Japan Academy Prize to:

Yasuhiko Arakawa
Professor, Institute of Industrial Science,
The University of Tokyo

for "Research on Quantum Dots and their Application in
Photonic Devices"

Outline of the work:

Research on the control of electron motion using a thin film semiconductor with a thickness of about 10 nm (close to the electron quantum-mechanical wavelength) began with a proposal for superlattices and quantum wells by Dr. Leo Esaki in 1969. This research has produced new electron and photonic devices such as quantum-well lasers, has increased our understanding of the physics of two-dimensional electron systems and has contributed greatly to the development of the IT society.

The quantum dot is an advanced semiconductor nanostructure that was proposed by Prof. Yasuhiko Arakawa in 1982 as a novel development of the quantum well. Since this proposal, Prof. Arakawa has consistently promoted research on quantum dots and their photonic-device applications and has pioneered several outstanding research achievements. His work can be divided into four aspects: early-stage research on quantum-dot lasers, realization and practical application of quantum-dot lasers, single-quantum-dot photonic devices and fundamental investigations into the optical properties of quantum nanostructures.

The dawn of research into quantum-dot lasers

In 1982, in collaboration with Prof. Hiroyuki Sakaki, Prof. Arakawa proposed the concept of quantum dots for removing the freedom of electron motion via three-dimensional quantum confinement and their application to lasers. At the same time, he predicted a reduction in the temperature dependence of the threshold current in quantum-dot lasers by theoretical calculations. Prof. Arakawa further advocated theoretical studies of quantum-well and quantum-dot lasers and found that not only the threshold current but also other characteristics, such as modulation bandwidth and quantum noise, were greatly improved. In addition, the possibility of improving the aforementioned properties was verified by realizing the multidimensional quantum-confinement effect of electrons by placing a quantum-well or bulk-semiconductor laser in a strong magnetic field.

These pioneering achievements have shown that reduction in the degrees of freedom of electrons is essential for improving various characteristics of semiconductor lasers.

Realization and practical application of quantum-dot lasers

Building upon his early research, Prof. Arakawa started to investigate the realization and commercialization of quantum-dot lasers. He began working on the crystal growth of quantum dots, though he himself considered it to be a monumental task. In 1994, he succeeded in fabricating self-assembled InAs-based quantum dots using metal-organic vapor-phase epitaxy for the first time. However, to realize a high-performance quantum-dot laser, it was necessary to form uniform and high-density quantum dots, which was even more challenging.

In collaboration with Fujitsu Laboratories, Prof. Arakawa aimed to establish a technology for fabricating high-quality quantum dots and finally succeeded in realizing a temperature-independent high-speed modulated-quantum-dot laser in 2004. Based on these achievements, a venture company was started in 2006, mass production began in 2010 and more than 3 million quantum-dot lasers were shipped to the market by 2015. In addition, he succeeded in incorporating quantum-dot lasers into silicon photonic integrated circuits in 2014, further opening up possible uses of quantum-dot lasers.

This academically significant achievement was the first realization of essential features of quantum mechanics, such as complete discretization of energy levels, in a practical device.

Single-quantum-dot optical-device research

Prof. Arakawa's research has not been limited to the development of lasers with active layers consisting of numerous quantum dots. He noted at the importance of optical devices using a single-quantum dot at an early stage, which has led to several remarkable results. In 2004, as part of an industrial collaboration, he succeeded in realizing single-photon sources operating in the telecommunications-wavelength band. This led to the world's longest transmission distance for quantum-cryptographic communication using single-photon sources in 2014. However, the operating temperature of single-photon sources has long been limited to extremely low temperatures. Prof. Arakawa started researching crystal-growth technology and the physical properties of GaN quantum dots around the end of the 1990s, and, by controlling the binding energy of the biexcitons, he successfully achieved single-photon emission at 350 K. In addition, he has also achieved excellent results in extremely small-laser research, including the fabrication of a single-quantum-dot laser in 2010.

Physics of quantum nanostructures

Prof. Arakawa has also achieved numerous important results in the study of the optical properties of quantum nanostructures. For example, in 1998, he clarified by single-quantum-dot spectroscopy that InAs quantum dots not only have state density due to discrete levels but also have continuous states. In addition, in a 1993 study using quantum wells in a vertical microcavity, he confirmed that strong quantum coupling (vacuum Rabi oscillation) between excitons and single photons exists even in the solid state. The paper that first reported this result is currently regarded as the original source of research on semiconductor-cavity quantum electrodynamics.

In summary, Prof. Arakawa is a world-leading scientist who has investigated quantum-dot lasers from initiation to practical application and has performed outstanding research on single-photon sources and quantum optics in semiconductor nanostructures. On account of these achievements, he has been bestowed with numerous awards, including the Leo Esaki Prize, the Fujihara Award, the Medal with Purple Ribbon, the C&C Prize, the IEEE David Sarnoff Award, the Welker Award and the Nick Holonyak, Jr. Award.

