China's Wuhan National Laboratory for Optoelectronics

Advancements in next-generation memory and photonics devices.

XIANGSHUI MIAO, TIELIN SHI, XINLIANG ZHANG, AND YUANDI ZHAO

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WUHAN NATIONAL LABORATORY For Optoelectronics (WNLO), coestablished by the Ministry of Education, Hubei Provincial Government, and Wuhan Municipal Government, is one of the first five national laboratories authorized by the Ministry of Science and Technology of the People's Republic of China. The laboratory is managed by Huazhong University of Science and Technology (HUST) in collaboration with Wuhan Research Institute of Posts and Telecommunications (WRI), Wuhan Institute of Physics and Mathematics (WIPM) affiliated to the Chinese Academy of Sciences (CAS), and Huazhong Institute of Optoelectronic Technology (HIOT).

Since its establishment in 2003, WNLO has achieved remarkable results in various research areas, winning 59 awards, of which four are national and 14 are provincial of first class. From 2004 to 2008, WNLO acquired nearly 200 patents for invention, and approximately 900 scientific papers were published in Science Citation Index and Engineering Index journals. In respect to research projects, WNLO has undertaken or participated in a large number of projects, with funds totaling more than ¥593.52 million, some of which have applied to production in different industries. The laboratory now has collaborative relationships with more than 40 major research institutions, universities, and businesses around the world. It was awarded the title "Innovation Base for Introducing Talents" by the Ministry of Education and the State Administration of Foreign Experts Affairs in 2007, "Innovation and Business Base for Overseas High-Qualified Talents" by the Organization Department of the Communist Party of China (CPC) Central Committee in 2008.

WNLO has also been approved as a "State-Level International Joint Research Center" by the Ministry of Research Center" by the Ministry of Science and Technology and the State Administration of Foreign Experts Affairs. On average, it engages over 60 overseas researchers and more than ten foreign academicians annually. It has hosted more than ten international conferences, including the International Photonics and Optoelectronics Meeting (POEM), and set up the Wuhan Optoelectronic Forum—a platform for high-level academic exchanges.

WNLO is not only a major component of the State Scientific and Technological Innovation System in China but also the innovation and research base of Wuhan Optics Valley of China (OVC). The outstanding achievements that WNLO has made are due to the 41 pioneering research teams with character and spirit, whose research disciplines cover nine cutting edge and strategic research areas, including fundamental photonics, integrated optoelectronics and micronanofabrication, laser science and technology, optical network and communication, optoelectro measurement and instrument, optoelectrical information storage, biomedical photonics and optoelectronic medical devices, organic optoelectronics, and advanced optoelectronic materials and nanotechnology. In this article, we give four examples of the major research activities currently at the WNLO including: nonvolatile phase-change random access memory, micro/nanometrology and surface biomimetics, silicon nanophotonics, and nanobiophotonics.

NONVOLATILE PHASE-CHANGE RANDOM ACCESS MEMORY

Phase-change memories [phase-change random access memory (PCRAM), PCM, and PRAM] are promising nonvolatile memory technologies for the next-generation devices. In comparison to the well-established nonvolatile memories, PCRAM is scalable, has a less complex fabrication process, lower power consumption, unlimited (up to 10^{12} times) switching, and a fast programming speed. The semiconductor industry is convinced that the PCRAM technology has a chance to replace flash and even dynamic random access memory (DRAM). So far, some demonstrations of PCRAM have been announced, but volume production has not yet been implemented. Two examples of memory devices fabricated at the WNLO include the full-function PCAM chip and the high-speed PCRAM cell.

FULL-FUNCTION PCRAM CHIP

The hierarchical circuit in the full-function PCRAM chip mainly includes I/O buffers, write drivers, main amplifiers, sense amplifiers, address buffers, decoding stages, and wordline drivers, as schematically drawn in Figure 1(a), where the PCRAM cells are 1T1R structured. The design was based on a 0.35-μm CMOS technology. The chip fabrication was divided into two steps. The structure, including all the CMOS devices, was fabricated by the Semiconductor Manufacturing International Corporation. After the multiproject wafer (MPW) dies were taped out [as shown in Figure 1(b)], the PCRAM array was integrated on the top of MPW wafer dies in our laboratory. The full-function memory chip [as shown in Figure 1(c)] automatically realized the address selection, data input, and data output.

