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## Highlighted Presentations Press Release

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**Demonstration of vertical crystal phase heterojunction transistor**

# Nanocrystals produce a transistor with new junctions


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**Summary**

- **Crystalline phase heterojunction transistors with indium phosphorus (InP) nanowires was demonstrated for the first time.**
- **The research group has demonstrated switching operation using a crystal phase heterojunction (CPHJ) based on its proprietary vertical gate-all-around (VGAA) structure fabrication technology.**
- **It offers a new junction concept and is expected to have many future applications.**


A research group led by Katsuhiro Tomioka of the Research Institute of Information Science and Technology and the Research Center for Integrated Quantum Electronics at Hokkaido University has been researching the application of nanowire materials to LEDs, transistors, and other devices with practical applications. The research group fabricated a transistor with a vertical structure using vertical gate-all-around (VGAA) structure fabrication technology, a process technology for fabricating transistors with a vertical structure, using the crystal phase heterojunction of the nanowire material, indium phosphorus (InP). The principle of operation was demonstrated. This is the first time a transistor operating with a new junction has been successfully developed.

**Details**

## Semiconductor materials with high design freedom, nanowires

Nanowires are one-dimensional semiconductor nanomaterials used in optical devices such as solar cells and LEDs, sensors, and memory materials. In addition, the research and development of miniature nanowire transistors has long attracted attention as an application for next-generation integrated circuits.

Nanowires are vertical, freestanding, one-dimensional nanostructures with diameters ranging from a few nanometers to several hundred nanometers. They are semiconductor nanomaterials that can be fabricated in large quantities and at low cost owing to advances in epitaxial technologies such as vapour-liquid-solid (VLS) growth and selective growth methods. Nanowires are characterized by their high degree of design freedom. In the development of semiconductor devices, heterojunctions of semiconductors with different properties or "pn junctions" consisting of p-type and n-type semiconductors can be made in the longitudinal (longitudinal heterostructure) or radial (core-multishell structure) direction of nanowires (Figure 1). When joining different semiconductors using conventional materials, it is common practice to fabricate the junction structure so that the lattice constants, which determine the size and shape of the crystal lattice, are equal to reduce defects. However, nanowires are a material system that can create various devices such as LEDs and vertical transistors by taking advantage of its high degree of freedom, even in the presence of "lattice mismatch," a heterojunction with different lattice constants.

### Invention of a new junction transistor, the "crystal phase heterojunction transistor"

A research group led by Katsuhiro Tomioka of the Graduate School of Information Science and Technology and the Research Center for Quantum Integrated Electronics (RCIQE) at Hokkaido University has been studying band structure control using crystal phase transitions in "semiconductor structural phase transition materials" based on indium phosphorus (InP) nanowires, a type III-V semiconductor. Indium phosphide (InP) nanowires undergo a "crystalline phase transition" in which the crystal structure and physical properties change while maintaining their state of matter under the appropriate crystal growth conditions. In a crystal phase transition, zinc-blende structure can transform into wurtzite structure, and the band gap can be changed from an indirect to a direct transition type in the same material system. In research, this property is utilized in applying light-emitting devices using materials with an artificial crystal structure. However, previous research has been limited to structural phase transition materials and their optical device applications, and no attention has been paid to new junctions created by structural phase transition materials. Therefore, we focused on this junction and conceived and fabricated the 'crystal phase transition heterojunction transistor' for use in "electronic devices," says Tomioka.

The research group focused on "crystal phase heterojunctions," which are junctions formed by crystalline phase transitions. InP nanowires are fabricated by growing crystals on a commercially available InP substrate using the metalorganic vapor selective growth method, and the crystal structure becomes a wurtzite-type crystal structure. Furthermore, the interface between this substrate and nanowires will be a defect-free heterojunction (crystal phase heterojunction) despite being made of the same material. In conventional semiconductor heterojunctions, defects (misfit dislocations) are introduced at the junction interface owing to lattice relaxation after a certain degree of crystal growth; however, for crystal phase transition heterojunctions, no such defects are created." The heterojunction can also be made with the same material," says Tomioka.

Tomioka and his colleagues used this crystal phase heterojunction in transistors. "One of the reasons crystal phase heterojunction could not be applied to electronic devices was that the technology used to create device structures in which an electric field is applied perpendicular to the junction interface had not been established," said Tomioka. Owing to the crystal structure, creating a structure in which an electric field is applied perpendicularly is complicated, and this has been a hurdle in electronic device applications.

