Pipelining innovation developed around quantum dots

Putting quantum dot lasers to practical use

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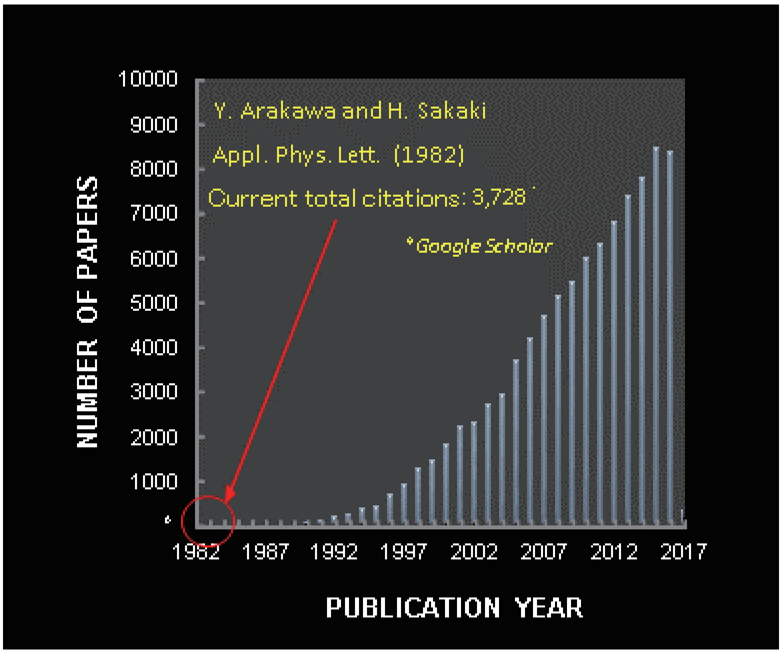
Revolutionizing information communications through quantum mechanics

The advent of an IoT ("Internet of Things") society where everything is connected to the Internet, as well as an AI ("Artificial Intelligence") society where AI is used to provide solutions to challenges that are well beyond the limits of human intelligence, requires the realization of an information society through ultra-fast broadband communications with high levels of security, and with ultra-low power consumption. To that end, an industry-academia collaborative research team led by Professor Yasuhiko Arakawa has continued to call for the fusion of nanoscience and quantum information science, and tackled the challenge of innovation based on quantum dots.

Quantum dots are semiconductor nanostructures with sizes of about 10 nanometers (nm). Confining electrons in these tiny nano-sized particles creates various unusual phenomena based on quantum mechanics. The application of these quantum dots to semiconductor lasers was proposed in 1982 by then Assistant Professors Yasuhiko Arakawa and Hiroyuki Sakaki. At that time, when the smallest size of even the most cutting-edge transistors was several micrometers, processing in nano-sized units was said to be an unrealistic dream. After the chance discovery of the realization of self-assembled quantum dot structures in the mid-1980s, the number of citations of Arakawa and Sakaki' s original paper began to rise significantly: a trend which still continues to this day. This is a sign of how quantum dots continue to be a popular and current theme of research.

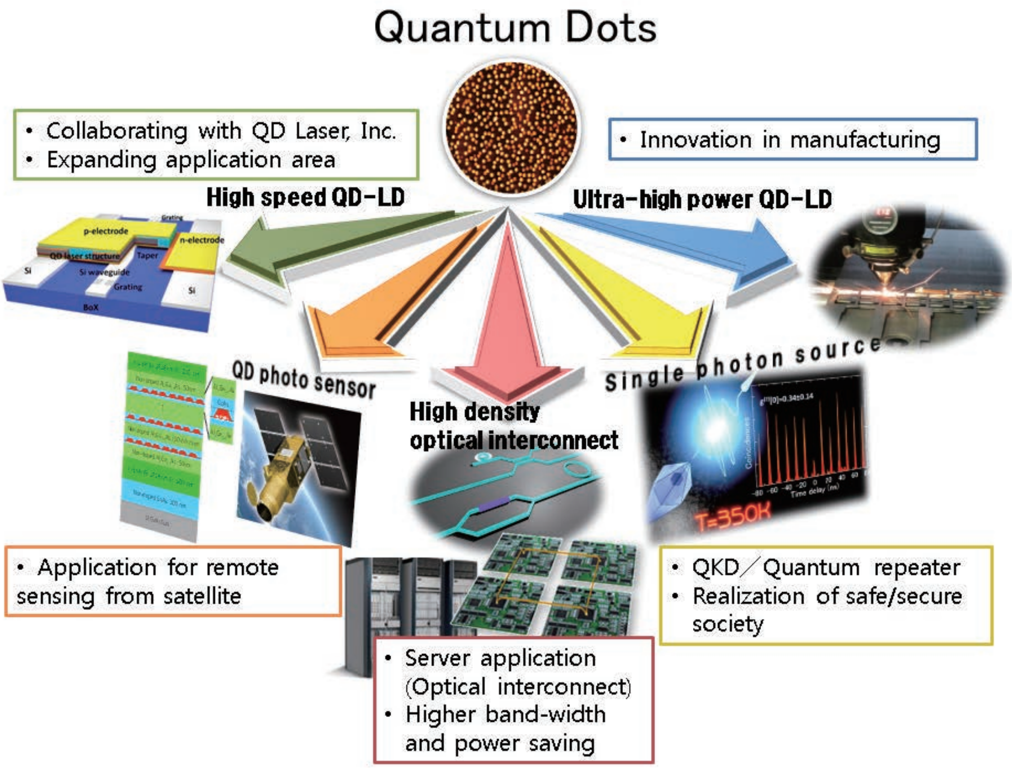
Graph of the citations of Arakawa and Sakaki's 1982 paper



