Title of Project : Development and elucidation of highly efficient photoreaction systems using a strong coupling between nanocavity and plasmon

Hiroaki Misawa
(Hokkaido University, Research Institute for Electronic Science, Professor)

Research Project Number : 18H05205 Researcher Number : 30253230

Keyword : Plasmon, Nanoresonator, Strong coupling, Electron transfer, Photoemission electron microscopy

【Purpose and Background of the Research】

To realize a sustainable society, it is essential to develop innovative photochemical reaction systems that can efficiently utilize the abundant visible light contained in sunlight. We have elucidated that a titanium dioxide (TiO_2)/Au-film, which is a constituent element of the Au nanoparticle (Au-NPs)/TiO_2/Au-film electrode, becomes a nano-sized Fabry-Pérot (FP) resonator and that the nano-FP resonator is strongly coupled with the localized surface plasmon resonance (LSPR) of Au-NPs on TiO_2. We have also elucidated that the strongly coupled structure shows a large near-field enhancement in a wide wavelength range and a remarkable enhancement of the quantum yield in photoelectric conversion using water as an electron source compared with that with an uncoupled electrode. In this study, we aim to clarify the theory of plasmon-induced electron transfer and explore a strongly coupled electrode that enables further enhancement of the near-field and quantum yield.

【Research Methods】

To realize a plasmon-induced electron transfer reaction exhibiting a high quantum yield, the key steps are 1) to optimize strongly coupled electrodes and 2) to elucidate the plasmon-induced electron transfer reaction mechanism. Fig. 1a shows a strongly coupled electrode. The characteristic of this electrode is that its color changes from yellow to black due to strong light absorption with a wide wavelength in the visible range when Au-NPs are formed on the TiO_2/Au-fim (Fig. 1b). In this study, we derive the design of the nano-FP resonator and Au-NPs using electromagnetic simulations to achieve a larger near-field enhancement, in collaboration with Prof. Sasaki of Hokkaido University (Co-I). The strongly coupled electrode is fabricated by the obtained optimum structural design, and its spectral and photoelectric conversion properties are provided as feedback to the structural design.

In parallel with these studies, we promote research to elucidate the mechanism of plasmon-induced electron transfer. A laser pulse with a pulse duration of ~20 fs, a center wavelength of 800 nm as a fundamental wavelength (ω) and its third harmonic generation (3ω, 267 nm) are introduced into the existing photoemission electron microscopy (PEEM) via an

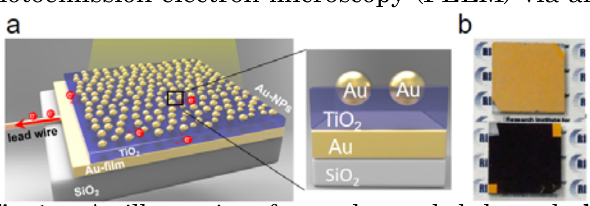

Fig. 1. a, An illustration of strongly-coupled electrode, **b**, Photographs of the TiO_2/Au-film (upper) and the strongly-coupled electrode (lower).

optical delay system, and the time-resolved two-photon PEEM is constructed (Fig. 2a). LSPR is excited by ω to generate hot electrons, and these are further excited by 3ω to generate photoelectrons. By measuring the energy distribution of the electron, we investigate the energy distribution of the hot electrons and holes involved in the electron transfer reaction (Fig. 2b). The near-field spectrum, phase relaxation time, and electron transfer dynamics are also studied. Furthermore, we explore the intermediates of water oxidation by surface-enhanced Raman scattering spectroscopy and elucidate the mechanism of oxygen evolution, in collaboration with Prof. Murakoshi of Hokkaido University (Co-I).

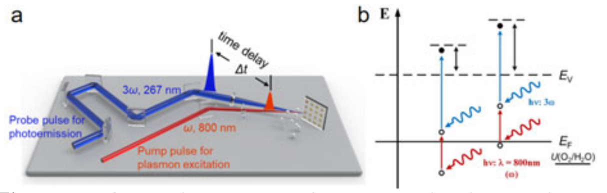

Fig. 2. a, Optical systems of time-resolved two-photon PEEM, **b**, Conceptual diagram of photoemission by 3ω.

