c. Hokkaido University – Research Center for Integrated Quantum Electronics

Prof. Hasegawa

The Center carries out intensive and focused advanced research on Integrated Quantum Nanoelectronics, based on high-density integration of quantum nanodevices, emphasizing III-V compound semiconductors, including nitrides. The operation principles of the devices are entirely new, being based directly on the quantum mechanics in which elementary quantum mechanical motions and processes of a single or a few electrons are controlled by arrays of artificial quantum nanostructures.

By quantum electronics, one can realize, for electronic devices, smallest possible power-delay products near quantum limit for switching, extremely large storage capacity and extremely high-integration density with ultra low power consumption. Entirely new functional capabilities are also expected from artificial atom and molecule features of quantum nanostructures with coherent oscillations of internal states as well as from phase-coherent transport of electron waves and their interactions. Research on these features may eventually lead to realization of non-dissipative quantum circuits from massively parallel and highly sophisticated quantum computing/quantum information processing. The research areas of the Research Center for Integrated Quantum Electronics are:

Research Area for Quantum Crystal Photonics

Objective

The main objective of this research area is to carry out intensive research on formation of compound semiconductor nanostructure arrays, characterization of their physical properties and their applications to novel electronic and photonic devices.

Research Topics

1. **Formation of III-V quantum nanostructure arrays by metalorganic vapor phase epitaxial growth**

Size- and site-controlled arrays of compound semiconductor quantum nanostructures, which one might call "artificial quantum crystals", are unique building grounds of supreme importance for novel integrated quantum electronic/optoelectronic devices, providing chances of fully utilizing superior electronic and optical properties of compound semiconductors in the ultimate quantum regime. In this research area, intensive efforts are being made to realize high-density quantum nanostructure arrays by the metalorganic vapor phase epitaxial (MOVPE) growth method, which is a standard key technology adopted by industry today to produce wireless and optoelectronic devices on marker. Some of our successful examples are "quantum dot network" structure (Fig.1) where quantum wires and quantum dots are arranged and coupled together with a 200nm periodicity, and a periodic triangular-lattice array of hexagonal pillars (Fig.2) for photonic crystal applications.

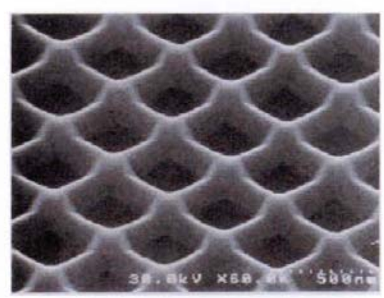

図1 MOVPE選択成長で形成した量子ドットネットワーク構造のSEM写真。
Fig. 1 SEM image of quantum dot network.

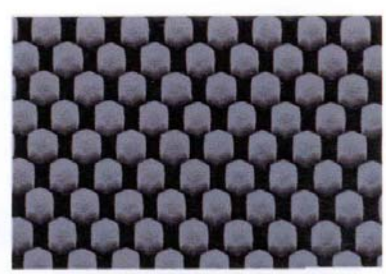

図2 有機金属気相選択成長法により作製したピラー型3角格子フォトニック結晶の電子顕微鏡写真。
Fig. 2 SEM image of triangular-lattice photonic crystal with hexagonal pillars formed by selective area MOVPE growth.

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Research Area for Quantum Crystal Photonics (Cont.)

2. Physics and device application of III-V quantum nanostructure arrays

Intensive research efforts are also made in this research area to understand physics of high-density coupled arrays of quantum nanostructures, and to create, based on such understanding, novel electronic and photonic devices based on simultaneous control of quantum states of electrons and photonic states of light. Properties of single and coupled quantum dots such as quantum states and single electron transport as well as properties of photonic crystals are also explored using sophisticated optical and electronic techniques. Recent successful examples include quantum wire lasers (Fig.3) realized by using high-density array of quantum wires, and demonstration of single electron transistors and their integrated circuits (Fig.4).

