also change the efficacy of synaptic connections between the synchronized cells (9). Riehle *et al.* detected the increased synchrony by comparing the number of observed coincident spikes (red bars) with the number expected by chance, based on a running estimate of rates over a longer interval (blue bar). This running comparison can identify exceptional synchronizations whenever they occur. Interestingly, these occurred at times when the monkey expected a possible cue, as well as when he made a motor response. Thus, synchronization and rate coding can occur separately or together (*8, 9, 12, 14, 15*).

Several other approaches can detect coherent activity in neural populations at millisecond resolution. Standard cross-correlations between simultaneously recorded neurons commonly reveal synchronous activity, and time-dependent cross-correlation measures (*11*) have revealed that synchronous firing can be rapidly modulated with behavior, even without changes in firing rates (*12*). Other studies have found evidence for precisely timed patterns occurring among neural groups in a behavioral situation (*5*). Simulations have shown that such synchrony can be preserved in chains of neurons with realistic synaptic connections (*13*). Another form of synchronized activity in neural populations is the widespread periodic oscillations seen in visual cortex neurons, which has been suggested to subserve a binding function (*9*), a suggestion potentially applicable to coordination of motor responses (*14, 15*). Another approach uses the "gravity" method to identify groups of neurons that tend to fire in synchrony: If n neurons are located in n-dimensional space, and their spikes are endowed with a transient "charge," those cells that fire synchronously tend to be attracted and form identifiable clusters (*6*).

Although all of these algorithms can detect the existence of precise temporal structure in neural activity, this does not yet establish their function as a temporal code. What is needed first is some demonstration that synchronization occurs reliably under particular behavioral conditions. The accumulating evidence is suggestive (*5–9, 12, 14*) but still leaves the exact function unproven. Establishing the functional mechanism may not be a matter of finding tighter correlations with behavioral events; for example, holographic mechanisms code distributed information in terms of phase relations rather than literal representations (*2*). Skeptics can still argue that the temporal events revealed by these methods are epiphenomena or products of the statistical models, and that anything temporal coding can do, population rate coding can do as well (*16*). Moreover, there are open questions about how temporal codes are established and how they interact with rate coding (*8, 15*). These issues can now be investigated with the tools at hand: Multiunit recordings can be analyzed with these algorithms, and the detected events can be related to behavior. Neural network simulations can also help to demonstrate how the putative coding mechanisms could actually work (*2, 5, 13*). This combination of approaches should crack the temporal code one way or the other.

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APPLIED PHYSICS

Longer Life for the Blue Laser

Gerhard Fasol

Less than 1 year after announcing the first continuous-output gallium nitride (GaN) blue light semiconductor laser at room temperature, Nakamura *et al.* at Nichia Chemical Industries Ltd. are now reporting such lasers with a demonstrated lifetime of 3000 hours and an estimated lifetime of over 10,000 hours (*1*). This now reaches the realm of commercial application, where lifetimes of 10,000 to 20,000 hours are required. Nichia estimates that commercial GaN laser diodes will be introduced in the fall of 1998.

Nakamura's recent development (*2*) of GaN-based violet, blue, and blue-green light-emitting diodes and laser diodes is certain to have a large impact on the world as we know it, and it has opened a new material system for scientific and commercial exploration. These devices have large ready-made commercial markets: displays, high-density data storage, laser printing, communications, and lighting, just to name a few. There may well be several other applications that have not yet been imagined.

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Not surprisingly, therefore, researchers of many large corporations and universities are competing to develop GaN lasers. To my knowledge, six laboratories in addition to Nichia have now reproduced variations of Nakamura's pulsed room-temperature GaN laser: Cree Research (on SiC substrates), Fujitsu, Toshiba, the University of California at Santa Barbara, Xerox, and Sony. This means that Nakamura is about 2 years in advance of his competition. Under today's circumstances, this is astonishing. High-temperature superconductivity, the scanning tunneling microscope, and other recent breakthroughs were reproduced much more quickly in competing laboratories. And this despite incomparably higher competitive market pressures in the case of the GaN laser.

Nakamura's new laser diodes are similar to those of 1 year ago (Fig. 1), which had a lifetime of only 27 hours. There are two main advances in the recent work. First, for the present lasers, modulation-doped superlattices are used with 120 periods of 2.5-nm thick doped GaN separated by undoped 2.5 nm $Al_{0.14}Ga_{0.86}N$, instead of thick AlGaN layers, which easily cracked. Second, the laser diodes are grown onto epitaxially laterally overgrown (ELOG) GaN substrates (Fig. 2).