【Expected Research Achievements and Scientific Significance】

The electron transfer reaction using a strongly coupled electrode can realize not only the efficient utilization of light but also a near-field enhancement in the entire visible region and an increase in the quantum yield of the reaction. It is expected to make great impacts in plasmon-induced solar energy conversion and photocatalytic studies. Moreover, it is possible to freely tune the wavelength at which the near-field enhancement is induced by selecting the size of the Au-NPs and the resonator length of the nano-FP resonator. Therefore, we believe that this technology induces a paradigm in shift not only plasmonic chemistry but also a wide range of other research fields, such as plasmonics, nanophotonics and spectroscopic research.

【Publications Relevant to the Project】

・H. Yu, Q. Sun, H. Misawa et al., "Exploring coupled plasmonic nanostructures in the near field by photoemission electron microscopy", *ACS Nano* **10**, 110373-10381 (2016).
・K. Ueno, T. Oshikiri, Q. Sun, X. Shi, H. Misawa, "Solid-state plasmonic solar cells", *Chem. Rev.* **118**, 2955-2993 (2018).

【Term of Project】 FY2018-2022

【Budget Allocation】 477,700 Thousand Yen

【Homepage Address and Other Contact Information】
http://misawa.es.hokudai.ac.jp

Title of Project : High Energy Neutrino Universe explored by IceCube-Gen2

Shigeru Yoshida
(Chiba University, Graduate School of Science, Professor)

Research Project Number : 18H05206 Researcher Number : 00272518
Keyword : cosmic-ray, neutrinos, south pole, particle physics, astronomy

【Purpose and Background of the Research】

The IceCube Neutrino Observatory, the three-dimensional detector array deployed in the deep glacier at the South Pole, made the first discovery of high energy cosmic neutrinos in 2013 and pioneered the new frontier of observing our cosmos, High-Energy Neutrino Astronomy. Neutrinos are charge-neutral elementary particles which can travel over cosmological distances without losing their energies. They are unique messengers to reveal dynamically evolving ultra-high energy universe, which could not be explored by the conventional astro-messengers like optical photons. Taking this advantage further, IceCube started operating a realtime neutrino alert system in 2016: Identifying astrophysical neutrinos real-timely to deliver detection information to world-wide astronomical observation facilities for follow-ups. It realized the great achievement last year that the observation of a neutrino in directional and temporal coincidence with high energy γ-rays identified a neutrino emission object. This "multi-messenger astronomy" powers capability of probing energetic phenomena in cosmos and therefore it is critical to improve statistics of high energy neutrino events for multi-messenger campaigns.

【Research Methods】

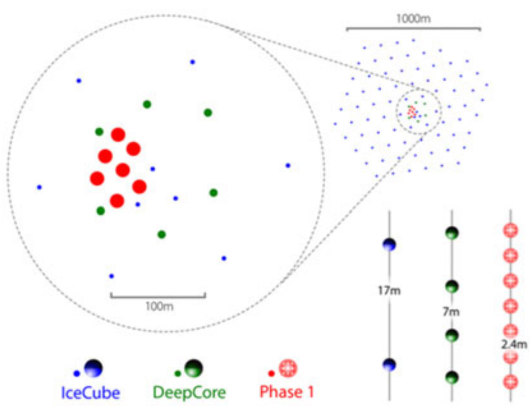

Figure 1. The concept of IceCube Upgrade

In order to greatly enhance the efficiency of high energy astrophysical neutrino detections, IceCube has planned the next generation project, IceCube-Gen2. As the phase 1 of this expansion, we upgrade IceCube facility by densely deploying the new optical detectors in the central area of the IceCube instrumentation volume.
The Japanese group has developed a new type of optical detectors, "D-Egg", which realize twice better photon detection efficiency than the present modules running in IceCube. We will deploy two hundred of D-Eggs down to the glacier ice. This upgrade is expected to improve accuracy in estimation of arrival directions of cosmic neutrinos. We also strengthen the radio detector array for seeking even higher energy neutrinos than ever detected. With this upgrade, we conduct a deeper survey of high energy universe by neutrinos in the wide energy band from TeV to EeV.