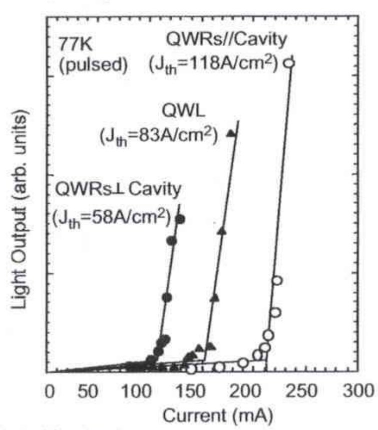

図3 量子細線レーザの発振特性。
Fig. 3 I-L Characteristics of a quantum wire laser.

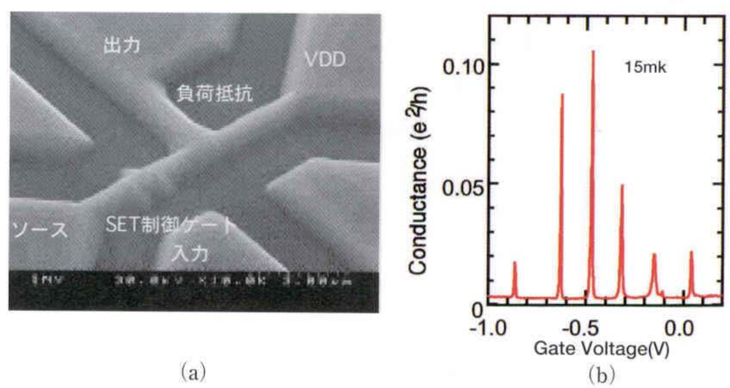

図4 (a) 選択MOVPE成長により作製した単電子インバーター回路のSEM像と(b) 単電子トランジスタのクーロン振動。
Fig. 4 (a) SEM image of single electron inverter and (b) Coulomb oscillation of single electron transistor formed by selective area MOVPE.

Research Area for Quantum Intelligent Devices

Objective

Based on the formation technology of quantum wire transistors and single electron transistors established in the previous RCIQE, intensive efforts are dedicated to create next generation quantum large-scale integrated circuits, GaN-based quantum devices, terahertz electromagnetic wave generators and detectors, neuron and fuzzy logic function device circuits, and quantum information processing circuits.

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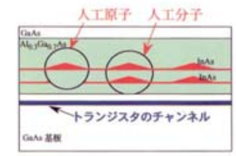
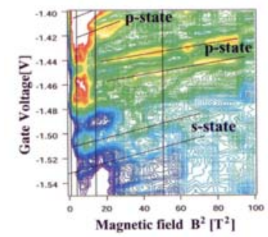
Research Area for Quantum Intelligent Devices (Cont.)

Research Topics

1. **Fabrication and characterization of compound semiconductor quantum devices**
   The objective of the projects is to fabricate various types of quantum devices utilizing InAs dots and selective doping technique for the MBE growth of nanostructures.
   Figure 1 shows a schematic illustration of a quantum effect transistor having InAs dots.



(a)量子ドット・トランジスタの構造

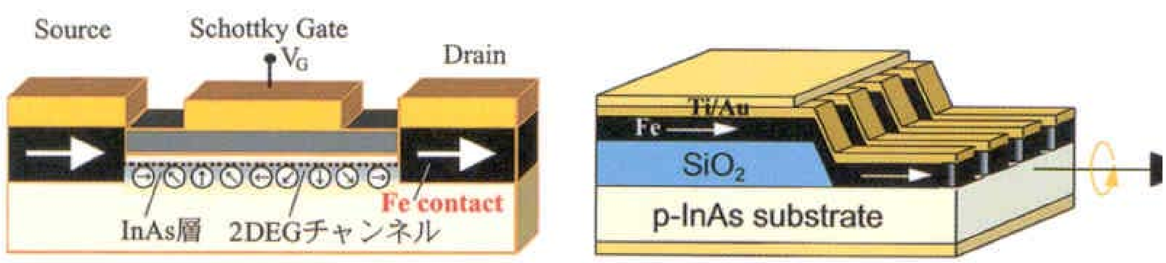


(b)単一ドット電子状態特性

図1 量子ドット（人工原子・分子）とHEMT（超高速トランジスタ）の集積による(a)量子ドット・トランジスタの構造と (b) 得られた単一ドット電子状態特性。

Fig.1 (a) Quantum dot (artificial atoms and molecules) are integrated with HEMT (high electron mobility transistor) to form a " quantum dot transistor." (b) Measured electron state of an artificial atom as a function of drain and gate voltage.