List of Main Publications

[1] The dawn of research into quantum-dot lasers

1-1 Y. Arakawa and H. Sakaki, "Multidimensional quantum well laser and temperature dependence of its threshold current", Appl. Phys. Lett. **40**, 939 (1982)

1-2 Y. Arakawa, H. Sakaki, M. Nishioka, H. Okamoto and N. Miura, "Spontaneous emission characteristics of quantum well lasers in strong magnetic fields−An approach to quantum-well-box light source−",

Jpn. J. Appl. Phys. **22**, L804 (1983)

1–3 Y. Arakawa, K. Vahala and A. Yariv, “Quantum noise and dynamics in quantum well and quantum wire lasers”, Appl. Phys. Lett. **45**, 950 (1984)

1–4 Y. Arakawa, K. Vahala, A. Yariv and K. Lau, “Enhanced modulation bandwidth of GaAlAs double heterostructure lasers in high magnetic fields: Dynamic response with quantum wire effects”, Appl. Phys. Lett. **47**, 1142 (1985)

1–5 Y. Arakawa and A. Yariv, “Quantum well lasers–Gain, spectra, dynamics”, IEEE J. of Quantum Electron. **22**, 1887 (1986)

[2] Realization and practical application of quantum-dot lasers

(Research on crystal growth of quantum-dot and related nanostructures)

2–1 Y. Nagamune, M. Nishioka, S. Tsukamoto and Y. Arakawa, “GaAs quantum dots with lateral dimension of 25 nm fabricated by selective metalorganic chemical vapor deposition growth”, Appl. Phys. Lett. **64**, 2495 (1994)

2–2 J. Oshinowo, M. Nishioka, S. Ishida and Y. Arakawa, “Highly uniform InGaAs/GaAs quantum dots (~15 nm) by metalorganic chemical vapor deposition”, Appl. Phys. Lett. **65**, 1421 (1994)

2–3 Y. Arakawa, “Fabrication of quantum wires and dots by MOCVD selective growth”, Solid-State Electron. **37**, 523 (1994)

2–4 J. Tatebayashi, M. Nishioka and Y. Arakawa, “Over 1.5 µm light emission from InAs quantum dots embedded in InGaAs strain-reducing layer grown by metalorganic chemical vapor deposition”, Appl. Phys. Lett. **78**, 3469 (2001)

2–5 M. Miyamura, K. Tachibana and Y. Arakawa, “High-density and size-controlled GaN self-assembled quantum dots grown by metalorganic chemical vapor deposition”, Appl. Phys. Lett. **80**, 3937 (2002)

2–6 Y. Arakawa and S. Kako, “Advances in growth and optical properties of GaN-based quantum dots”, Phys. Stat. Sol. (a) **203**, 3512 (2006)

(Realization and practical application of quantum-dot lasers)

2–7 K. Otsubo, N. Hatori, M. Ishida, S. Okumura, T. Akiyama, Y. Nakata, H. Ebe, M. Sugawara and Y. Arakawa, “Temperature-insensitive eye-opening under 10-Gb/s modulation of 1.3-µm p-doped quantum-dot lasers without current adjustments”, Jpn. J. Appl. Phys. **43**, L1124 (2004)

2–8 Y. Urino, N. Hatori, T. Akagawa, T. Shimizu, M. Okano, M. Ishizaka, T. Yamamoto, H. Okayama, Y. Onawa, H. Takahashi, D. Shimura, H. Yaegashi, H. Nishi, H. Fukuda, K. Yamada, M. Miura, J. Fujikata, S. Akiyama, T. Baba, T. Usuki, Y. Noguchi, M. Noguchi, M. Imai, N. Hirayama, S. Saitou, M. Yamagishi, M. Takahashi, E. Saito, D. Okamoto, M. Mori, T. Horikawa, T. Nakamura and Y. Arakawa, “Athermal silicon optical interposers with quantum dot lasers operating from 25 to 125℃”, Electron. Lett. **50**, 1377 (2014)

[3] Single-quantum-dot optical-device research

(Research on single-photon sources)

3–1 K. Takemoto, Y. Sakuma, S. Hirose, T. Usuki, N. Yokoyama, T. Miyazawa, M. Takatsu and Y. Arakawa, “Non-classical photon emission from a single InAs/InP quantum dot in the 1.3-µm optical-fiber band”, Jpn. J. Appl. Phys. **43**, L993 (2004)

3–2 T. Miyazawa, K. Takemoto, Y. Sakuma, S. Hirose, T. Usuki, N. Yokoyama, M. Takatsu and Y. Arakawa, “Single-photon generation in the 1.55-µm optical-fiber band from an InAs/InP quantum dot”, Jpn. J. Appl. Phys. **44**, L620 (2005)