【Expected Research Achievements and Scientific Significance】

The upgrade is expected to reveal various objects to emit high energy neutrinos. Follow-up observations by radio, optical, X-rays, and γ-rays will bring us understanding of origin of ultra-high energy cosmic rays, the most energetic radiation in Universe. We also expect to discover neutrino-only luminous objects.

【Publications Relevant to the Project】

・ S.Yoshida et al, IceCube Collaboration, "Constraints on Ultrahigh-Energy Cosmic-Ray Sources from a Search for Neutrinos above 10 PeV with IceCube" Physical Review Letters **117** 141101 1-9 (2016)
・ S,Yoshida et al IceCube Collaboration "The IceCube realtime alert system", Astroparticle Physics **92** 30-41 (2017)

【Term of Project】 FY2018-2022

【Budget Allocation】 411,400 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.icehap.chiba-u.jp

Title of Project : Study on time-domain-multiplexed 2D continuous-variable cluster states and its application to large-scale quantum information processing

Akira Furusawa
(The University of Tokyo, Graduate School of Engineering, Professor)

Research Project Number : 18H05207 Researcher Number : 90332569
Keyword : Cluster states, Quantum entanglement, Quantum Computer

【Purpose and Background of the Research】

By using the technology of continuous-variable (CV) quantum teleportation, we will try to establish a methodology to build a large-scale optical quantum computer. Here, we succeeded in CV quantum teleportation for the very first time in the world and the technology has become a "world standard" in these days. Since we can build a large-scale quantum computer by combining quantum teleportation technology and a large-scale 2D entangled state (cluster state), we will try to create a large-scale 2D CV cluster state by time-domain multiplexing and will establish a methodology how to use it with CV quantum teleportation technology to build a large-scale optical quantum computer. Here, we also developed the technology of time-domain multiplexing.

【Research Methods】

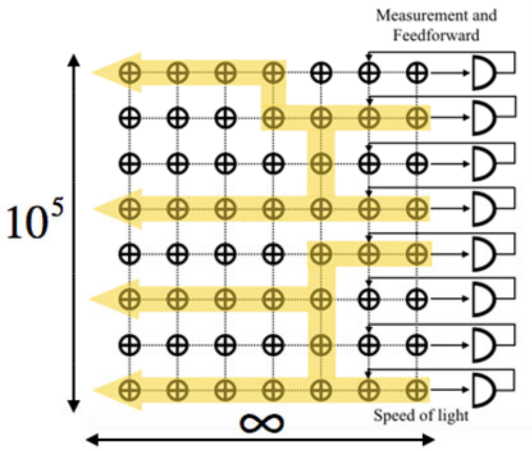

Fig. 1 Large-scale quantum computing with time-domain multiplexing.

By using a large-scale 2D cluster state, we can make a large-scale universal quantum computer as shown in Fig.1. Here a large-scale 2D cluster state corresponds to a superposition of all possible quantum computing patterns. We can select one of them by changing the measurement bases and can make a collapse of the cluster state to the desired state, which is the output of the quantum computer. The randomness of the measurement results can be eliminated by operations depending on the measurement results, which is called "feedforward". The whole process is called "one-way quantum computing", because a measurement process is irreversible.

This type of large-scale 2D cluster states can be created only by using four squeezed vacua, five beam splitters, and two delay lines as shown in Fig. 2. We will realize the large-scale 2D cluster states by using this methodology.

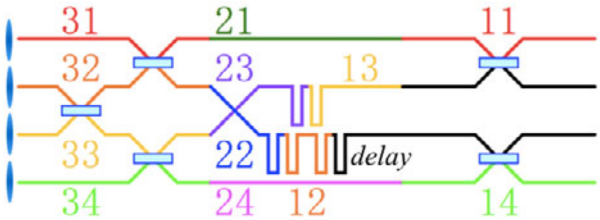

Fig. 2 Schematic of experimental setup for the creation of large-scale 2D cluster states.