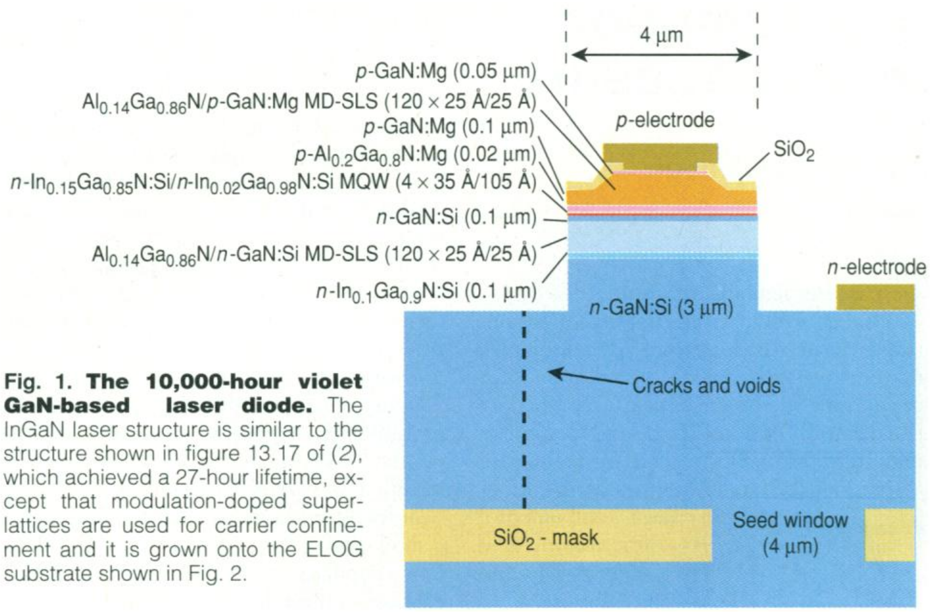

Fig. 1. The 10,000-hour violet GaN-based laser diode. The InGaN laser structure is similar to the structure shown in figure 13.17 of (*2*), which achieved a 27-hour lifetime, except that modulation-doped superlattices are used for carrier confinement and it is grown onto the ELOG substrate shown in Fig. 2.

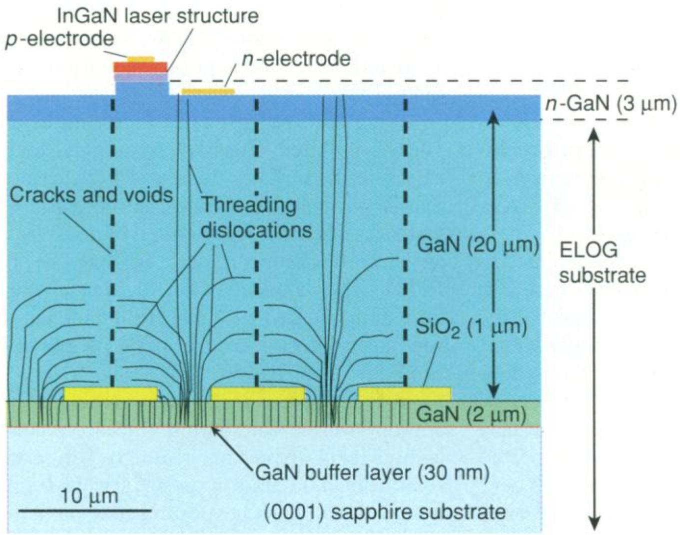

Fig. 2. Substrate for laser growth. The 4-μm-wide windows between SiO_2 barriers are used as seeds to grow 20-μm-thick GaN layers. Because of the strain fields, harmful threading dislocations change their propagation direction parallel to the substrate plane and are largely confined to within 5 μm of the SiO_2 barriers. A GaN substrate with low dislocation density results.

Because of the strong lattice mismatch, GaN grown onto sapphire is known to have a large number of threading dislocations, which propagate along the (0001) direction, parallel to the growth direction, and which eventually pierce through the active device layer and reduce the performance.

Sakai *et al.* (*3*) and Nam *et al.* (*4*) recently found that by growing GaN with 4-μm-wide windows between SiO_2 masks as seeds, the threading dislocations are bent over by the strain fields and propagate laterally, parallel to the substrate (Fig. 2). Most threading dislocations become restricted to an area about 5 μm above the substrate. By growing 20 μm of GaN, Nakamura obtains a low density of threading dislocations above the SiO_2 mask areas, except at the center, where voids and cracks still propagate upward. By locating the 4-μm-wide laser structure directly above the SiO_2 mask but away from the cracks in the center, Nakamura dramatically improved the laser lifetimes.

The laser emits one or more violet lines with wavelengths around 401 to 402 nm. It was still working after 3000 hours (125 days) at 20°C. To obtain an estimation of the actual lifetime in a short time, they performed accelerated lifetime measurements at elevated temperatures. The best lifetimes were 700 hours at 60°C and 1000 hours at 50°C. By measuring the degradation speed for different temperatures, the best lifetime at 20°C was estimated to be approximately 10,000 hours, which is already close to the lifetime needed for commercial application.

This work reveals a new trend toward sophisticated substrate engineering. Although epitaxial growth of compound semiconductor quantum structures has been performed for many years, only recently has effort been spent in putting more intelligence into the substrate. An interesting approach is the twist-wafer bonded substrates of Lo and coworkers (*5*). They trick a thin layer into complying with an epitaxial layer of quite different structure and lattice constant by bonding it onto a substrate twisted (rotated) by a large angle and removing its carrier substrate.

Because only a few months have been spent on the development of GaN ELOG substrates, I expect that the ideal ELOG structure may not have been found yet. For example, the present structures still have voids and cracks that propagate upward directly above the center of the SiO_2 masks (Nakamura fabricates his lasers away from these cracks). I expect that further work could greatly improve the quality of the laterally overgrown GaN substrates. At present, detailed transmission electron microscopy work and theoretical work are progressing in several laboratories to explore the interaction of the different types (at least three) of threading dislocations in GaN, with the strain field created by GaN overgrowing the SiO_2 masks laterally from the seed windows.

It is significant that this progress is much faster than that of the original gallium arsenide lasers, which took over 20 years to develop. As Pankove points out (*6*), the reason is that Nakamura confines excitons into narrow (35 Å) quantum wells, so that the breakup of excitons by the Franz-Keldysh effect in the electric fields caused by the potential fluctuations due to dislocations is much reduced.

It is also puzzling that present-day commercial GaN LEDs and the almost commercial LDs work at all, considering their high defect densities. Today's best reported GaN has about 10^8 defects/cm^2. Gallium arsenide LEDs or LDs with defect densities this high would be useless; they usually have about 10^4 defects/cm^2. Lester *et al.* (*7*) argue that the strong ionicity of GaN causes the absence of Fermi level pinning at the surface and therefore neutralizes the effect of dislocations, which have the character of internal microsurfaces.

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