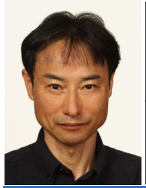
【Grant-in-Aid for Specially Promoted Research】

Developing new materials and properties through the fusion of superconductivity and magnetism



Principal Investigator	Kyoto University, Institute for Chemical Research, Professor ONO Teruo	Researcher Number : 90296749
Project Information	Project Number : 24H00007 Keywords : Superconductivity, magnetism, diodes, spintronics	Project Period (FY) : 2024-2028

Purpose and Background of the Research

●Outline of the Research

Based on the findings of the superconducting diode effect and zero-field superconducting diode effect discovered by the Principal Investigators, we aim to develop new materials and new properties and applications by fusing superconductivity and magnetism. By combining the inversion symmetry breaking due to multilayer structure and time-reversal symmetry breaking due to magnetism, we will create new superconductors, and develop new physical properties based on new concepts such as controlling the phase of superconductors by magnetization.

●Background leading to the conception of this research

In an artificial lattice with an asymmetric structure consisting of niobium (Nb), vanadium (V), and tantalum (Ta) layers (Fig. 1(a)), the principal investigators found that the magnitude of the superconducting critical current depends on the current direction when an external magnetic field is applied perpendicular to the current (Figs. 1(b) and 1(c)). The result in Fig. 1(c) indicates that for current values between the forward and reverse critical currents, in the forward direction, the device is in the superconducting, while in the reverse direction, the device is in the normal-conducting state, a phenomenon that we call the superconducting diode effect. Furthermore, this superconducting diode effect has a feature not found in conventional diodes: its polarity can be switched by an external magnetic field. This finding is the result of the Grant-in-Aid for Specially Promoted Research (FY 2015-2019). After the finding of the superconducting diode effect, we succeeded in creating a nonvolatile superconducting diode device through the Grant-in-Aid for Challenging Research (Pioneering) (FY 2021-2023) (Fig. 2).

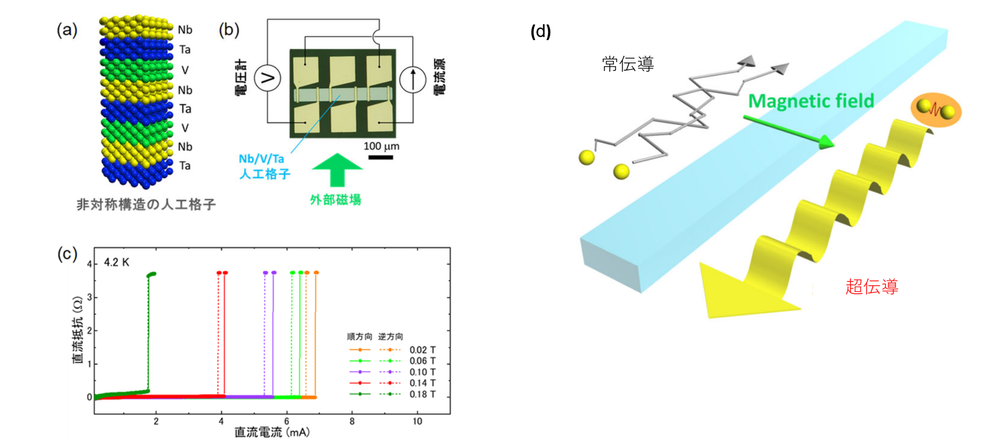


Figure 1. Superconducting diode effect

●Nonvolatile superconducting diode effect

In the device used in Fig. 1, an external magnetic field must be applied to obtain the superconducting diode effect, but for applications, it is preferable to obtain the diode effect without a magnetic field. The Principal Investigators have succeeded in obtaining the superconducting diode effect without a magnetic field by inserting a ferromagnetic iron (Fe) layer into the device (Fig. 2). Therefore, it is possible to record information as the direction of iron magnetization, and by using multiple such devices, reconfigurable superconducting logic circuits can be fabricated.

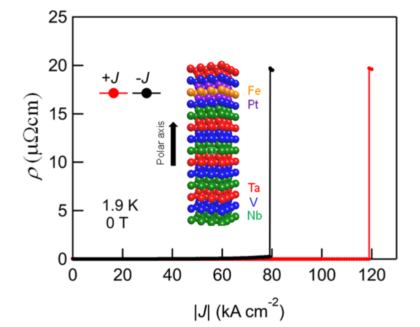


Figure 2. Nonvolatile superconducting diode

Expected Research Achievements

We will measure the frequency dependence of the rectification characteristics of superconducting diode devices to clarify their potential for application and to elucidate the mechanism of the superconducting diode effect. Furthermore, we will improve the characteristics of superconducting diode effect by optimizing the composition, etc., and demonstrate the operation of logic circuits by combining zero-field superconducting diode devices. We will theoretically consider the possibility of an ultimate diode effect that is superconducting in the forward direction and an insulator in the reverse direction, and attempt verification based on the theoretical analysys (Fig. 3).We will fabricate Josephson junction superconductors by using superconducting/magnetic/superconducting multilayers and try to control the phase of superconductivity by magnetization.

In this research, we will create new materials and pioneer new physical properties, based on the perspective of new fusion of magnetism and superconductivity. The application of the superconducting diode effect to rectifier devices and logic circuits is not only of engineering significance, but is also expected to have a great impact on future superconducting circuits in general, including quantum computers. By pioneering new physical properties based on new concepts such as controlling the phase of superconductors by magnetization, we hope to create new physical properties that will have an impact on society that is unimaginable from the present.

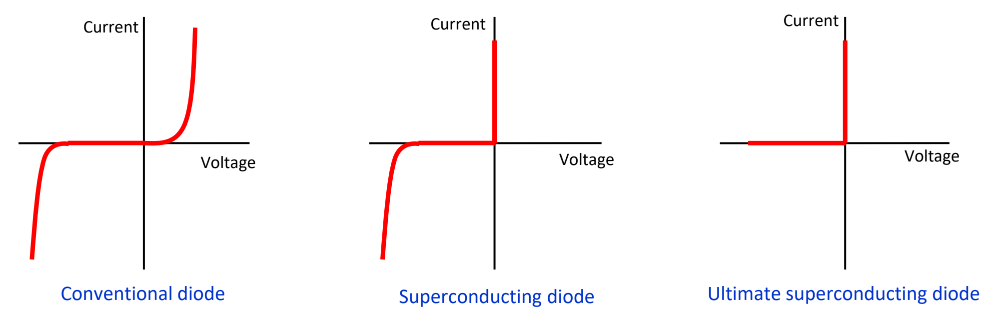


Figure 3. Current-voltage characteristics of conventional diode, superconducting diode, and ultimate superconducting diode

Homepage Address, etc.	https://www.kuicr.kyoto-u.ac.jp/sites/ https://www.scl.kyoto-u.ac.jp/~onoweb/