【Expected Research Achievements and Scientific Significance】

We will show that our methodology works well for building a large-scale universal quantum computer.

【Publications Relevant to the Project】

・A. Furusawa et al., Science **282**, 706 (1998)
・N. Lee et al., Science **332**, 330 (2011)
・H. Yonezawa et al., Science **337**, 1514 (2012)
・S. Yokoyama et al., Nature Photonics **7**, 982 (2013)
・S. Takeda et al., Nature **500**, 315 (2013)

【Term of Project】 FY2018-2022

【Budget Allocation】 489,200 Thousand Yen

【Homepage Address and Other Contact Information】

http://alice.t.u-tokyo.ac.jp

Title of Project : Development of novel photo-induced phase conversion materials based on quantum dynamic control of Charge-Structure-Spin-Photon coupled systems

Shinya Koshihara
(Tokyo Institute of Technology, School of Science, Professor)

Research Project Number : 18H05208 Researcher Number : 10192056
Keyword : Optical Properties of Materials, Photoinduced Phase Transition, Ultrafast Structural Dynamics

【Purpose and Background of the Research】

An attractive target for materials science is to achieve control of phase transitions using light (photo-induced phase transitions: PIPTs). To date, PIPT dynamics has been governed by the slow relaxation/dissipation of photo-injected energy leading to decoherence of the multi-electron state in a cooperatively interacting system (classical PIPT). Utilization of the quantum dynamics of a multi-electron state (quantum PIPT) that is coherently and strongly coupled to the electromagnetic field of the excitation photon itself is essential for creating photonic phase-switching materials with ultrahigh speeds and sensitive responses. Combining ultrafast modifications of three main physical degrees of freedom in solids (Charge-Structure-Spin, C-S-S) within the vibrational periods of elementary excitations will enable us to find unique C-S-S-ordered states, which can be obtained only by quantum PIPT (i.e., quantum hidden states: QHS).

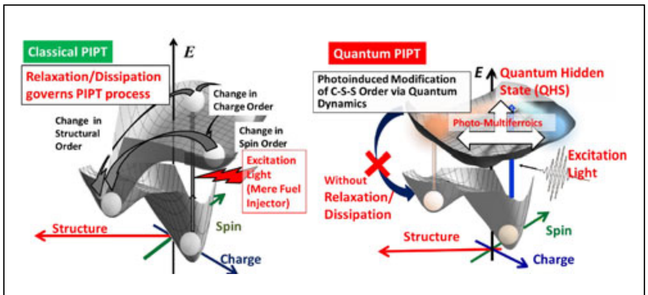

Figure 1 Illustration of classical PIPT dynamics (left-hand side) and quantum PIPT (right-hand side)

【Research Methods】

To clarify the ultrafast C-S-S coupled dynamics in a quantum PIPT system and develop new materials, this project establishes the following three teams and involves deep collaborations among materials scientists, specialists in ultrafast spectroscopy/ electron diffraction, and theoreticians:

Team 1: Search and develop candidate materials that show QHS *via* ultrafast quantum PIPT based on the strong coupling among C-S-S freedoms.

Team 2: Construct an ultrashort (30 fs) pulsed electron-diffraction facility with a spin-polarized /depolarized electron source.

Team 3: Construct a theoretical framework for quantum PIPT.

【Expected Research Achievements and Scientific Significance】

In this project, a pulsed electron-diffraction system with a 30-fs width, combined with a spin-polarized electron source will be constructed to enable observations of ultrafast C-S-S dynamics. The combined use of this system and an ultrafast spectroscopic probe will reveal the quantum natures of the microscopic mechanisms driving the initial PIPT process. The accumulated knowledge will unveil a realistic manner for photo-controlling the sensitive and ultrafast changes in magnetic, electronic, optical, dielectric, and structural properties of materials based on C-S-S strong coupling *via* QHS (photo-multiferroics). This research will have a large impact on the general field of photo-functional materials while opening the door for photonic and quantum control of a wide class of materials with ultrahigh speeds.