2. **Control of ferromagnetic film/semiconductor interfaces and its application to spin-injection transistor**
   Based on the control of ferromagnetic film/semiconductor interfaces, we try to fabricate spin-injection transistors (Fig.2). The combination of this device with a single electron transistor will open up the possibility for realization of a new quantum system.



(a)スピン注入トランジスタ模式図　(b)スピン注入検証実験の構造図

図2 (a)InAs チャンネル中の電子スピンをゲート電圧によって制御する ピン注入トランジスタの構造図と (b) 磁化方向の揃った強磁性体（鉄） 膜から半導体（InAs)へのスピン注入検証実験の構造図。これまでで最 のスピン注入効率が得られている。

Fig.2 (a) A schematic diagram of a spin transistor using Fe/InAs hybrid stru ture. (b) Device setup for detection of spin injection. To date, the highest sp polarization has been obtained in the Fe/InAs hybrid structure.

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Research Area for Quantum Intelligent Devices (Cont.)

3. Fabrication of GaN-based HFET based on the surface control of GaN-related materials

GaN and related heterostructures are the promising candidates as materials for the production of high-power/high-frequency hetrostructure field effect transistors (HFETs) and hetero-junction bipolar transistors (HBTs). Understanding and controlling surface properties of GaN and GaN-based heterostructure field effect transistors (HFETs) and hetero-junction bipolar transistors (HBTs). Understanding and controlling surface properties of GaN and GaN-based heterostructures is of utmost importance for reliable performance of these devices. Based on the atomic scale control and passivation of surfaces, intensive efforts are dedicated to realize GaN-based high-power/high-frequency electron devices.

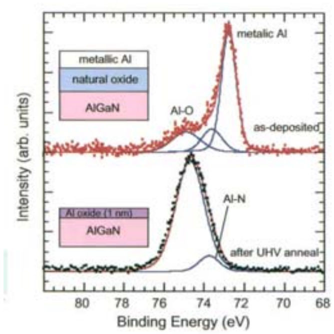

図3 1nm の超薄 Al 酸化膜を形成したAlGaN表面の光電子分光スペクトル。

Fig. 3 XPS spectra from the AlGaN surface passivated with a 1-nm AlO_X layer.

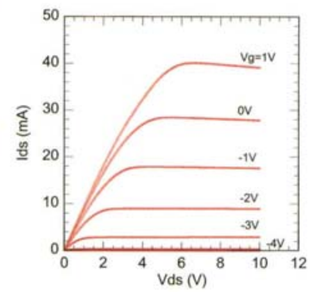

図4 超薄Al酸化膜を有するAlGaN/GaN HFETのI-V特性。

Fig. 4 Drain I-V characteristics of AlGaN/ GaN HFET with a 1-nm AlO_X layer.

Research Area for Quantum Integrated Processing

Objective

The objective of this research area is to create novel devices, processing technologies and system architectures in such a way that their combinations are best suited for realization of next generation electronic and photonic quantum integrated circuits/systems. For their fabrication using III-V near-surface quantum nanostructures, one promising approach is to carry out all the necessary steps for integration, including initial crystal growth of nanostructures up to final nano-scale metallization in a UHV-based multi-chamber system.

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Research Area for Quantum Integrated Processing

Research Topics

1. Novel III-V quantum devices and logic architectures for large scale integration

Quantum devices such as single and coupled quantum wire transistors and single electron transistors have been realized by control of III-V nanowires with novel nanometer scale Schottky gates, and their quantum transport properties have been clarified. For large scale integration of quantum devices, a novel hexagonal binary decision diagram (BDD) quantum logic circuit approach has been proposed and successfully demonstrated (Fig.1), using etched GaAs/AlGaAs hexagonal nanowire networks. Applications of the above device technology to microwave/millimeter wave transistors and novel terahertz devices are also being investigated.

2. Selective MBE growth of III-V quantum nano-structure arrays and development of nano-processing technologies

GaAs-based and InP-based high-density arrays of quantum wires (QWRs) and quantum dots (QDs) are grown by selective MBE techniques on patterned substrates, achieving, for example, QWR networks with wire width below 10 nm and submicron pitches (Fig.2) Damage-free nano-processing technologies such as electrochemical metal deposition and nanopore formation processes are also being developed.

