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Introducing Researchers

Featured in this issue is Associate Professor Junko Hayase, who is in pursuit of a quantum leap in the innovation of informatics. Associate Professor Hayase strives toward realizing practical use of quantum-mechanical optoelectronics.

Applying principles of quantum mechanics to semiconductors and photonics

Possibility of "A world with 0 and 1 used simultaneously"

In the extreme micro-world of atoms, molecules, electrons and elementary particles, phenomena that cannot be explained by classical mechanics often take place. This is the field of study quantum mechanics handles. A century has passed since the theory of quantum mechanics was established. As its correctness is verified through experiments, quantum mechanics has made rapid progress and grown into a technology within the reach of humankind for practical use. Associate Professor Hayase is tackling the practical application of quantum-mechanical optoelectronics by pioneering technologies to control quantum-mechanical characteristics of light and semiconductors.

Creating new technology by combining pulsed light and semiconductors

"Quantum-mechanical informatics is a focus of attention today as the greatest application of quantum mechanics. Effective and advanced use of quantum-mechanical characteristics enables many wonderful things that conventional informatics couldn't even imagine previously – things, such as quantum teleportation capable of communicating information to remote places in an instant; a quantum computer that can solve extremely demanding tasks in an instant via super-parallel computing – a task that would take hundreds of millions of years for currently available computers to perform; and a quantum cryptographic system that is absolutely safe against eavesdropping," remarks Dr. Hayase.

Dr. Hayase's specialty is quantum-mechanical optoelectronics. The focus of her studies is on systems based on a combination of pulsed light and nanostructured semiconductors that can freely control quantum-mechanical characteristics of photons* and electrons.

"Today our information-oriented society is supported by optoelectronics, but it's far from perfection in terms of effective application of the principles of quantum mechanics. If we succeed in making the most of quantum-mechanical characteristics, it would be possible to create totally new technologies that revolutionize our common knowledge. One such example is quantum informatics," she adds.

What is "quantum superposition" – a state with 0 and 1 in a state of stack alignment?

As you may know, all information we handle on our PCs, cellular phones, the Internet, and so on is represented by sequences ("01101 ...") of binary numbers of "0" or "1" with a "bit" as the minimum unit (see Fig.1). It is the intensity (ON/OFF) of light or electric current that expresses "0" or "1." However, this technology merely constitutes a part of the characteristics of light and semiconductors. Therefore, scientists around the world are expecting much of quantum-mechanical informatics. The truly wondrous phenomena of "0 can be 1 simultaneously" that can take place in the world of quantum mechanics are said to enable a new horizon of informatics no one had ever dreamed of previously.

"It is the famous 'Schrödinger's Cat' experiment (Fig.2) that well illustrates the concept of quantum mechanics. In this experiment, a cat is put in Chamber A in which a poisonous gas generating device is set up. On the other hand, with Chamber B, a randomly operating switch is connected to it. When the Chamber B switch is turned ON, the gas generating device in Chamber A is actuated. Until one looks into either one of the chambers after a certain lapse of time, it is impossible to know whether the cat is alive (0) or dead (1). This state is referred to as "quantum superposition" – a state where 0 can be 1 simultaneously. A quantum computer uses this superposition as a unit of information (quantum bit). Since one quantum bit is capable of 0 and 1 processing simultaneously, numerous quantum bits enable super-parallel computation."