【Publications Relevant to the Project】

・"Direct Observation of Collective Modes Coupled to Molecular Orbital Driven Charge Transfer", T.Ishikawa, M.Hada, *R.J.D. Miller, K.Onda, S.Koshihara, et al. Science 350, pp.1501 (2015)
・"Coherent dynamics of photoinduced phase formation in a strongly correlated organic crystal", T.Ishikawa, S.Koshihara, *K.Onda et al. Phys. Rev. B 89, 161102(R) (2014)

【Term of Project】 FY2018-2022

【Budget Allocation】 484,700 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.chemistry.titech.ac.jp/~koshihara/english2/index.html

Title of Project : Development of Ultimate Functions Based on Helical Polymers with Helicity Memory

Eiji Yashima
(Nagoya University, Graduate School of Engineering, Professor)

Research Project Number : 18H05209　Researcher Number : 50191101
Keyword : Helical polymer, helical structure, chirality, asymmetric catalysis, chiral separation

【Purpose and Background of the Research】

Mother nature applies the one-handed helical structure in biological systems at the macromolecular and supramolecular levels, which links to their sophisticated functions. Chemists have been challenged to develop artificial helices to mimic such biological helices and functions. Apart from the previous studies, the present project aims to develop ultimate functions based on synthetic helical polymers with a unique "static memory of helicity" that cannot be achieved by the biological helical systems. Our helical polymers possess outstanding exclusive features, such as (1) remarkable chiral amplification of the helical chirality, (2) ultrafast helicity induction and subsequent memory of the helicity, (3) spring-like motion accompanied by a significant visible and fluorescence color change, (4) flexible and adaptable helical cavity, and (5) easy modification of the pendant groups. With these key features in hand, we will establish rational strategies for developing helical polymers with a unique static memory of the helicity and then develop [1] an ultimate chirality detection system for the extremely small chirality, [2] practically useful switchable chiral stationary phases (CSPs) for HPLC and asymmetric catalysts, [3] an in-situ colorimetric/fluorescence sensing system, and [4] enantioseparation and asymmetric catalysis within a helical cavity of the helical polymers.

【Research Methods】

Taking advantage of the outstanding features of the helical polymers with the static helicity memory, the structure-property relationships of the helical polymers will be explored to realize the ultimate functions. The unique and versatile static helicity memory strategy makes it possible to further modify the side groups with the desired functional groups, while maintaining their static helicity memory, leading to the developments of the ultimate functions.

【Expected Research Achievements and Scientific Significance】

While a huge number of studies on helical systems have been reported, our helical polymers are unique and exclusive among those prepared before because of their unique static memory of the helicity with a remarkable amplification of the helical chirality. Therefore, making the best use of our helical polymers enables to develop innovative chiral materials with specific functions that cannot be achieved by the biological helical systems. The fundamental knowledge gained from this project will also contribute to understanding the origin of the biomolecular homochirality.

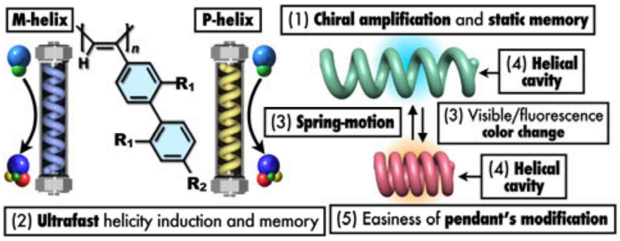

Figure Outstanding properties of helical polymers with a static memory of helicity.

【Publications Relevant to the Project】

- E. Yashima, N. Ousaka, D. Taura, K. Shimomura, T. Ikai, K. Maeda, Supramolecular Helical Systems: Helical Assemblies of Small Molecules, Foldamers, and Polymers with Chiral Amplification and Their Functions, *Chem. Rev.* **116**, 13752-13990 (2016).
- K. Shimomura, T. Ikai, S. Kanoh, E. Yashima, K. Maeda, Switchable Enantioseparation Based on Macromolecular Memory of a Helical Polyacetylene in the Solid State, *Nature Chem.* **6**, 429-434 (2014).

