Open up Future Electronics by Organic Molecules

Research Center of Integrative Molecular Systems
Division of Functional Molecular Systems

YAMAMOTO, Hiroshi
Professor
[yhiroshi@ims.ac.jp]

Education
1993 B.S. The University of Tokyo
1998 Ph.D. The University of Tokyo

Professional Employment
1998 Research Associate, Gakushuin University
1999 Special Postdoctral Fellow, RIKEN
2000 Research Scientist, RIKEN
2007 Senior Research Scientist, RIKEN
2012 Professor, Institute for Molecular Science
Professor, The Graduate University for Advanced Studies
2015 Visiting Professor, Tohoku University

Awards
2009 RSC Publishing CrystEngComm Prize
2009 Young Scientist Awards, Japan Society for Molecular Science
2010 RIKEN-ASI Award for the Young Scientist
2019 The CSJ Award for Creative Work

Member
Assistant Professor
SUDA, Masayuki
HIROBE, Daichi
IMS Research Assistant Professor
KAWAGUCHI, Genta
Technical Associate
URUICHI, Mikio
Visiting Scientist
SAENNAWA, Wiyada*
Graduate Student
CHOOPPAWA, Tianchai
MORISHIMA, Masaki
AIZAWA, Hiroki
NABEI, Yoji
Technical Fellow
MURATA, Ryosuke
Secretary
SUZUKI, Ai

Keywords Organic Mott Insulator, Field Effect Transistors, Organic Spintronics

Organic molecules are attracting recent attention as new ingredients of electronic circuits. Our group focuses on the development of organic electronics in the next era by providing new mechanism and concepts of the device operation and fabrication. For example, an electronic phase transition is utilized for the ON/OFF switching of our field-effect-transistor (FET). This special FET is called an organic Mott-FET, where the conduction electrons in the organic semiconductor are solidified at the OFF state because of Coulomb repulsion among carriers. In the operation, these solidified electrons can be melted by applying a gate voltage, and show an insulator-to-metal transition so-called Mott-transition to be switched to the ON state. Because of this phase transition, a large electric response of the device can be achieved, resulting in the highest device mobility ever observed for organic FETs. In addition to this high performance, the Mott-FET is interesting in terms of superconductivity. Because the Mott-transition sometimes accompanies superconducting phase in between metal and insulator, modulation of gate electric field at low temperature may induce superconductivity. In fact, we have achieved first example of field-induced superconductivity in an organic FET. By combining a strain effect that can tune the bandwidth, this type of electric-field-induced superconducting transition can be utilized for mapping the phase diagram around the Mott-insulator as shown in Figure 1.

Another approach to the future electronics is the development of spintronic devices based on chirality of organic material. We aim to implement chirality-induced spin selectivity (CISS) effect into molecular devices that can generate spin-polarized current. This type of device is expected to realize spintronics devices without magnet or topological insulator.

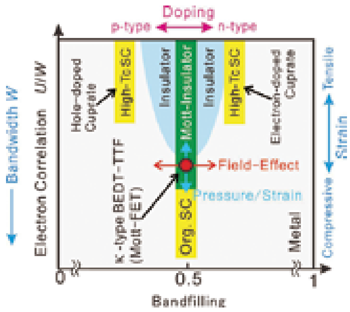

Figure 1. Phase diagram surrounding a Mott-insulator. SC denotes superconductor, while *U* and *W* are on-site Coulomb repulsion and bandwidth, respectively.

Selected Publications

- H. M. Yamamoto, M. Suda and Y. Kawasugi, "Organic Phase-Transition Transistor with Strongly Correlated Electrons," *Jpn. J. Appl. Phys.* **57**, 03EA02 (7 pages) (2018).
- Y. Kawasugi, K. Seki, Y. Edagawa, Y. Sato, J. Pu, T. Takenobu, S. Yunoki, H. M. Yamamoto and R. Kato, "Electron–Hole Doping Asymmetry of Fermi Surface Reconstructed in a Simple Mott Insulator," *Nat. Commun.* **7**, 12356 (8 pages) (2016).
- M. Suda, R. Kato and H. M. Yamamoto, "Light-Induced Superconductivity Using a Photo-Active Electric Double Layer," *Science* **347**, 743–746 (2015).
- H. M. Yamamoto, M. Nakano, M. Suda, Y. Iwasa, M. Kawasaki and R. Kato, "A Strained Organic Field-Effect Transistor with a Gate-Tunable Superconducting Channel," *Nat. Commun.* **4**, 2379 (7 pages) (2013).