Continued application of quantum dots based on various principles

Electrons confined in quantum dots have discrete energy levels, just like the electrons in atoms. For that reason, quantum dots are also known as artificial atoms. Due to the discrete nature of this energy, semiconductor lasers that make use of quantum dots are characterized by properties such as excellent temperature stability and spectral purity. If only one electron were placed in a quantum dot to emit light, a single photon could be generated. Such a single photon source serves as the basic element in quantum cryptographic communication, and can also be applied to quantum information processing for applications such as quantum computers. Furthermore, through use of the discrete energy level of quantum dots, the absorption of long-wavelength light could be used to enable the development of high-efficiency solar cells in the future. There is also wide scope for the application of quantum dots including high-sensitivity, low-dark-current infrared detectors produced using quantum dots that allow for strong carrier confinement.

Illustration of the expansion in the scope of application for quantum dots



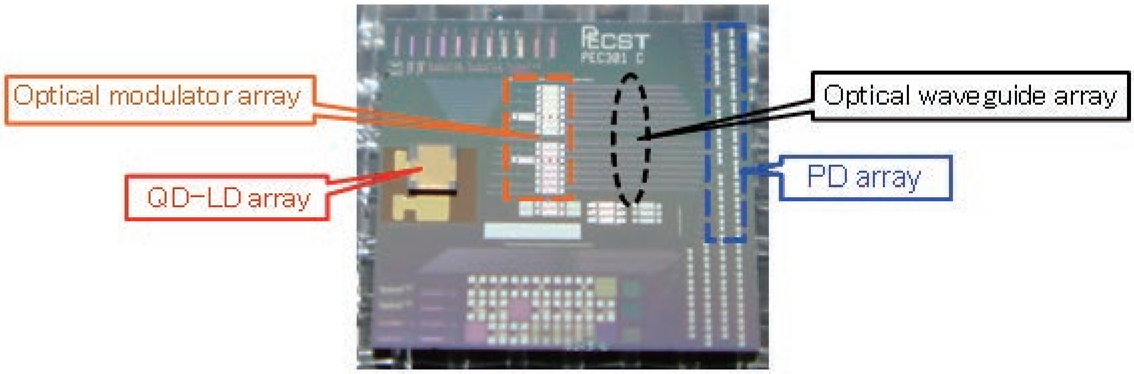
Initiatives at the Innovation Centers for Advanced Interdisciplinary Research Areas

The progress in the development of various quantum dot devices has been made possible through Professor Arakawa' s supervision and involvement since 2006 in the "Center of Excellence for Nano Quantum Information Electronics" project, based on the "Creation of Innovation Centers for Advanced Interdisciplinary Research Areas Program" established by MEXT and JST.

Of particular note is the industry-academia collaborative research undertaken with Fujitsu Laboratories Ltd. and the venture enterprise QD Laser, Inc., which sought to increase the density of grown quantum dots in order to create a quantum dot laser with an extremely low level of temperature dependence. This is the "third wave" of semiconductor lasers, and more than 3 million chips have already been mass-produced and shipped out. In addition, based on the outstanding temperature properties of quantum dots, this research project has achieved high-temperature laser operation at 220⊠C. Such devices will allow application in sensing technologies that can be used in extreme conditions, and will furthermore open up new markets that had been unthinkable for semiconductor lasers until now. There are also high expectations for these quantum dot lasers to be used as an integrated light source for optical interconnect modules between LSI chips, which are anticipated to experience further market growth. The team has already quantum dot lasers onto silicon optical interconnect chips, and have achieved high-speed modulation operation at 20Gbps in high-temperature environments of up to 125⊠C, as well as high-speed transmission density operations with a rate of 15Tbps/cm2. These developments have surprised the world. Such achievements were validated and demonstrated through collaborative research between three parties—the Photonics Electronics Technology Research Association (PETRA), The University of Tokyo, and QD Laser, Inc., in a " Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST)" project that Professor Arakawa is involved in as a principal researcher.