【Term of Project】 FY2018-2022

【Budget Allocation】 457,300 Thousand Yen

【Homepage Address and Other Contact Information】

http://helix.mol.nagoya-u.ac.jp/e/index.html
yashima@chembio.nagoya-u.ac.jp

Title of Project : Nuclear Emulsion
- New deployments for fundamental and interdisciplinary researches in the 21st century -

Mitsuhiro Nakamura
(Nagoya University, Institute of Materials and Systems for Sustainability, Professor)

Research Project Number : 18H05210 Researcher Number : 90183889
Keyword : Nuclear Emulsion. elementary particle physics, Astronomy, Muon radiography

【Purpose and Background of the Research】

Nuclear Emulsion, which has a history of about 100 years, is still contributing to the progress in elementary particle physics by the discovery of Tau-neutrino and the discovery of Tau-neutrino appearance in neutrino oscillation. Adding to those, applications to interdisciplinary researches are rapidly extending. Examples are Muon radiography (e.g. discovery of a big void in Khufu Pyramid) and balloon born large aperture Gamma-ray telescope.

Those movements are realized by fully automated nuclear emulsion read-out system developed by us and the lab-made nuclear emulsion also developed by us from 2010. The latter has a meaning to take back still-worth technical resources from the company to the university dealing with the market shrinkage, and to give additional values through new developments.

In this research project, we will develop an automated nuclear emulsion read-out system which has ~40times faster scanning speed than the current system, a nuclear emulsion film production system which can deal with 10000m^2/year and adding new features to nuclear emulsion. Those developments will push forward strongly the currently running and coming researches in the region of fundamental and interdisciplinary researches.

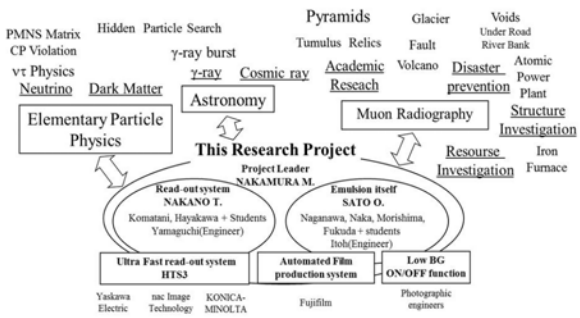

Fig1. This research project
and the related research regions.

【Research Methods】

① R&D of 40times faster read-out system by adopting slant optics.
② R&D of automated emulsion film production systems to deal with 10000m^2/year level request.
③ Preparation of the gel production recipe database to give the best solution to a specified purpose. Realization of low background nuclear emulsion and sensitivity ON/OFF function.

【Expected Research Achievements and Scientific Significance】

In the field of elementary particle physics, application to interdisciplinary research region becomes important in parallel with the search for the phenomena beyond the established standard model. As we have nothing in the energy frontier until today. We must extend the frontier to any possible directions, neutrino research at where the first break of the standard model was found, the intensity frontier to explore the hidden sectors. Also dark matter is the subject beyond the standard model. NINJA@JPARC, DsTAU & SHiP@CERN and NEWSdm@LNGS are the related emulsion projects.

Relating to the application, discovery of new structures in Khufu Pyramid by muon radiography shows how the technologies developed for particle physics can shed new light on the interdisciplinary field. In the region of astronomy, nuclear emulsion can realize a balloon born γ ray telescope with 10times larger aperture and one order finer resolution than Fermi satellite.

In those interdisciplinary researches, repeat of “try and error” is very important. Nuclear emulsion can lower the barrier of “try and error”, by its low cost, easily accessible tools for detector production and analysis. Also its scalability will allow easy project extension.

The outputs from this research project will become a powerful motive force to push forward the fundamental & interdisciplinary researches.

