sequence of Ig gene rearrangements. A lymphoid-specific DNA recombination machinery, the V(D)J recombinase, juxtaposes a subset of alternative gene

The authors are at the University of California, San Francisco–Hooper Foundation, 513 Parnasuss Avenue, San Francisco, CA 94143, USA. E-mail: defranco@socrates.ucsf.edu and proth@itsa.ucsf.edu