Nichia's Shuji Nakamura: Dream of the Blue Laser Diode

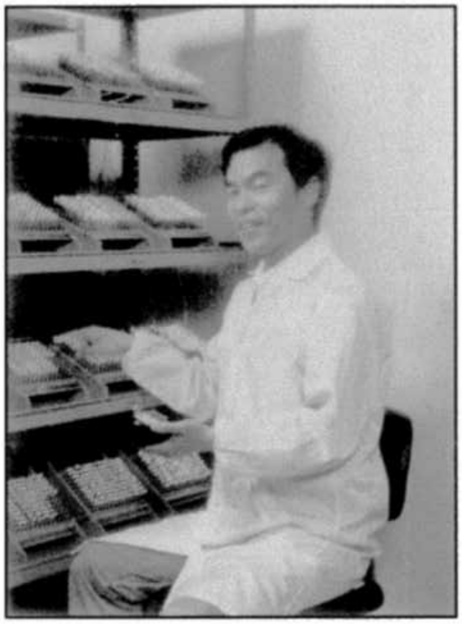
The history of science has more than its share of underdog stories—researchers working off the beaten track who succeed where others can't—but few of them, if any, are as remarkable as the story of Shuji Nakamura and the blue laser diode. For decades the blue laser was the ultimate dream in laser technology. The reason was a simple combination of physics and market economics. Blue light has the shortest wavelength of visible light. Build a blue laser diode, and you could quadruple the amount of data that could be read and stored on a compact disc, a CD-ROM, or a digital video disc (DVD) player. With red and green laser diodes already on the shelves, blue was the last of the primary colors left to tackle, and if that could be done, one could imagine a device that combined blue, red, and green and emitted white light, perhaps putting the light bulb as we know it out of business.

For two decades, researchers working for the biggest players in the electronics industry, from RCA and Hewlett-Packard to Matsushita and Sony, tried their hands at the blue laser diode and failed. Nakamura, a self-described country boy, did it while working for Nichia Chemical Industries Ltd. in Tokushima, Japan.

Nakamura may have single-handedly, or virtually so, changed the technological face of the world. And his research papers certainly reflect his influence: a few years back his paper on "InGaN-based multi-quantum well-structure laser diodes" (see the table on page 4, paper #1) was number 6 on the Science Watch *list of Red Hot Research Papers of 1996—one of only three physical-sciences papers to rank among the year's most-cited reports. That paper subsequently enjoyed a long run in the Physics Top Ten during 1997. More recently, a 1998 paper, "Continuous-wave operation of InGaN/GaN/AlGaN-based laser diodes grown on an epitaxially laterally overgrown GaN substrate"* (Appl. Phys. Lett., *72[2]:211-3, 1998), has also appeared among the Top Ten. "What I have managed to achieve," Nakamura has written, "shows that anybody with relatively little special experience in the field, no big money, and no collaborations with universities or other companies, can achieve considerable success alone when he tries a new research area without being obsessed with conventional ideas and knowledge."*

Nakamura, now 45, received both his bachelor's degree (1977) and master's degree (1979) in electronic engineering from the University of Tokushima. In 1994, the same insititution awarded him a Doctor of Engineering degree. Since 1993, Nakamura has been head of the Department of Research & Development at Nichia Chemical Industries. He spoke to Science Watch *correspondent Gary Taubes from his office in Tokushima.*

SW: Your background was not in lasers at all. How did you get started in this business, and why Nichia Chemical, which had no research in this area?



"I actually thought it looked very easy to make blue LEDs," says Shuji Nakamura of Nichia Chemical Industries, Ltd., Tokushima, Japan. "I thought, blue means I just have to change the color—I just have to change the material."

Nakamura: After I graduated from the University of Tokushima with a master's degree in electrical engineering, I expected I would go to work for a big consumer electronic company such as Sony or Toshiba. But while I was studying I got married and my wife and I had a baby, and I wanted to raise my child in a small city like Tokushima, because I thought Tokyo was too big and too noisy. So I decided I would stay in Tokushima, but the only companies around were very small. My advisor, Professor Osama Tada, knew the president of Nichia Chemical and recommended me to him. At that time, the company was making a phosphor for CRT tubes and fluorescent lamps.

SW: What did you start off doing?