HIGH-SPEED PCRAM CELL

PCRAM cells with traditional T-type and novel side-contact structures were both fabricated using aligner-based lithographic technique. Their electrical properties were characterized by a developed testing system, with the voltage/current pulses being generated by Keithley 4200 or a picosecond pulse generator. Figure 2(a) is the *I*–*V* curve of a typical T-type PCRAM cell with GeSbTe thickness of 20 nm. It can be concluded that the phase-change cell is capable of transitioning to an amorphous state under a 5-ns pulse with 6.7-V amplitude, which enables a speed-competitive PCRAM. Figure 2(b) discloses how its resistance changes with the input voltage pulse width.

In general, the development of PCRAM is currently being done in multilevel and stacked PCRAM technology, with characterization and modeling of the phase-change switching process. Several critical and open issues remain, such as the scaling limitation of this technology, the thermal interference between neighboring cells, the reliability, and the resistance drift in the amorphous

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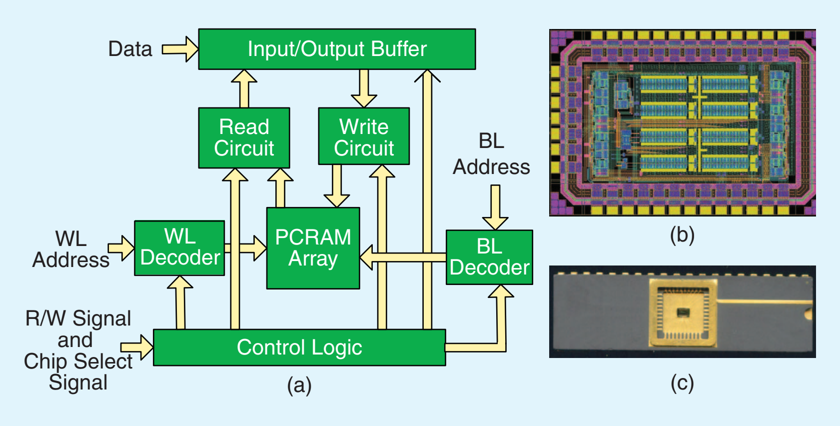

FIGURE 1 (a) Block diagram of a full-function 256-b PCRAM chip. (b) Microscopic image of an MPW chip using 0.35-μm CMOS technology. (c) Full-function PCRAM chip.

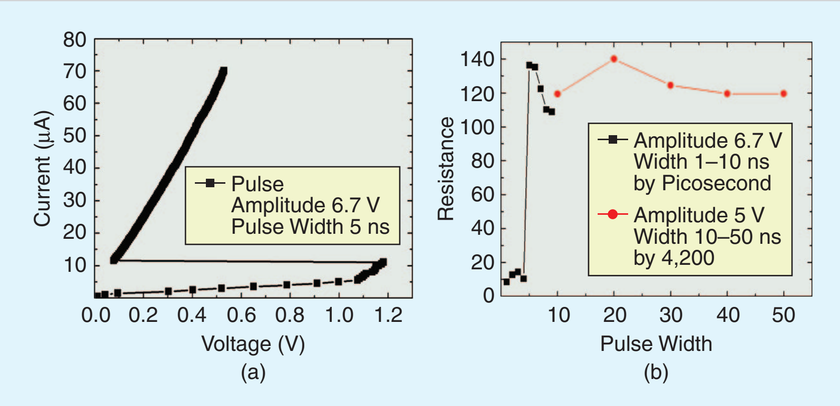

FIGURE 2 (a) *I–V* curve of a T-type PCRAM cell with GeSbTe thickness of 20 nm. (b) Relationship between the resistance and reset pulse width.

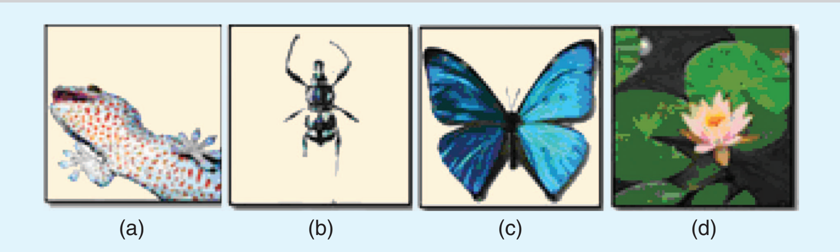

FIGURE 3 (a) Gecko feet, (b) beetle shell, (c) butterfly wing, and (d) lotus leaf.

state. We are also putting efforts into investigating new materials and new structures to reduce the programming current to the amorphous state, as well as understanding nanoscale phase-change mechanism and designing PCRAMs with high switching speed.