1. Light-Driven Spin Switching Device Using an Artificial Molecular Motor[1)]

Artificial molecular switches and machines that enable the directional movements of molecular components by external stimuli have undergone rapid advances over the past several decades. Particularly, overcrowded alkene-based artificial molecular motors are highly attractive from the viewpoint of chirality switching during rotational steps. However, the integration of these molecular switches into solid-state devices is still challenging. In this study, solid-state spin-filtering devices that can switch the spin polarization direction by light irradiation or thermal treatment have been examined. We measured magnetoresistance of a device, in which M-cis form (Figure 2) of the motor is sandwiched by two electrodes as tunnelling layer, before and after photo irradiation. The magneto-resistance showed switching of spin polarization from up-spin selective to down-spin selective by the irradiation of light. This result indicates that the M to P chirality conversion by light is switching the spin of electrons that tunnel through the motor molecule because of CISS effect. We also confirmed that spin direction switching is possible in the next step, too, where heat treatment inverts the molecular chirality from P to M. During this study we found that the flexibility at the molecular scale is essential for the electrodes in solid-state devices using molecular machines. The same device operation was also confirmed by conductive AFM (atomic force micro-scope) measurement with magnetized tip. We also evaluated the strength of spin–orbit interaction by quantum chemical calculation, and found that state transitions between σ and π electron states are good to enhance the interaction. This result demonstrates a possibility of novel spintronics based on solid-state functionalities emerging from nano-sized motions of molecular switches.

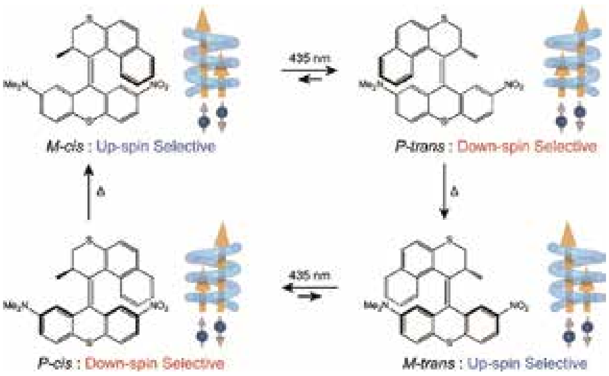

Figure 2. Spin selectivity switching by light irradiation and heat. The molecular motor has four steps for the 360 degree rotation, during which the four times chirality switching and associated spin switching occurs.

2. Ambipolar Superconductivity in Organic Field-Effect Devices[2,3)]

Because Mott-FET shows ambipolar operation, field-induced superconductivity in both p-type and n-type regimes is expected. This idea coincides with the fact that both hole-doped and electron-doped cuprates show superconductivity in the vicinity of Mott-insulator. We performed both FET and EDLT (electric double-layer transistor) measurement with organic Mott-insulator at low temperature. In the EDLT experiment, a flexible substrate was employed to tune not only the gate voltage but also the strain. With such a device, we could perform the scanning of bandwidth and bandfilling simultaneously. The phase diagram thus obtained at 5.5 K is shown in Figure 3.[2)] This is the first experimental example of a phase diagram in which ambipolar superconductivity and strain-induced superconductivity are continuously surrounding the Mott-insulator. From theoretical insights, a p/n asymmetry evident in this diagram seems to originate in the band structure calculated without correlation. A similar ambipolar switching of superconductivity was also observed in Mott-FET with κ-$(BEDT\text{-}TTF)_2Cu(NCS)_2$.[3)]

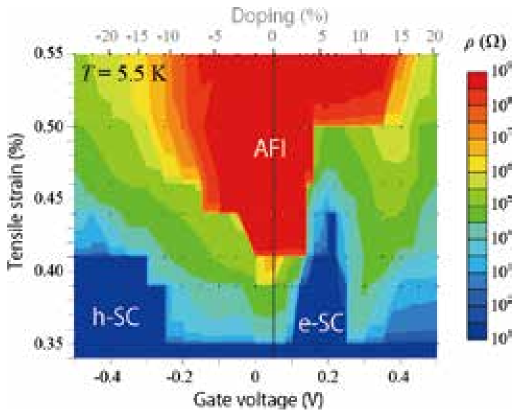

Figure 3. Emergence of both p-type (h-SC) and n-type (e-SC) superconductivity by gate voltage at various tensile strain. The strain is controlling electron correlation *U*/*W* while gate voltage controls bandfilling (see also Figure 1). AFI denotes antiferromagnetic insula-tor, meaning a Mott-insulating phase.

References

1) M. Suda, Y. Thathong, V. Promarak, H. Kojima, M. Nakamura, T. Shiraogawa, M. Ehara and H. M. Yamamoto, *Nat. Commun.* **10**, 2455 (2019).
2) Y. Kawasugi, K. Seki, S. Tajima, J. Pu, T. Takenobu, S. Yunoki, H. M. Yamamoto and R. Kato, *Sci. Adv.* **5**, eaav7282 (2019).
3) G. Kawaguchi, A. A. Bardin, M. Suda, M. Uruichi and H. M. Yamamoto, *Adv. Mater.* **31**, 1805715 (2019).

Award

YAMAMOTO, Hiroshi; The CSJ Award for Creative Work (2019).

* IMS International Internship Program