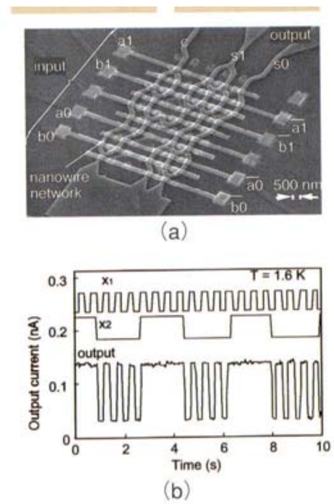

図1 (a)二分決定グラフ(BDD)ヘキサゴナル量子集積回路(2bit加算機)と(b)OR回路の動作例。

Fig.1 (a) Hexagonal binary-decision-diagram (BDD) quantum integrated circuit (2bit adder) and (b) demonstration of OR logic operation.

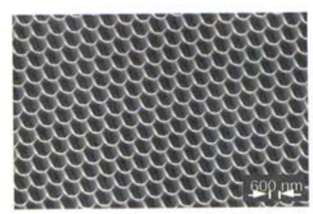

図2 InGaAsヘキサゴナル量子細線ネットワーク。

Fig. 2 InGaAs hexagonal quantum wire network.

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Research Area for Quantum Integrated Processing (Cont.)

3. In-situ quantum structure processing in a UHV-based multi-chamber system

Since high-density quantum nanostructures are grown and processed near-surface to fabricate electronic and photonic quantum integrated circuits/systems, realization and maintenance of perfection of surfaces and interfaces in atomic scale are key issues. In-situ processing in a UHV-based multi-chamber system is one most promising way. For this purpose, approaches to characterize and control surfaces and interfaces in the UHV-based multi-chamber system are being explored. For example, surface states on MBE surface are detected by UHV STM/STS technique (Fig.3). A silicon interface control layer (SiICL) technique for surface passivation has been successfully developed.

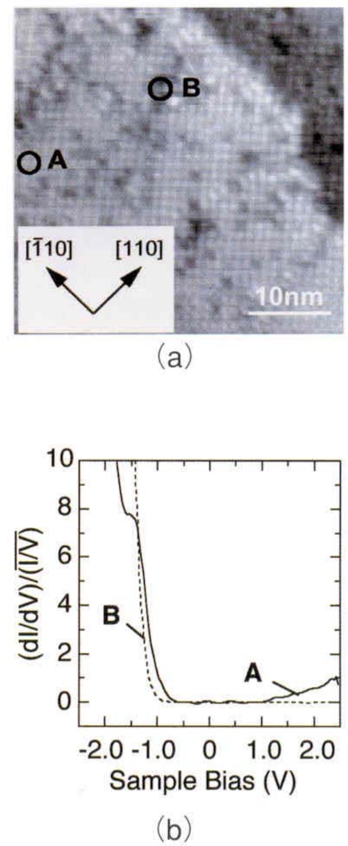

図3 表面準位が原子的尺度で可視化された(a)GaAs(001)表面のUHV-STM像と(b) STSスペクトル。

Fig. 3 (a) UHV-STM image and (b) STS spectra of (001) GaAs surface showing presence of surface states.

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Research Area for Integrated Quantum Systems

Objective

Future multimedia systems should be human-friendly and environment-friendly, in such a way that they allow any of us to access any desired information, any time, anywhere, easily and immediately at ultra-low energy consumption and without causing serious environmental problems. If we continue to use conventional system-architectures and hard wares of the present-day systems, however, efforts toward such systems will saturate and face severe limitations in the near future. The objective of this research area is to create the basis for innovative future multimedia systems by exploiting quantum devices, quantum circuits and quantum architectures for computation, information processing and communication of tomorrow. Extensive efforts will be made from viewpoints of both system architecture and hardware architecture to create basis of future multimedia systems.