【Publications Relevant to the Project】

・“Expanding Horizon of the Nuclear Emulsion Applications”, Journal of the Society of Photographic Science and Technology of Japan, Vol 71, No5, 2008 (in Japanese).

【Term of Project】 FY2018-2022

【Budget Allocation】 455,400 Thousand Yen

【Homepage Address and Other Contact Information】
http://flab.phys.nagoya-u.ac.jp/2011/

Title of Project : Research on ultra-low power sub-terahertz superconducting quantum digital systems based on pulse-driven circuits

Akira Fujimaki
(Nagoya University, Graduate School of Engineering, Professor)

Research Project Number : 18H05211 Researcher Number : 20183931
Keyword : single flux quantum, half flux quantum, magnetic Josephson junction

【Purpose and Background of the Research】

Our social life has been changing with the extensive spread of the digital technologies such as the internet, AI. While convenience is improved remarkably, energy- efficient digital technology is needed for supporting the improvement.

Impulses with widths of a few pico seconds are used as an information carrier in the superconductor single flux quantum (SFQ) circuit. The SFQ circuits are relieved of the recharge process that hampers speed-up and reduced power consumption in semiconductor integrated circuits (ICs). The SFQ ICs have been expected to operate around 100 GHz with very high energy-efficiency.

However, matrix memories proposed so far require recharge process even in the SFQ circuit. In this study, we will develop matrix memories driven by an impulse based on the half flux quantum (HFQ) circuit. We can reduce the energy required for the transition between the two stable states in the HFQ circuit by introducing magnetic Josephson junctions (MJJs). The elementary unit of the HFQ circuit is almost the same as that of flux qubits. This means our technology has high affinity to the qubits, so that we can unify the SFQ/HFQ circuits with the quantum computers in the future.

【Research Methods】

πSQUIDs composed of a π MJJ and a 0JJ play an important role in the HFQ circuits. Here, the initial phase difference of a π MJJ is shifted by π, while conventional JJ (0JJ) has no phase shift.

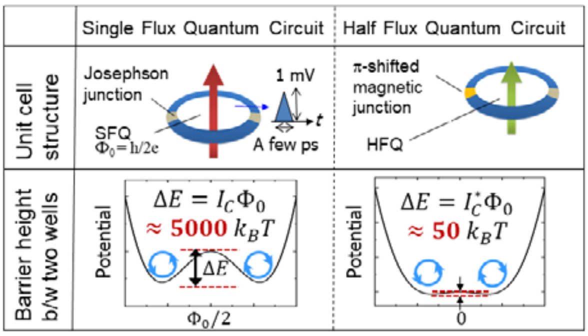

Figure 1 Unit cell structures and potential shapes in the SFQ/HFQ circuits

The barrier height between the two states in the HFQ circuits is about 1/100 compared to that of the SFQ circuits as shown in Figure 1. In addition, the bi-stable stable states are achieved without any applied field in the HFQ circuits. These lead to extremely-energy efficient circuits.

【Expected Research Achievements and Scientific Significance】

We will achieve an SFQ microprocessor operating around 100 GHz and a pulse-driven HSQ-based matrix memory. We will also demonstrate a digital system by combining both circuits.

Ultimately fast operations are expected by using πSQUIDs. We will try to obtain information about the relationship between the uncertainty principle and the classical computation through this experiment. In future, we will combine the SFQ/HFQ technology and the quantum computers.

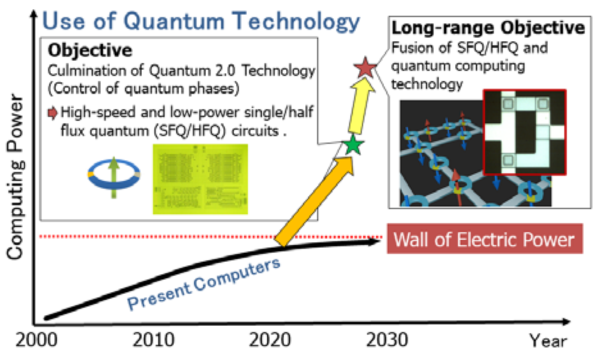

Figure 2 Roadmap of the technology

【Publications Relevant to the Project】

・T. Kamiya, M. Tanaka, A. Fujimaki, et al., IEICE Trans. Electron., E101-C(5), pp.385-390, 2018.

