Pallab Bhattacharya:
The Race is On! Quantum Dot Technology Leads the Pack

Pallab Bhattacharya, professor in the Solid-State Electronics Laboratory (SSEL), is a sprinter, pushing himself and his research group to be the best in the world in new technologies and device performance, and a long-distance runner – relying on a strong foundation while continually replenishing his reserves to continue the race. His work involves the conception and realization of synthetically modulated semiconductor structures, and nanophotonic devices, placing his work in the field of science now known as nanotechnology. He has been working in this field for close to three decades.

Professor Bhattacharya joined the EECS Department in 1984, and was instrumental in establishing The University of Michigan as a premier institution in optoelectronics research. He has made fundamental contributions in the area of compound semiconductor materials, and uses this knowledge to build novel and state-of-the-art optoelectronic and electronic devices.

Self-Assembled Quantum Dots
Using molecular beam epitaxy (MBE), Bhattacharya grows materials atom by atom. It takes significant resources to do this work. At an initial cost of about $1M per MBE system, each system then requires $100K in annual maintenance costs. Bhattacharya once had four in his research group, and now maintains two, having given one each to former student and now colleague in the SSEL, Professor Jamie Phillips, and to Professor Rachel Goldman, collaborator in Materials Science and Engineering (MSE).

Much of Bhattacharya’s groundbreaking research is founded on his accidental realization of a new technique for growing unique semiconductor structures in 1988. Prior to this, his group was creating quantum wells using MBE technology. Quantum wells are formed in semiconductors by having a specific material, like indium gallium arsenide, sandwiched between two layers of another material, like gallium arsenide. An unexpected result occurred in the lab after increasing the concentration of indium in one of the materials, so that instead of having flat planar structures, the indium gallium arsenide began to coalesce into three-dimensional structures, more like pyramids, or islands. They did this naturally, and therefore came to be known as self-assembled quantum dots.

The first paper to provide a quantitative understanding of the formation of quantum dots appeared in 1988, resulting from the collaborative work of Bhattacharya and Jasprit Singh, professor in SSEL. This paper has been cited repeatedly for its early and foundational work in quantum dots. Paul Berger, now on the faculty at Ohio State University, was a member of Bhattacharya’s group who conducted the experimental work behind the paper. He recalls the extreme novelty of their early work, saying "it took the rest of the research community seven years to catch up to what we were doing."

To learn more about these semiconductor nanostructures, Bhattacharya collaborated with colleagues, namely Rachel Goldman, associate professor in MSE, Ted Norris, professor in the Center for Ultrafast Optics (CUOS), Brad Orr, professor of Physics, and Jasprit Singh. “Without the great work done by Goldman, Norris, Orr, and Singh, I wouldn’t have been able to do what I’m doing now,” he said.

Bhattacharya and his group were among the first to report room temperature operation of a quantum dot laser in 1996. Since then, they have done pioneering work in the development of high-
performance quantum dot lasers, which currently outperform any other semiconductor laser. He paved the way during the late 1990s for research into quantum dot infrared photodetectors with high temperature operation, research that continues today. In 2000, Bhattacharya began exploring the application of quantum dots to the emerging field of spintronics – where the spin of electrons and holes in semiconductors can be exploited for communication and computing applications. He and his students recently reported a new material – diluted magnetic quantum dots – formed by selectively incorporating manganese atoms in the self-assembled islands. These quantum dots display magnetism at room temperature. Using these materials, Bhattacharya and his students recently realized and reported the first spin-laser, which will be able to transmit more information with less power consumption. In fact, Bhattacharya’s Distinguished University Professorship Lecture, to be hosted by University President Coleman on April 4, 2006, will be entitled, “From Pigeons to Spin-polarized Lasers: Carriers of Information Through the Ages.”

Bhattacharya received several awards in recognition of his research on quantum dot lasers, including the IEEE Paul Rappaport Award (1999), shared with his co-authors for their 1999 paper, the Nicholas Holonyak, Jr. Award from the Optical Society of America (2002), and the International Quantum Devices Award (2003).

