【Grant-in-Aid for Scientific Research (S)】

Electronic phase tuning in organic two-dimensional hole-gas system and organic quantum electronics

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Project Information	Project Number : 22H04959 Keywords : organic semiconductor, organic quantum electronics, two-dimensional electron gas, organic single crystal semiconductor	Project Period (FY) : 2022-2026

Purpose and Background of the Research

●Outline of the Research

We have constructed a "soft and clean" electronic system in the self-organized periodic structure of organic semiconductor molecules, and have achieved metal-insulator transition of the two-dimensional electron gas (2DEG) for the first time. This transition will be a base for quantum electronics necessary for high-speed and large-scale information processing. In this study, we investigate 2DEG system in which the electronic state is flexibly changed while maintaining the original structure by applying strain (pressure control) and redox state (chemical potential control). We will clarify the electron interaction effect in the 2DEG, and develop next-generation devices such as superconducting qubits.

●Electronic state tuning by "softness" and strain in organic semiconductors

In inorganic semiconductors, such as silicon, the atoms are bound together by strong covalent bonds, which clearly form the electron conduction path. In organic semiconductors the molecules are bound by Van der Waals force which is an order of magnitude smaller, and the electron conduction relies on the slight overlap of orbitals splayed out of adjacent molecules. Therefore, organic semiconductor devices are characterized by their mechanical softness, and because they are cost-effective to create semiconductor bonds by simple low-energy processes such as printing, they will be needed in large quantities in the coming IoT society. The development of low-cost sensor devices on plastic film, e.g., is drawing much attention.

The "soft" lattice structure of organic semiconductors is strongly coupled with the electronic system, and due to the electron-lattice interaction, a mere 3% lattice deformation causes a giant strain effect that causes a 70% increase in mobility [Nature Commun. **7**, 11156 (2016)].

●Composite Material of Polymer substrate for applying strain/Two-dimensional crystal of quantum well molecules/Electrical double layer

Using pi-conjugated molecules with alkyl chains such as alkyldinaphthobenzodithiophene (Cn-DNBDT), although the bonds between molecules are weak, we have developed a break-through technology in which crystal thin films with excellent periodicity can be easily grown over a large two-dimensional area. It was clarified that a coherent delocalized electronic state is spreading between molecules in a "soft and clean electronic system". Moreover, the 2DEG formed in Cn-DNBDT shows meta-insulartor transition (metallization).The reason for the success of metallization is that the bonding points between the units of the two-dimensional crystal constitute a flat interface on the atomic scale, and the two-dimensional clean system is confined in the quantum well.

In this study, we will construct a composite system consisting of a polymeric substrate for applying strain, two-dimensional ultrathin crystals of quantum well molecules, and an electric double layer of ion gel, and achieve a high carrier density similar to that of organic charge-transfer complex superconducting compounds. We plan to realize a phase transition to a superconducting state by a high carrier density mentioned above introduced by e.g., biaxial strain. Moreover, the resonant-tunneling device will be realized in this structure. This type of device uses the stable oxidation state of the non-localized electric state and is expected to be a useful high speed one.

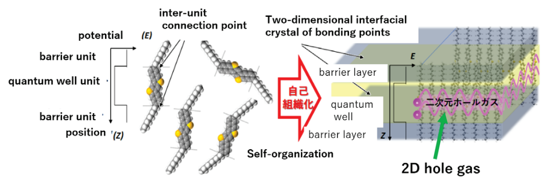

Figure 1. 2D hole gas

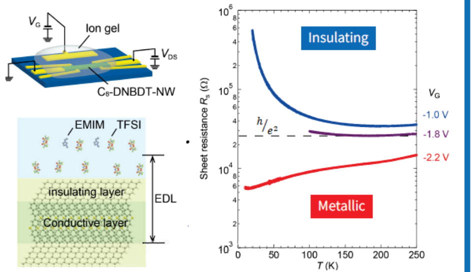

Figure 2. Metal-insulator transition at cryogenic temperatures

Expected Research Achievements

In this research, based on quantum well molecular single crystal in organic semi-conductors and polymer composite materials, we will work on the following research items. 1) Clarifying two items :to what extent the electron density can be tuned, and to what extent the enormous response of the molecular arrangement due to strain is possible. 2) developing electronic devices such as superconducting electronic phase transition device and resonant tunneling ones that are expected as a result.

Composite material: Developing novel quantum well molecules by two-dimensional crystallization of electron-confining molecules.

Cryogenic electronic phase control: Realizing a new electronic phase by controlling two-dimensional intermolecular distance.

Electronic phase transition mechanism: Understanding the electronic phase transition quantitatively to obtain higher superconducting transition temperature.

Resonant tunneling diode: Confirming the operating principle at low temperature and moreover the room temperature operating one.

Patterning technology: Developing the fabrication method of Josephson junctions and superconducting wires to realize devices for read and write of quantum information.

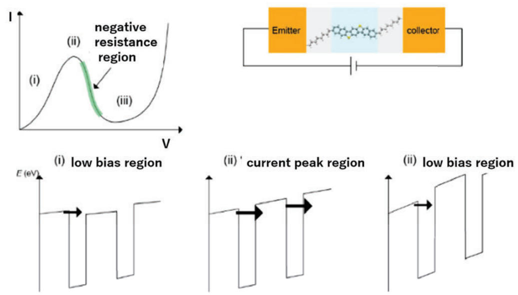

Figure 3. Resonant tunneling diode

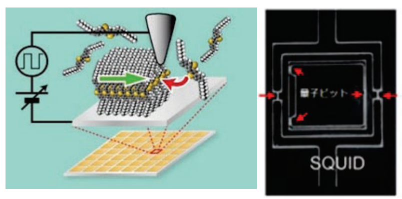

Figure 4. Patterning technology

Homepage Address, etc.	http://www.organicel.k.u-tokyo.ac.jp/ http://www.bk.tsukuba.ac.jp/~cmslab/