【Term of Project】 FY2018-2022

【Budget Allocation】 473,400 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.super.nuee.nagoya-u.ac.jp/tokusui/

Title of Project : Development of semiconductors intra-center photonics

Yasufumi Fujiwara
(Osaka University, Graduate School of Engineering, Professor)

Research Project Number : 18H05212　Researcher Number : 10181421
Keyword : Semiconductor, Thin films, Optical properties of condensed matter, Optical devices

【Purpose and Background of the Research】

Our surroundings are full of various light sources, which are produced from semiconductors. These lights use transitions that occur between the conduction band and the valence band of the semiconductor, which is referred to as interband photonics. However, this application has critical problems, which lie at the heart of the light emission principle known as Fermi's Golden Rule.

We have worked on the development of semiconductors intra-center photonics. This novel photonics uses the intra-4*f* shell transitions of rare-earth (RE) ions doped in semiconductors. In 2009, we invented a narrow-band red light-emitting diode (LED) using Eu-doped GaN (GaN:Eu). Due to optimization of the device processing, the output power of the LED has been increasing steadily to over 1 mW.

In this project, we move to the next and final step for the development of the GaN:Eu red LED (Fig. 1). We will further enhance the output parameters by intentional manipulation of the radiative recombination probability at the atomic level of the Eu ions, which will be achieved through control of their photon fields using micro- and nano-cavities. Subsequently, we will extend this approach to other RE ions for the realization of a RE-based full-color high-resolution display with exceptional characteristics.

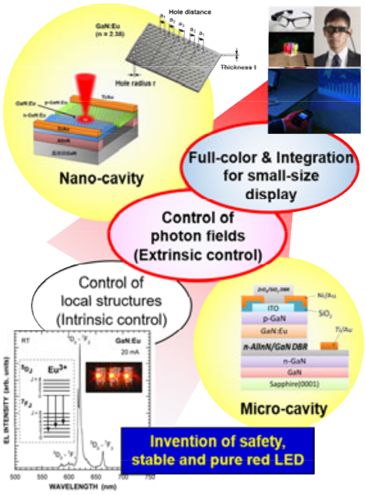

Fig. 1　Contents and flow of this research project

【Research Methods】

(1) Fabrication of micro- and nano-cavities using GaN:Eu, and the characterization of newly emerging Eu intra-4*f* shell luminescence properties under optical pumping in a cavity that has a sufficiently high Q factor.
(2) Fabrication of a LED structure using GaN:Eu with the cavities. The unique luminescence properties will be investigated under current injection.
(3) Extension of the research to Tm- or Er-doped nitride semiconductors to realize a new family of LEDs that operate in the blue and green emission range. Finally, these red, green and blue LEDs will be integrated on the same substrate to demonstrate the feasibility of a monolithic full-color LED display.

【Expected Research Achievements and Scientific Significance】

Research on RE-doped materials has been based on experience obtained through trial and error, not on material design by the precise control of RE doping and an understanding of the energy-transfer mechanisms. This project will provide guiding principles to design RE-doped materials with "made to order" optical characteristics.

【Publications Relevant to the Project】

・B. Mitchell, Y. Fujiwara *et al.*: "Perspective: Highly efficient GaN-based red LEDs using europium doping," Journal of Applied Physics **123** (2018) pp. 160901/1-12.
・B. Mitchell, Y. Fujiwara *et al.*: "Utilization of native oxygen in Eu(RE)-doped GaN for enabling device compatibility in optoelectronic applications," Scientific Reports **6** (2016) pp. 18808/1-8.

【Term of Project】 FY2018-2022

【Budget Allocation】 490,300 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.mat.eng.osaka-u.ac.jp/mse6/