The research group has already established a three-dimensional process for fabricating a structure in which an electric field is applied to the junction interface in a vertical direction. This is their original vertical gate-all-around (VGAA) structure fabrication technology (Figure 2). Using this technology, they created a vertical transistor with a crystalline phase transition junction and a crystalline phase transition heterojunction transistor and confirmed its operation (Figure 3).

The crystal phase heterojunction transistor is thought to behave similarly to a Schottky transistor. The Schottky transistor uses the energy barrier at the metal-semiconductor junction interface as a switch. In contrast, the crystal phase heterojunction transistor uses the same material to create a potential by changing the order of the crystal structure; hence, it can be used as a high-speed switch similar to the Schottky effect using the same material. Conventionally, n-type InP is one of the most challenging semiconductors to produce a metal/semiconductor Schottky barrier; nonetheless, with a junction created by structural phase transition, a barrier can be created without worrying about defects. "In the long history of transistor research and development, the concept of structural phase transition heterojunctions is completely new, and we expect this demonstration to be the starting point for various device ideas," said Tomioka.

In a Schottky transistor, when a metal and a semiconductor are junctioned, an energy barrier is created by the work function difference (Schottky junction). This transistor uses this energy barrier as a potential. Tomioka and his research group have demonstrated that the Schottky transistor structure can create device operation using only InP nanowire material without a metal. "Since the invention of the point-contact transistor with germanium 75 years ago, many different types of transistors have been invented," said Tomioka. Through this demonstration, we believe we can provide a new junction concept in the long history of transistors.

The company plans to devise more electronic devices using this new junction and will proceed with applied research based on social implementation.

**Figures**

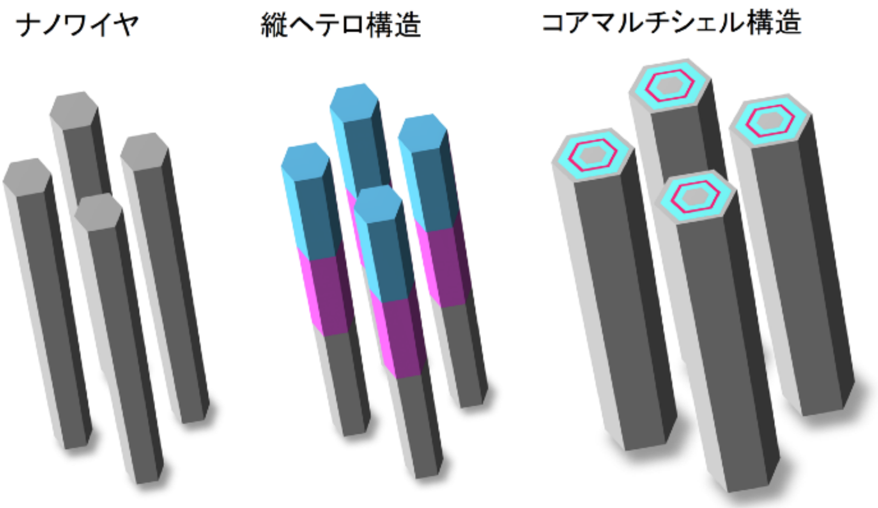


Figure. 1 Conceptual diagram of the longitudinal heterostructure and core-multishell structure that nanowires can create