3–3 S. Kako, C. Santori, K. Hoshino, S. Götzinger, Y. Yamamoto and Y. Arakawa, “A gallium nitride single-photon source operating at 200 K", Nat. Mater. **5**, 887 (2006)

3-4 M. J. Holmes, K. Choi, S. Kako, M. Arita and Y. Arakawa, "Room-temperature triggered single photon emission from a III-Nitride site-controlled nanowire quantum dot", Nano Lett. **14**, 982 (2014)

3-5 K. Takemoto, Y. Nambu, T. Miyazawa, Y. Sakuma, T. Yamamoto, S. Yorozu and Y. Arakawa, "Quantum key distribution over 120 km using ultrahigh purity single-photon source and superconducting single-photon detectors", Sci. Rep. **5**, 14383 (2015)

(Research on nanolasers such as single-quantum-dot lasers)

3-6 M. Nomura, N. Kumagai, S. Iwamoto, Y. Ota and Y. Arakawa, "Laser oscillation in a strongly coupled single-quantum-dot-nanocavity system", Nat. Phys. **6**, 279 (2010)

3-7 A. Tandaechanurat, S. Ishida, D. Guimard, M. Nomura, S. Iwamoto and Y. Arakawa, "Lasing oscillation in a three-dimensional photonic crystal nanocavity with a complete bandgap", Nat. Photonics **5**, 91 (2011)

3-8 Y. Ota, S. Iwamoto, N. Kumagai and Y. Arakawa, "Spontaneous two-photon emission from a single quantum dot", Phys. Rev. Lett. **107**, 233602 (2011)

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[4] Physics of quantum nanostructures

(Research on optical properties of quantum dots/wires and quantum-dot solar cells)

4-1 Y. Nagamune, Y. Arakawa, S. Tsukamoto, M. Nishioka, S. Sasaki and N. Miura, "Photoluminescence spectra and anisotropic energy shift of GaAs quantum wires in high magnetic fields", Phys. Rev. Lett. **69**, 2963 (1992)

4-2 Y. Toda, O. Moriwaki, M. Nishioka and Y. Arakawa, "Efficient carrier relaxation mechanism in InGaAs/GaAs self-assembled quantum dots based on the existence of continuum states", Phys. Rev. Lett. **82**, 4114 (1999)

4-3 X.-Q. Li, H. Nakayama and Y. Arakawa, "Phonon bottleneck in quantum dots: Role of lifetime of the confined optical phonons", Phys. Rev. B **59**, 5069 (1999)

4-4 T. Nozawa and Y. Arakawa, "Detailed balance limit of the efficiency of multilevel intermediate band solar cells", Appl. Phys. Lett. **98**, 171108 (2011)

4-5 M. Holmes, S. Kako, K. Choi, P. Podemski, M. Arita and Y. Arakawa, "Measurement of an exciton Rabi rotation in a single GaN/Al$_x$Ga$_{1-x}$N nanowire-quantum dot using photoluminescence spectroscopy: Evidence for coherent control", Phys. Rev. Lett. **111**, 057401 (2013)

4-6 K. Kamide, S. Iwamoto and Y. Arakawa, "Impact of the dark path on quantum dot single photon emitters in small cavities", Phys. Rev. Lett. **113**, 143604 (2014)

(Research on semiconductor-cavity quantum electrodynamics)

4-7 C. Weisbuch, M. Nishioka, A. Ishikawa and Y. Arakawa, "Observation of the coupled exciton-photon mode splitting in a semiconductor quantum microcavity", Phys. Rev. Lett. **69**, 3314 (1992)

4-8 Z. L. Zhang, M. Nishioka, C. Weisbuch and Y. Arakawa, "Demonstration of confined optical field effect in a vertical microcavity by examining the low temperature photon-excition interaction in two kinds of quantum wells", Appl. Phys. Lett. **64**, 1068 (1994)

4-9 K. Aoki, D. Guimard, M. Nishioka, M. Nomura, S. Iwamoto and Y. Arakawa, "Coupling of quantum-dot light emission with a three-dimensional photonic-crystal nanocavity", Nat. Photonics **2**, 688 (2008)

4-10 Y. Arakawa, S. Iwamoto, M. Nomura, A. Tandaechanurat and Y. Ota, "Cavity quantum electrodynamics

and lasing oscillation in single quantum dot-photonic crystal nanocavity coupled systems", IEEE J. Sel. Topics in Quantum Electron. **18**, 1818 (2012)

4-11 Y. Ota, R. Ohta, N. Kumagai, S. Iwamoto and Y. Arakawa, "Vacuum Rabi spectra of a single quantum emitter", Phys. Rev. Lett. **114**, 143603 (2015)