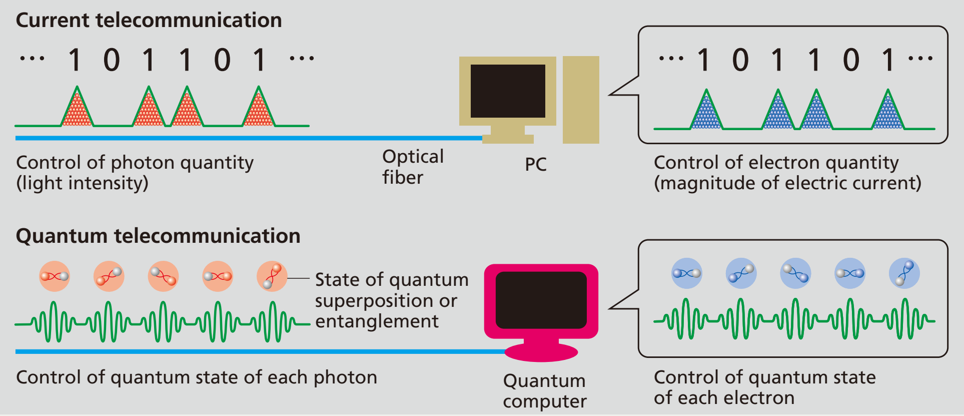

Fig.1 Quantum-based future information technology

With current information technology, information (0 or 1) is represented via control of light intensity (quantity of photons) or the magnitude of electric current (quantity of electrons). By contrast, if we can take advantage of "quantum superposition" or "quantum entanglement," revolutionary information technologies, such as quantum teleportation, quantum computers, and quantum cryptographic systems will become a reality.

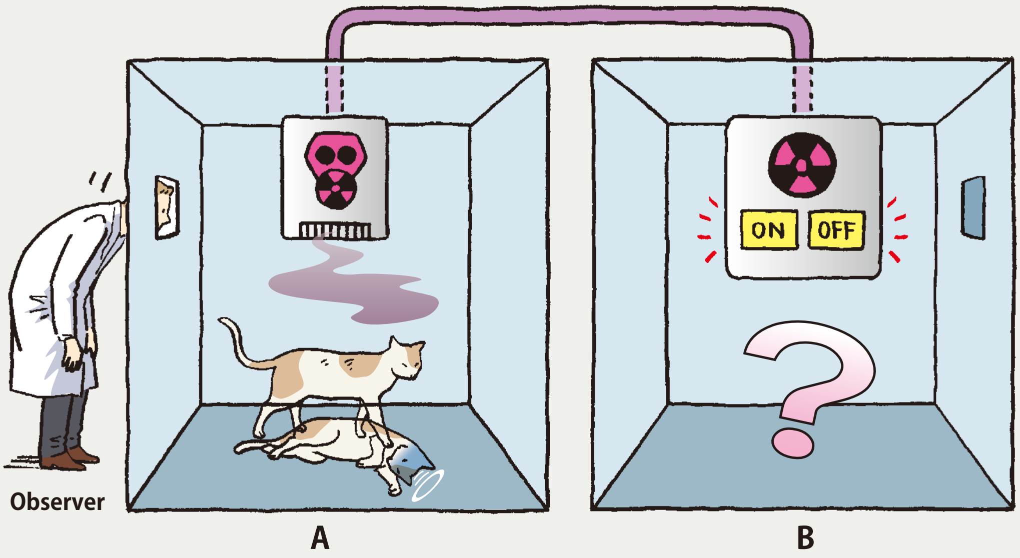

Fig.2 Schrödinger's Cat
The illustration of the famous 'Schrödinger's Cat' experiment is an easy-to-understand explanation of the wondrous world of quantum mechanics. Being alive (0) or death (1) of the cat remains unknown until the observer looks into Chamber A – a state known as "superposition." Also, before the Chamber B switch is turned ON (B=0), the cat in Chamber A is alive (A=0), whereas the cat is dead (A=1) if the switch has been turned ON (B=1), which remains unknown until the inside of either Chamber A or B is checked. This state is known as "quantum entanglement."

Another important concept is "quantum entanglement." The cat is alive (A=0) before the switch is turned ON (B=0), while it is dead (A=1) after the switch has been turned ON (B=1). In other words, it is either "if A is 0, B is 0" or "if A is 1, B is 1." But you cannot tell which is which until you actually observe it. This state is known as quantum entanglement. If Chambers A and B are placed at separate locations, the state of Chamber B becomes definite the moment Chamber A is observed, making it possible to communicate information between two remotely distant locations. This is the principle of quantum teleportation.