For his contributions to the design and development of high-performance integrated photoreceivers, work that was published in 1996 and which represented a decade of research, he was awarded the 2000 SPIE Technology Achievement Award, and the 2000 IEEE (LEOS) Engineering Achievement Award. Virtually all contemporary high-performance photoreceivers use the integration technique pioneered by Bhattacharya and his co-workers, and it is expected that these photoreceivers will eventually be used in every optical fiber communication link.

The Group That Does Everything
The study of material growth and characterization, and the transference of this basic research to actual devices, are areas of research that are rarely pursued by the same individual. Professor Bhattacharya does both.

His students have benefited from this great breadth. Phillips said, “One thing I learned by being in his group is something about everything. Usually in this work you have two distinct groups, the materials group, and the device group. Not many people do both – but to really make an impact, you need to understand both areas.” Bhattacharya credits Phillips, who was placed at the intersection
of both areas, with pioneering the development of quantum dot photo infrared detectors while still a student.

Bhattacharya’s recent work in quantum dot infrared photo detectors has attracted the interest of Lockheed Martin, as well as the federal government. He takes great satisfaction in developing a novel technology to the point where devices based on it are finding viable applications. “We are making focal plane arrays in our lab for Lockheed Martin to couple them to readout circuits. Similar to the lasers, they are being produced commercially.”

The Drive For Success
Bhattacharya drives himself and inspires his students to conduct world-class research. He expects much from his students, because he knows they can do it. “What brings me to this department every morning are my students. They are the single most important factor in my work here,” said Bhattacharya. “My students work hard because they are excited about what they do. They are doing forefront research, and are in the middle of worldwide competition. That’s their driver – new ideas.”

The productivity of Bhattacharya and his students is truly remarkable; he has written 450 journal publications, and given more than 75 invited and plenary talks, 300 conference presentations, and nearly 100 seminars, presented all over the world. His students graduate with extensive experience in presentations, writing, and interactions with colleagues around the world, as well as training in time management skills.

Adrienne Stiff-Roberts, now assistant professor at Duke University, said that “learning time management, working at an intense level while managing my work, has been very helpful.” She felt that Professor Bhattacharya prepared her well to become a faculty member. Significantly, half of his 56 PhD students have followed the path of academia.

The Future is Now: Silicon and Sensors
Bhattacharya continues to find new applications using MBE technology. The most exciting current research involves silicon photonics – transmitting information on a silicon chip, or between chips, by light. Moore’s law, that predicts the doubling of the number of transistors on a chip every 18 months, is pushing the computer industry to seek out technologies with significantly different physics than is currently used. As Bhattacharya explains, “there are miles and miles of interconnects on a chip, whether they are aluminum, or copper, or gold. This ultimately creates a bottleneck. There are problems with crosstalk, heating, and propagation delay. The wisdom is to use optical interconnects to transmit information on a single chip, or between chips. This means putting photonic devices on a silicon chip.” However, silicon is not known to give out light. With Bhattacharya’s entry into this new line of research, employing quantum dot technology, this is changing.

“One of the most exciting results we’ve received recently is that we now have good quantum dot lasers grown directly on silicon,” says Bhattacharya. Working with his students, and Professor Pipe of Mechanical Engineering, he expects to achieve results others will have to follow. “The race is on to develop real light sources on silicon, and we’ve done that.” His focus now is on increasing the reliability of a silicon-based laser that is compatible with CMOS processing. It should be no surprise that Bhattacharya already knows how to do that. It’s just a question of time.

One of Bhattacharya’s newest avenues of research is in the area of photonic crystal quantum dot devices, which has applications in the field of quantum computing, and sensing. He states with excitement, “these photonic crystals can be used in all kinds of sensors - beautiful nanosensors. The sensors will be very small, and highly sensitive to a variety of gases and fluids. They will be competing head on with the best sensors out there today.”

If we can glean one thing from the way Bhattacharya works, we can safely say, “The race is on.”