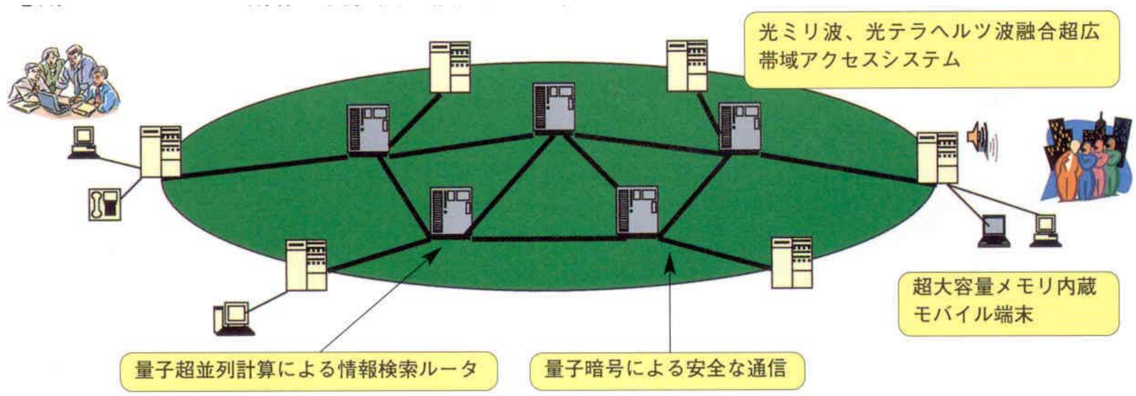

図1　人に優しい、環境に優しいネットワーク：誰もが簡単にかつ即座に欲しい情報にアクセスできる超低エネルギーネットワーク。

Fig.1 A human-friendly and environment-friendly network allows anyone of us to access any desired information, any time, anywhere, easily and immediately at ultra-low energy consumption and without causing serious environmental problems.

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Research Area for Integrated Quantum Systems (Cont.)

Research Topics

1. Creation of novel concepts and design methodologies for novel massively parallel computation and highly secure information-processing systems based on quantum nanodevices

Quantum switching devices operating near the quantum limit of power-delay products, and, in longer term, dissipationless quantum circuits based on quantum nanostructures where quantum coherence extends over the entire circuit, provide opportunities of constructing unprecedented massively parallel information-processing/computation systems based on quantum mechanics that can solve various problems far beyond reach of present-day computers. Novel system concepts and design methodologies are explored in this research area. An example under investigation on computer is a quantum Hopfield network based on single electron devices (Fig.2). Efforts will also be made for realization of highly secure communication network systems based on quantum cryptography and quantum teleportation.

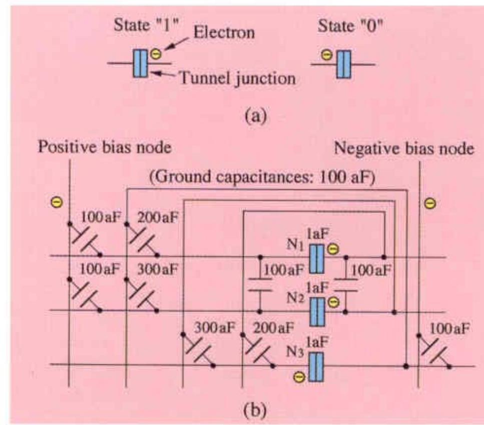

図2　単電子回路による量子ホップフィールドネットワーク（局所最小値問題の無いニュートラルネットワーク）。(a)ニューロンと(b)ネットワーク構成例。

Fig. 2 A quantum Hopfield network using single-electron circuits—a neural network free from the local-minimum difficulty. (a) A neuron, and (b) a sample network.

2. Novel silicon nanoelectronics

A strong material candidate for hardware implementation of abovementioned future multimedia systems is silicon with SOI (silicon-on-insulator) configuration. Intensive efforts are being made to establish SOI quantum device and processing technologies suitable for implementing future system architectures. Examples under investigation are hardware realization of stochastic neuron quantum circuits consisting of SOI single-electron devices, and multiple-valued logic circuits consisting of SOI single-electron multiple-valued logic devices.

3. Quantum devices for terabit optical communication networks

For realization of future terabit communication networks, novel key components have to be created. The fact that quantized energy levels in nanostructures can resonate with terahertz, combined with availability of photonic crystals as functional optical wave-guides, provides us new and unique opportunities of designing and constructing such key components. For example, quantum dot-based optical modulators/demodulators with terahertz rates are under investigation.