Efforts are underway to realize a paradigm shift in electronic devices where LSI shoulders the burden of arithmetic operations and memory using electrons, but optical signals shoulder the burden of data transmission between different LSI chips. Professor Arakawa dreams of creating a supercomputer the size of a baseball in 20 years' time.

Silicon optical interconnect chip



Large market anticipated for direct retinal imaging laser eyewearolution

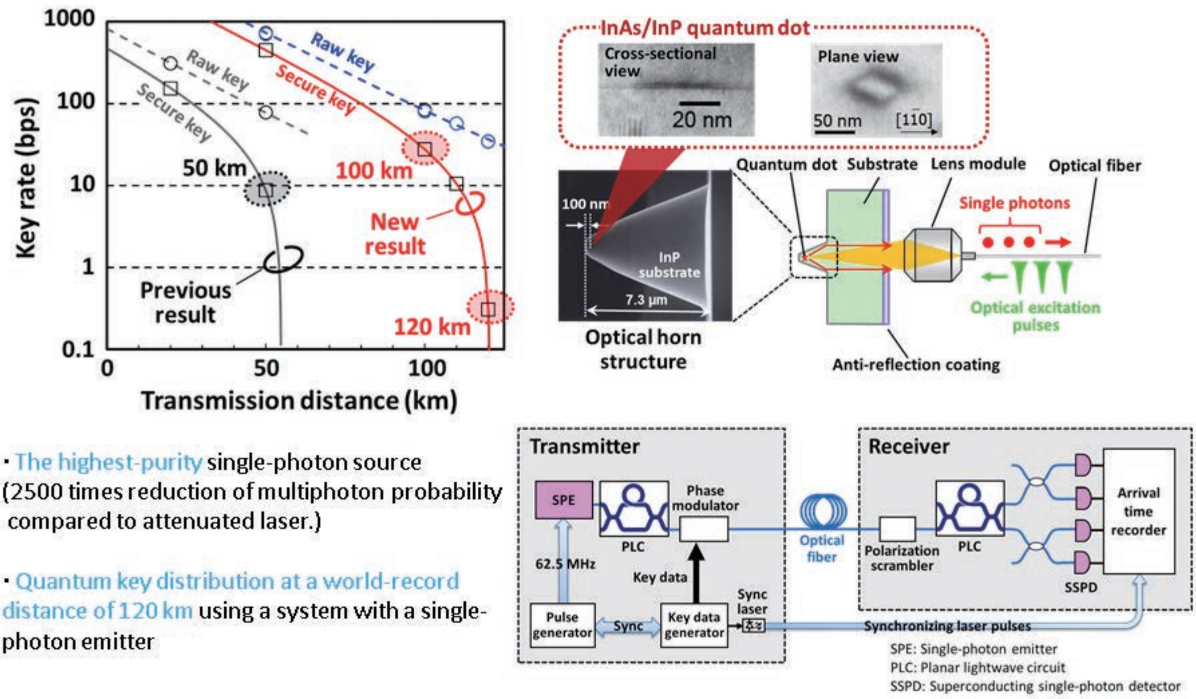
Professor Arakawa and his research team have also collaborated with QD Laser, Inc. on the development of a new type of laser eyewear. A visible semiconductor laser module is installed in a pair of spectacles, and is used to directly project images onto the retina of the wearer. Clinical trials are currently being conducted for this eyewear, which will be used in medical treatment for the vast number of low-vision patients around the world. By using this laser eyewear, those with poor eyesight will experience improvements in visibility in their everyday lives. The global market for this laser eyewear is anticipated to reach about 150 billion yen by 2020. This also represents another form of innovation.