Nakamura: Virtually everyone in the company was working to make this phosphor. I managed to get to the R & D department, which was all of three people, working on purified gallium metal. This was a source material of gallium arsenide and gallium phosphide, which could be used to make red and infrared light-emitting diodes. Since I had also studied semiconductor theory and technology, and my interests were in material science, I thought I could do some research to make a crystal of gallium phosphide.

SW: Did you succeed?

Nakamura: Yes. It took me three years. I made gallium phosphide crystals but my sales were not good, because the bigger companies—Toshiba and others—were by then selling the same product. Because Nichia was small and its name was not a familiar one, I couldn't compete. My company wasn't happy with me. I quit the gallium phosphide research and switched to gallium arsenide crystal growth in 1982. That can also be used to make infrared and red LEDs. I spent another three years making a gallium arsenide crystal.

SW: How did that do?

Nakamura: It was the same story. By 1985, I had a product to sell, but again sales were not good, because the same big companies were already selling the same product. My company couldn't win the competition with the big companies and the bosses weren't happy.

SW: You still weren't doing laser research?

Nakamura. Not yet. In 1985, I went to work on a gallium aluminum arsenide epitaxial wafer. This is also used for LEDs. It's called an epitaxial wafer because you use very thin layers to make the LEDs. So I spent the next three years on that and came out with these gallium aluminum wafers for red and infrared LEDs, but the same thing happened: Our sales were not good because the bigger companies were already selling the same product by the time I was. The quality of our LEDs and epitaxial wafers was just as good and the prices were the same, but our company was small and local and couldn't compete. So once again my company was not happy.

By this time the R&D department was down to just me—the other two people left because the results were so terrrible. I kept at it, but I was dispirited. For ten years I had worked very hard to make these products. I worked twelve hours a day, seven days a week, except holidays. I had a very, very small budget and had to make everything I needed myself. I even made my own reactors—the furnaces needed to do the crystal work. The commercial reactors were too expensive. I made three products all by myself, and still my salary and position were not good at the company. My bosses always complained that my results were terrible, because I spent a lot of money, as far as they were concerned, and nothing sold. But for ten years I had been working to make these LED materials and I knew at the time there were no high-brightness blue LEDs. For LED researchers, this was a dream. But my bosses said it would be impossible to create a blue LED at Nichia, because many big companies and many research teams in big universities were trying to do it and were failing. So I went to went to my company's chairman, Nobuo Ogawa, who was my professor's friend, and the president Eji Ogawa, who was his son-in-law. I asked them if they would let me do research on blue LEDs and they said "Sure. No problem. Go ahead." I was very surprised. I asked them

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Nakamura's Blue Heaven

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to give me a large budget so I could do it. "Please give me three million U.S. dollars," and they said "Sure. No problem." They had faith in me because, despite the dismal sales, I had developed three new products for this company and I was the only one at Nichia who had succeeded in making new products.

SW: Weren't you worried? After all, you were going after the single hardest challenge in your field.

Nakamura: For ten years, all of my research had been on LED material and LEDs. I had lot of knowledge and experience in the research. I actually thought it looked very easy to make blue LEDs. I thought, blue means I just have to change the color—that's all. I just have to change the material. To me, it looked very easy.

SW: Why did you decide to use gallium nitride?

Nakamura: At that time, in 1989, there were two materials for making blue LEDs: zinc selenide and gallium nitride. These had the right band gap energy for blue lasers. But everybody was working on zinc selenide because that was supposed to be much better. I thought about my past experience: if there's a lot of competition, I cannot win. Only a small number of people at a few universities were working with gallium nitride so I figured I'd better work with that. Even if I succeeded in a making a blue LED using zinc selenide, I would lose out to the competition when it came to selling it.

SW: What was it about zinc selenide that made it seem so superior?

Nakamura: The crystal quality of zinc selenide is very good. The dislocation density, which is a measure of the number of defects in the crystal, was less than 10^3 per cubic centimeter. Gallium nitride was more than 10^{10} per cubic centimeter. And when people wanted to make reliable LEDs and laser diodes, they knew that the dislocation density has to be lower than 10^3 or even 10^2. This is just physics.

SW: That sounds almost insurmountable. How did you get around that defect problem?

