Open up Future Electronics by Organic Molecules

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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.

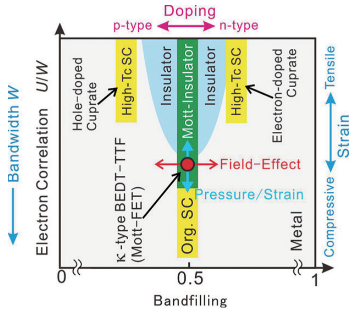

Figure 1. Phase diagram surrounding a Mott-insulator. SC denotes superconductor, while U and W are on-site Coulomb repulsion and bandwidth, respectively.

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, S. Tajima, J. Pu, T. Takenobu, S. Yunoki, H. M. Yamamoto and R. Kato, “Two-Dimensional Ground-State Mapping of a Mott-Hubbard System in a Flexible Field-Effect Device,” *Sci. Adv.* **5**, eaav7282 (9 pages) (2019).
- 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. Current-Induced Spin-Polarization in a Chiral Crystal $CrNb_3S_6$[1,2)]

CISS effect has remarkable ability which generates highly polarized spin current even with light element molecules. However, its extension to inorganic chiral materials has not been well investigated. Moreover, detection of CISS effect in metals that show ohmic response is quite interesting because one can discuss the CISS-based spin polarization in terms of band theory if metallic CISS effect in linear response regime is observed. So far, however, CISS experiments have been investigated only in tunnelling conduction regime.

We detected CISS-based spin transport phenomena in a monoaxial chiral dichalcogenide $CrNb_3S_6$. This material has chiral structure and metallic conduction, so that we could perform CISS experiments with metallic conduction regime. Spin polarization was detected in this chiral bulk crystal under a charge current flowing along the principal c axis at room temperature without magnetic field. The detection was made by an inverse spin Hall signal which is induced on the tungsten electrode that absorbs polarized spin from the chiral crystal (Figure 2). An inverse response was also observed when applying the charge current into the detection electrode, which implied an inverse CISS effect. The signal sign reversed in the device with the opposite chirality, which is consistent with the symmetry required for CISS effect. Furthermore, the spin signals were found over micrometer length scale in a nonlocal configuration. Such a robust generation and protection of the spin-polarized state can be discussed based on a one-dimensional model with spin–momentum locking.

In addition to the above experiments, we also detected bulk magnetization generated by applying electric current to the crystal. When the current amplitude was swept from negative to positive, the current-induced magnetization changed linearly. Directly detecting such magnetization by magnetometry enables one to estimate the number of spin-polarized electrons. Using this number, we evaluated the spin polarization rate within the framework of Boltzmann's equation and found that spin polarization generated by CISS effect was enhanced by 10^5 times inside this material. It seemed that effective magnetic field generated by CISS could reach 10^3 T at high current density, which again confirmed the robustness of CISS effect. We also observed that the current-induced magnetization increased in the vicinity of the phase boundary between paramagnetic and forced ferromagnetic phases, which could be attributed to the spin fluctuation associated with the phase transition.

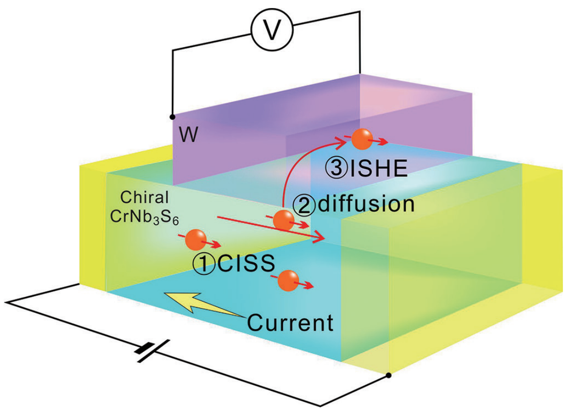

Figure 2. Detection of spin polarization in a chiral metal $CrNb_3S_6$. By applying electrical current (①), electron spins are polarized along the current direction by CISS effect. Then the spin current is diffused into W electrode (②) and generate a voltage by inverse spin Hall effect (③).

2. Anomalous Superconducting Phase in an Organic Field-Effect Device[3)]

We have achieved simultaneous control of bandwidth and bandfilling for organic Mott-insulators by using field effect device that can control the lattice strain to the organic crystal to observe the phase diagram for superconducting state. A new superconducting field-effect transistor (FET) in the vicinity of bandwidth-controlled Mott transition has been developed using molecular strongly correlated system κ-(BEDT-TTF)$_2$ Cu[N(CN)$_2$]Br laminated on CaF_2 substrate. This device exhibited significant cooling-rate dependence of resistance below about 80 K, associated with glass transition of terminal ethylene group of BEDT-TTF molecule, where more rapid cooling through glass transition temperature leads to the decrease in bandwidth. We demonstrated that the FET properties such as ON/OFF ratio and polarity can be changed by utilizing cooling rate. Therefore, this is another device that can control both bandwidth and bandfilling of an organic Mott-insulator simultaneously, to find phase diagram associated with superconducting and Mott-insulating phases. By analyzing the FET behaviors of the device at different cooling rates, an enhanced superconducting state at exactly half-filling was discovered.

[BEDT-TTF = bis(ethylenedithio)tetrathiafulvalene]

References

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Award

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