Direct retinal imaging laser eyewear

Realization of the world's longest single-photon source quantum cryptography communication

Quantum dot devices are truly at their best in the field of quantum information. A breakthrough achievement has been made in the development of quantum key distribution through the telecommunication wavelength-band using a single-photon source based on quantum dots. The world' s longest quantum key distribution distance of 120 km has been reached, which will enable secure intercity communications. At the research base in The University of Tokyo, researchers from competing companies Fujitsu Laboratories Ltd. and NEC Corporation have succeeded in accelerating research and development, through a rare industry-academia collaboration, to build an experimental system working on the same lab bench. In typical quantum cryptographic communication, laser beams are strongly attenuated to a pseudo-single-photon limit. However, when quantum dots are used, high-purity single photons can be generated. Such single-photon source quantum cryptography holds a key advantage in practical application, and also the simplification of system operation and management.

Experiment for world's longest distance quantum key distribution through single-photon source

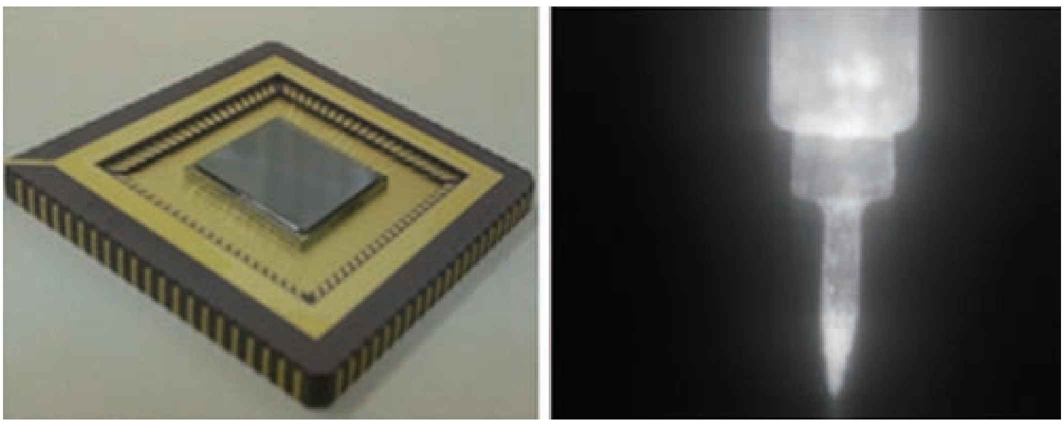


Expanding application to high-sensitivity quantum dot infrared detectors and quantum dot solar cells

Professor Arakawa has also engaged in collaborative research with NEC in the development of quantum dot infrared detectors, with the aim of application to remote sensing in the medium/far infrared regions by harnessing the properties of wavelength selectivity and high sensitivity in dot structures. Already, infrared imaging devices have been produced through the creation of 256×320 array elements; sharp infrared images have been obtained, and practical applications such as remote sensing devices mounted on satellites may soon be realized.

In collaboration with Sharp Corporation, research is also being conducted on intermediate-band solar cells using quantum dots. For the first time, it was demonstrated that the theoretical photoelectric conversion efficiency of such devices can reach 75 – 80%. Two-step optical absorption from a single quantum dot has also been confirmed by experiment, backing up the principle behind intermediate-band quantum dot solar cells. Starting from such foundations, research and development are progressing steadily.

Infrared imaging device that uses quantum dots, and an image obtained



Pipelining innovation through nanoscience

Major fundamental research achievements have also been produced in the Center of Excellence for Nano Quantum Information Electronics project. In addition to being the first in the world to succeed at the room-temperature oscillation of a quantum dot single nanowire laser, which is the smallest quantum dot laser, Professor Arakawa has also succeeded in realizing room-temperature oscillation of plasmonic nanowire lasers, which can be further miniaturized. In these ways, he has produced results towards the technology for next-generation eyewear.

Furthermore, he has developed a single-photon source using quantum dots made from gallium nitride (a wide-gap semiconductor), and further succeeded in going beyond room temperature to enable operation at high temperatures exceeding 70°C (350K). This achievement opens up possibilities for quantum information processing integrated circuits at room temperature.

If quantum dots can control single electrons, this analogy can be contrasted with photonic crystals, which control photons. In addition to 1D and 2D structures, he has produced three-dimensional photonic crystals that can control light in all directions. By applying this technology, he was also the first in the world to succeed in realizing the oscillation of a three-dimensional photonic crystal nano-resonator laser.

Professor Arakawa is successively producing cutting-edge technology that pursues ultra-high speed and ultra-safe/secure operation, and with ultra-low power consumption. These include the results of these fundamental research activities, and are not limited to application to quantum dot laser communications; they also include light sources for inter-chip optical wiring, light sources for laser eyewear, quantum cryptographic communications, and quantum information processing. Professor Arakawa is continuing with the challenge to produce pipeline innovations.

Single photon source using gallium nitride quantum dots