Nakamura: Well,first I needed a MOCVD reactor. MOCVD stands for "metal organic chemical vapor deposition." Since I had money now, I bought a commercial reactor and used it to grow gallium nitride crystals, but I couldn't get them to grow on the substrate. So I spent two years modifying my commercial reactor and succeeded in making what I called the two-flow MOCVD reactor. Usually a MOCVD has only one gas flow. That's a reactive gas that blows parallel to the substrate. I added another subflow, with an inactive gas blowing perpendicular to the substrate. That suppressed the large thermal convection you get when you're trying to grow a crystal at 1,000 degrees. Using this two-flow MOCVD I succeeded in 1991 in making the highest quality of gallium nitride crystals in the world. The dislocatoin density was still 10^{10}. But there's another measure of crystal quality, which is hole mobility, and I achieved a hole mobility of 200. That was a world record. The highest hole mobility ever achieved with gallium nitride was 100.

High-Impact Papers by Shuji Nakamura, Published Since 1994

(Ranked by average citations per year)

Rank	Paper	Total citations	Average cites per year
1	S. Nakamura, *et al.*, **"InGaN-based multi-quantum-well-structure laser diodes,"** *Japan J. Appl. Phys. 2*, 35(1B):L74-1, 1996.	601	172
2	S. Nakamura, T. Mukai, M. Sengh, **"Candela-class high-brightness InGan-AlGan double heterostructure blue light-emitting diodes,"** *Appl. Phys. Lett.*, 64(13):1687-9, 1994.	572	104
3	S. Nakamura, *et al.*, **"Superbright green InGaN single-quantum-well structure light-emitting diodes,"** *Japan J. Appl. Phys. 2*, 34(10B): 1332-5, 1995.	207	59
4	Y. Narukawa, *et al.*, **"Role of self-formed InGaN quantum dots for exciton localization in the purple laser-diode emitting at 420 nm,"** *Appl. Phys. Lett.*, 70(8):981-3, 1997.	142	57
5	S. Nakamura, *et al.*, **"High-brightness InGan blue, green and yellow light-emitting diodes with quantum-well structure,"** *Japan J. Appl. Phys. 2*, 34(7A):797-9, 1995.	238	53

SOURCE: ISI's Personal Citation Report, 1981-June 1999.

SW: So the two-flow MOCVD reactor was the key breakthrough?

Nakamura: Yes—suddenly it was easy to make any type of gallium nitride. In 1991, I made n-type gallium nitride. The following year I succeeded making p-type using a thermal annealing technique. Now all gallium nitride researchers use my technique for p-type gallium nitride. Another big breakthrough was making the first single crystal of indium gallium nitride, which we needed for an emitting layer. Finally at the end of 1993, I succeeded in making the first commercial-based blue LEDs.

SW: Did you beat the competition this time?

Nakamura: There was no competition. Suddenly we announced the production of blue LEDs. People working with zinc selenide announced that they had green LEDs, but their brightness was an order of magnitude lower than ours and their lifetime was very, very short. I made green LEDs in 1995 and also succeeded in increasing the brightness of my blue LEDs using a quantum-well structure. Then finally I switched to laser diodes.

SW: What was the biggest obstacle to the blue laser?

Nakamura: The dislocation density problem. The dislocation density of gallium nitride is still 10^{10}. We didn't reduce that. That's the amazing thing. Physicists are still wondering why gallium nitride is so efficient in spite of the large number of dislocations. Nobody knows. Gallium nitride is an amazing material. Nobody knows what kind of a structure would make the best blue laser diode with it. I tried many kinds of structures using the two-flow MOCVD. Finally, at the end of '95, I succeeded. Since that time many other groups have tried to make the same structures, but they haven't been so successful. The problem is they use commercial reactors, but they don't get the same quality of gallium nitride and indium gallium nitride that I do. Their results are terrible, because of the difference in the reactors. Nobody can imitate my reactor.

SW: What do you expect to be the major commercial use of the laser?

Nakamura: The main target is for digital video disc players—DVDs. The next generation of DVD players will all use our blue laser diodes.

SW: So it's selling?

Nakamura: Yes. Now my company's total sales of the blue LEDs are around $200 million a year. And the blue lasers are selling at around $2 million a year.

SW: What do you do next?

Nakamura: Right now the blue laser has a lifetime of 10,000 hours, but in that instance the power is only 5 milliwatts. For DVD use, they need 30 milliwatts of power, but then the lifetime is much shorter. So I'm still working to lengthen the lifetime at 30 milliwatts. I can only work on one thing at same time. I can't do new things at the moment. I have to concentrate on this.

SW: Is the R&D division at Nichia still just you?

Nakamura: No. Now it's about 20 people, all of them working on blue laser diodes. ■