MICRO/NANOMETROLOGY AND SURFACE BIOMIMETICS

Prof. Tielin Shi is leading a research group focusing on micro/nanometrology and surface biomimetics. With the support of the National Major Fundamental Research Program, Natural Science Foundation of China, the group is undertaking a series of multiscale research, including dynamic testing of microelectromechanical systems (MEMS)/nanoelectromechanical systems (NEMS), periodical and quasi-periodical micro/nanostructural characterization, multiscale modeling, design and optimization of biosurface hierarchical multilayers, and integrated fabrication process development and its applications. Much progress has been achieved in the area of stroboscopic characterization of dynamic MEMS, high aspect ratio micro/nanostructural measurement, atomic force microscope (AFM) characterization, and fabrication of three-dimensional multilayer micro/nanostructures. Excellent optical, mechanical, structure color, and self-cleaning properties of biosurfaces will continue to inspire humans to learn from nature through biomimicking, such as gecko feet, beetle shell, butterfly wing, lotus leaf, and so on (Figure 3). Prof. Shi's research group will continue to explore the possibilities of biomimetic applications through further multidisciplinary study.

SILICON NANOPHOTONICS

Silicon nanophotonics is a rapidly growing field in worldwide science and technology. Prof. Jinzhong Yu and Prof. Xinliang Zhang have led a research team to realize chip-scale optical interconnection by silicon nanowire waveguide and photonic crystals at WNLO.

Conventional electric interconnection in today's computers has been a bottleneck for high-speed and large-capacity data transmission. To break through this

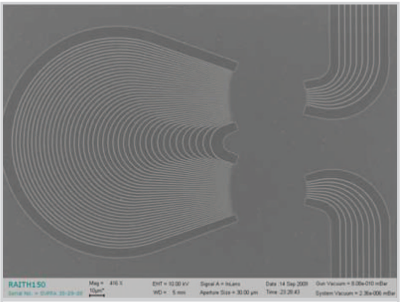

FIGURE 4 SEM photo of 8×8 AWG device on an SOI wafer.

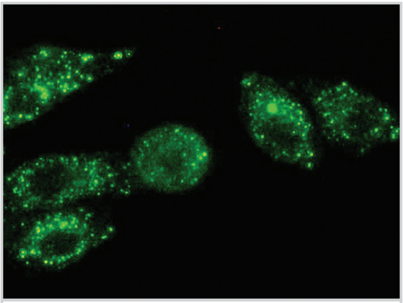

FIGURE 5 Fluorescence images of HeLa cells labeled with transferrin-conjugated QDs.

bottleneck, substituting electric interconnection by optical interconnection is a possible direction. The silicon photonics group at WNLO is trying to transfer the dense wavelength division multiplexing (DWDM) technology from optical fiber system to chip-scale optical interconnection usage. They hope that this chip-scale DWDM technology will greatly increase the data transfer rate from 100 Mb/s to above 10 Gb/s in future computers.

To reach this goal, the group is designing and fabricating an ultracompact array waveguide grating (AWG) to realize chip-scale DWDM functions. The AWG device can divide one multiwavelength input signal to different output ports to realize demultiplexing, or combine different single-wavelength input signals to one output waveguide to realize multiplexing. Different from the normal AWG for optical fiber communication, the developed AWG is composed of a silicon nanowaveguide to shrink the device size. The fabrication processes include transfer of the device pattern to photoresist by electron beam lithography, and, following dry etching, to transfer the pattern to the top silicon layer of a silicon-on-insulator (SOI) wafer.

Prof. Dingshan Gao and Dr. Qingzhong Huang in the group have designed and fabricated 8×8 AWG on a standard SOI wafer (Figure 4), in which the silicon nano waveguide is 450 nm wide and 340 nm thick. The central wavelength of the AWG is 1.55 μm, and the wavelength space between adjacent outputs is 3.2 nm. The crosstalk is below −5 dB and can be improved further by optimizing the design and fabrication process. The most important thing is that the device size is only $200 \times 260\ \mu m^2$.

The next objective of the group is to fabricate 16×16 and 32×32 AWGs. In the near future, they want to integrate the AWG with lasers, modulators, and electrooptical switches to construct high-speed and large-capacity chip-scale optical interconnection systems.

> Nowadays, silicon nanophotonics is a rapidly growing field in worldwide science and technology.