More than one quantum state, such as superposition and entanglement, remain coexisting possibilities until being revealed. Once revealed, a particular quantum state becomes definite. In other words, this means that quantum states as possibilities are broken once you observe them.

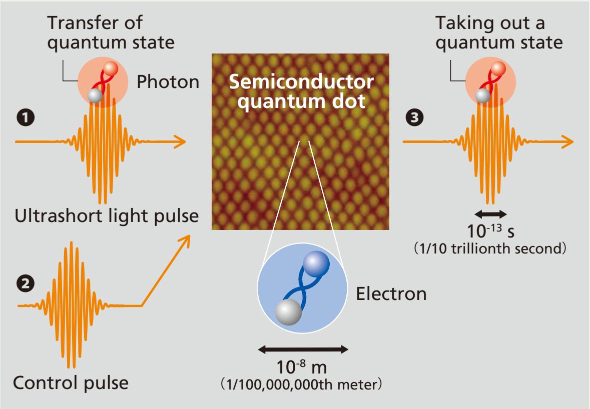

Fig.3 Quantum-mechanical exchange of information between photons and electrons
Photons' quantum-mechanical information (quantum state) is transferred to electrons within the semiconductor by irradiating ultrashort light pulses to semiconductor quantum dots ❶. After a certain lapse of time, control pulses are irradiated ❷ to allow the transferred quantum-mechanical information to be taken out ❸ in the form of photons.

"The photon is useful for cryptography partly because it is the smallest particle that cannot be further divided. It is also because eavesdropping can be easily revealed since quantum states fail if someone attempts to eavesdrop (= observe) on a particular piece of information. Furthermore, the ultimate in energy-saving telecommunication is possible because quantum-mechanical telecommunication works with only an extremely small amount of energy," Dr. Hayase added.

Combining semiconductor quantum dots with ultrashort light pulses

Working energetically to achieve quantum optoelectronics, Dr. Hayase is currently engaged in experiments – exchanging quantum states between semiconductor electrons and photons, controlling these states, and so on (Fig.3). However, numerous problems are encountered to convey quantum-mechanical information to semiconductors.

"A quantum state is so fragile that it can be rapidly broken . Therefore, information needs to be controlled and transferred while maintaining the quantum state, which is extremely difficult."

Coming to the fore as a possible solution are semiconductor quantum dots – a type of semiconductor suitable for maintaining and controlling quantum states. Quantum dots are ultrafine particles of semiconductor whose size is 10^{-8} meter. With this semiconductor, electrons can be confined in a very small area, making that area work as if it were an atom. This makes it easy to control and maintain the quantum state of each one of the electrons.

"What's outstanding about quantum dots is that their characteristics can be controlled freely according to their size and shape. My research team employs a special technique to produce quantum dots that can interact strongly with the light used in optical fiber communication. We have also succeeded in retaining the state of superposition much longer than those developed by other groups."

That said, it is unavoidable that quantum states are constantly being broken every moment. So, as an ultrafast flash, Dr. Hayase uses ultrashort pulse laser capable of emitting light instantaneously in an incredibly short period of 10^{-13} second. This enables her team to make use of nonlinear phenomena that cannot take place under ordinary light conditions, which in turn makes it possible to control superposition and quantum entanglement.

Given the extremely weak intensity of light that corresponds to one photon, it is very difficult to cause intended effects between photons and electrons. So Dr. Hayase is looking for a method of collecting many quantum dots that could enhance interactions between photons and electrons.

"What makes quantum mechanics intriguing is that it has virtually unlimited potential. I'm tackling research activities with the hope of achieving a fantastic discovery that could revolutionize the world in decades ahead."

(Reporter & text writer: Madoka Tainaka)

＊Photon: Photon is the smallest unit of light energy. Speaking from a quantum-mechanical viewpoint, light has properties as both waves and particles (photons).