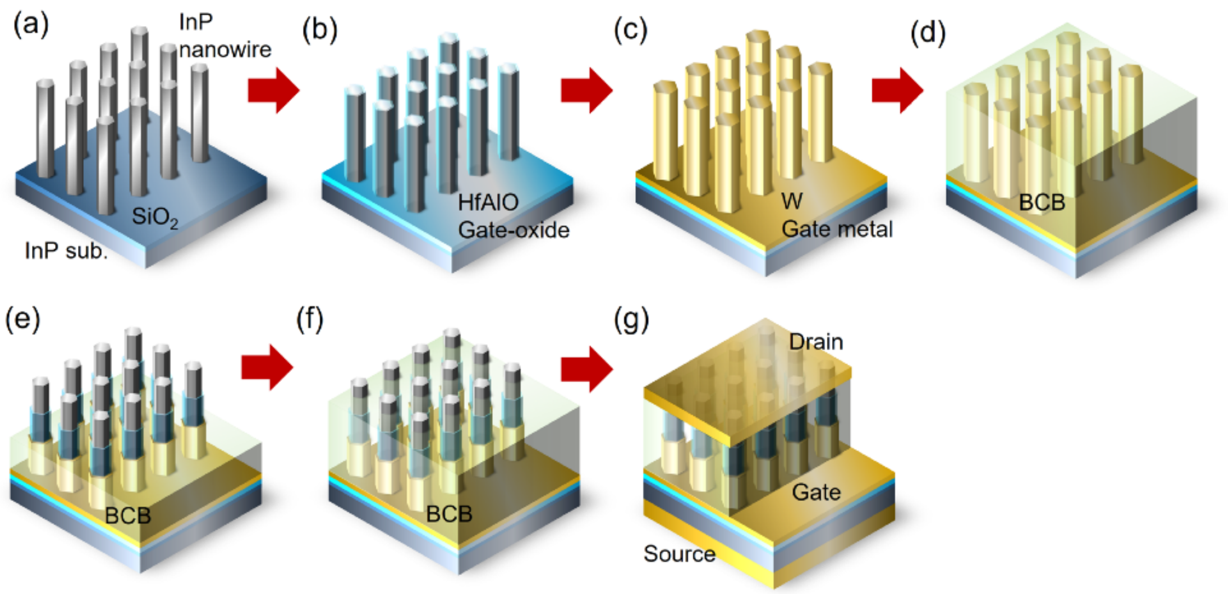


Figure 2: Crystal phase transition transistor fabricated by vertical gate-all-around (VGAA) structure fabrication technology

a: Nanowires are fabricated by selective growth method. b: Gate oxide film is deposited around the nanowires. c: Metal gate electrode is deposited around the nanowires. d: Resin is filled. e: Dry etching (head removal process). f: Fill with resin again, then dry etch again to expose the nanowire tips. g: Final structure with electrodes deposited on the exposed area and backside of the substrate. h: Fill with resin again, then dry etch again to expose the nanowire tips. i: Dry etch again to expose the gate electrode. j: Dry etch again to expose the gate electrode structure. k: Dry etch again to remove the gate electrode. l: Dry etch again to remove the gate electrode structure. g: The final structure with electrodes deposited on the exposed area and backside of the substrate. This is called gate all-around because the gate stacking structure covers the entire lateral orientation of the nanowires

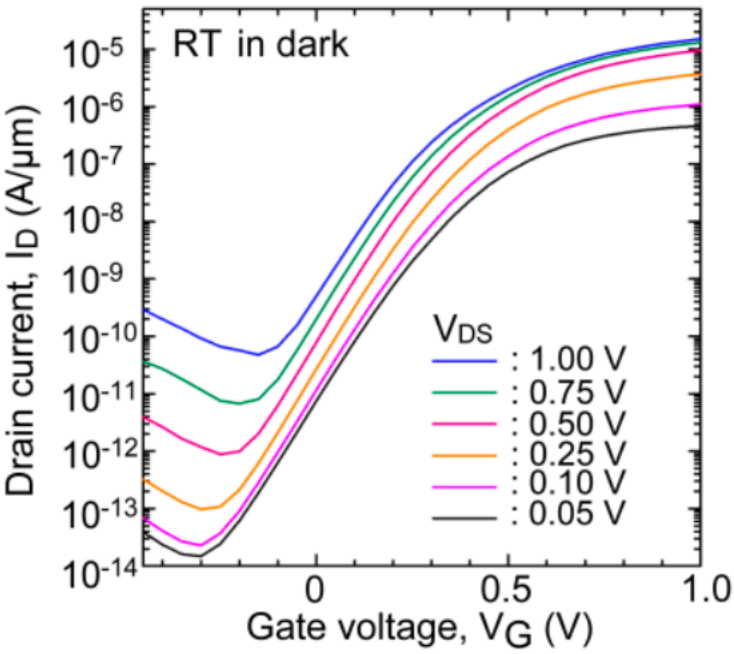


Figure 3: Transfer characteristics of a crystal phase heterojunction transistor. The energy barrier at the crystal phase transition heterojunction interface causes a switching operation