NANOBIOPHOTONICS

Nanobiophotonics is one of the major research themes at the Britton Chance Center for Biomedical Photonics (BC CBMP) at WNLO. Yuan-Di Zhao is working on the fluorescent labeling and tracing technology based on quantum dots (QDs). The research goal of Zhao's group is to develop a nanofluorescent probe with high optical property and low toxicity. QDs developed in recent years have many attractive features, including high photobleaching threshold, good chemical stability, and relatively narrow and symmetric luminescence bands. (Figure 5) These unique optical properties made QDs to be widely used in cell imaging and biolabeling. However, as probes in biological labeling, the toxicity

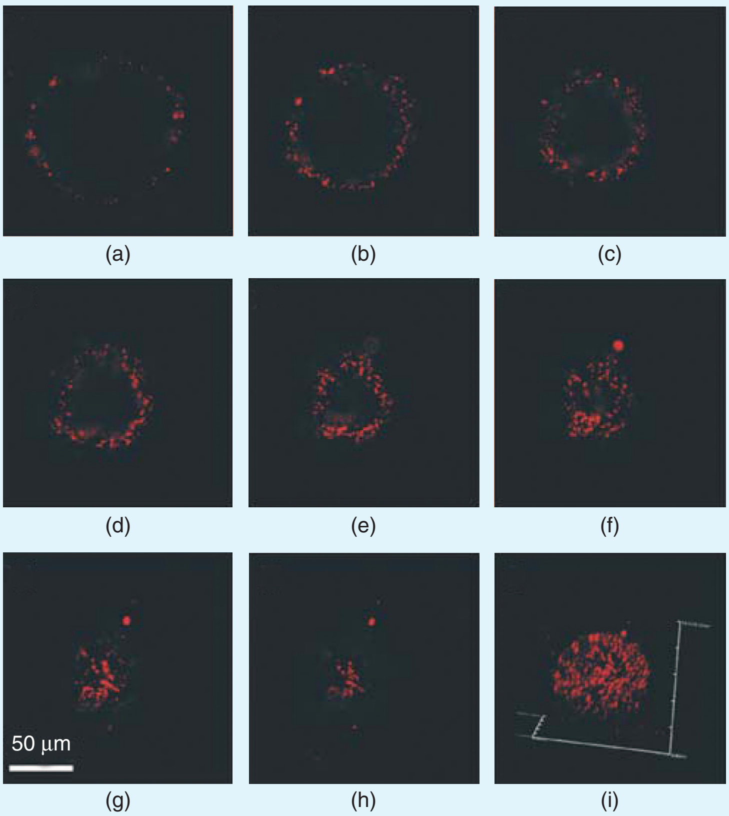

FIGURE 6 Confocal fluorescence imaging of QDs on beads at different focalized plane from (a)–(h) equator to bottom of bead and (i) three-dimensional reconstruction of each plane.

> Suspension microarray is a high-throughput analysis technology with the fast development in the biological science.

is of great concern. When QDs were coupled to bimolecules to prepare specific bioprobes, the photoluminescence quantum yield was usually affected.

The research group tried to screen a suitable modified method for the surface of those nanoparticles and found that probes presented least toxicity and superior photoluminescence after special modification of bimolecular onto QDs (Figure 5). Preparation of this probe was very simple, and coupling agents were not involved in the program of synthesis, and so purification processes were unnecessary. They have found that this is a simple way to prepare nanoparticles with high photoluminescence quantum yield and low toxicity. And the subsequent handling for QDs was also used to reach the expected goals. It was observed that the quantum yield of QDs was greatly increased after special heating–cooling cycle without changing the wavelength. The work is of significance to the preparation of high-quality QDs. And in the next step, multifunctional bioprobes with fluorescence and magnetism will be developed based on the above results.

Another research goal of the group is to study optical encoding of microbeads for suspension microarray. Suspension microarray is a high-throughput analysis technology, which is fast developing in the biological science research disciplines. In comparison with organic dyes, QDs as optical coding materials have many unique optical properties. However, the actual studies of multicolor encoding of beads with QDs still had many deficiencies that need to be further improved. For example, QDs were found to leak from the beads in some degree, which would lead to the inaccuracy of the coding signals (Figure 6).

Two methods were established by Zhao's group to solve these problems. In one of the methods, silica particles were used to coat the QD-encoded bead to prevent the leakage of QDs. In the other one, water-soluble QDs were directly encapsulated into the silica shell, and formed into Si@QD particles. Then, the previously obtained Si@QD particles were utilized to coat on the microbeads for optical encoding," says Zhao (see Figure 6). Based on above works, the next challenge in Zhao's laboratory is to apply the QD-encoded bead to real-time detection of biomedicine.

ABOUT THE AUTHOR

Xiangshui Miao (miaoxs@mail.hust.edu.cn) is with the Wuhan National Laboratory for Optoelectronics in China. He is the primary author of this article.