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Rectification effect of non-centrosymmetric Nb/V/Ta superconductor

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The superconducting diode effect in which electrical resistance is zero in only one direction has recently been reported in superconductors without inversion symmetry. Previous studies investigated the nonreciprocity of the critical current, but little has been known about the rectification effect when AC currents are applied. Herein, we examined the rectification characteristics of a non-centrosymmetric Nb/V/Ta artificial superlattice under AC currents. The rectification strength can be modulated by an applied magnetic field, and its polarity can be tuned by the magnetic field. Furthermore, we find that the magnetic field dependence of the rectification is different from that of the nonreciprocal critical current.

Key words: superconducting diode, rectification, artificial superlattice, inversion symmetry breaking

1. Introduction

Rectification, the conversion of a bidirectional current into a unidirectional current, is an essential process in modern electronics. The electronic devices that enable rectification are called diodes and are widely used to convert alternating current (AC) to direct current (DC), protect electrical circuits from overvoltage, and detect electromagnetic radiation. Conventional diodes, composed of different types of semiconductors connected to form a p-n junction, exhibit a low resistance in one direction and a high resistance in the other direction. Although the diode effect forms the basis for numerous electronic components, energy loss is inevitable in the semiconductor diodes due to their finite resistance. Therefore, superconducting diodes with zero electrical resistance in one direction hold great promise for practical use. Wakatsuki *et al.* demonstrated that the nonreciprocal resistance in a low-symmetry 2D material increases by orders of magnitude in the fluctuating regime of superconductivity as compared to the normal conduction state.[1)] In addition, a rectification effect has been detected in superconducting thin films designed to control the magnetic fluxes that pierce the superconductor.[2)-10)] However, such superconducting diode effect can only manifest itself when the superconductors have a non-zero resistance.

We fabricated an artificial superlattice consisting of stacked alternating layers of Nb, V, and Ta, and demonstrated an ideal superconducting diode that has zero resistance in only one direction.[11)-12)] Stimulated by our experiment, theoretical groups proposed an intrinsic mechanism to cause the superconducting diode effect.[13)-14)] They suggested that the Cooper pair of a superconductor without inversion symmetry acquires a finite momentum under an in-plane magnetic field, and that the depairing current, the upper limit of the critical current, is non-equivalent in the directions parallel and anti-parallel to its momentum. Subsequently, several experimental results on the superconducting diode effect using materials without inversion symmetry have been reported.[15)-18)] In the study of the superconducting diode effect exhibited by non-centrosymmetric superconductors, the nonreciprocity of the critical current has been investigated so far, but for its application, it is necessary to investigate the rectification characteristics when an AC current is applied. In this study, we examined the rectification effect when an AC current was injected into a non-centrosymmetric Nb/V/Ta artificial superlattice.

2. Experimental Results

2.1 Nonreciprocal Critical Current

We used the same [Nb(1.0 nm)/V(1.0 nm)/Ta(1.0 nm)]$_{40}$ superlattice used in Ref. 19. Figure 1(a) shows a photograph of the device and a schematic diagram of the experimental setup. The transport measurement was performed in a four-terminal configuration by using a nanovoltmeter (Keithley2182A) and a current source

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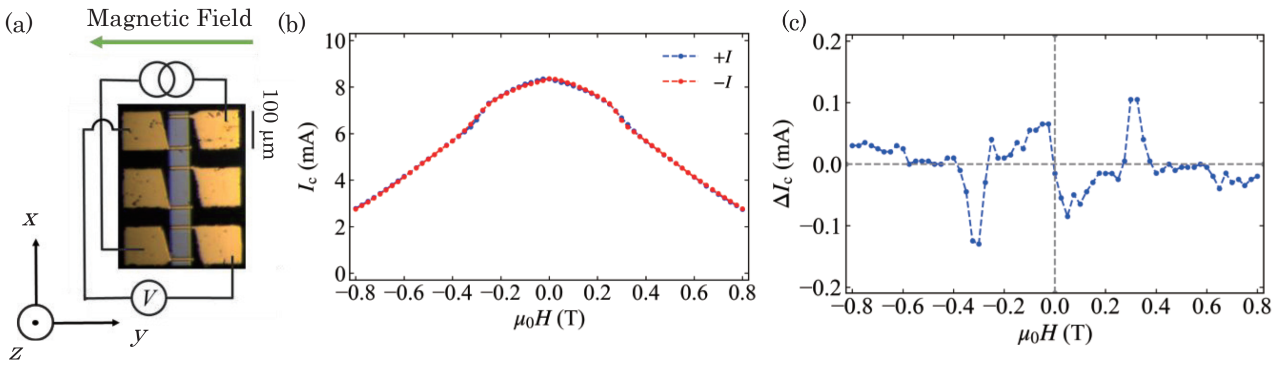

Fig. 1 (a) Photomicrograph of device and experimental setup. Current was applied in x direction and magnetic field in y direction. z-axis is polar axis of $[Nb/V/Ta]_{40}$ artificial superlattice. (b) Magnetic field dependence of positive critical current I_{c+} and negative critical current I_{c-}. (c) Magnetic field dependence of nonreciprocal component ΔI_c (= $|I_{c+}| - |I_{c-}|$). Temperatures in (b) and (c) are both 2 K.

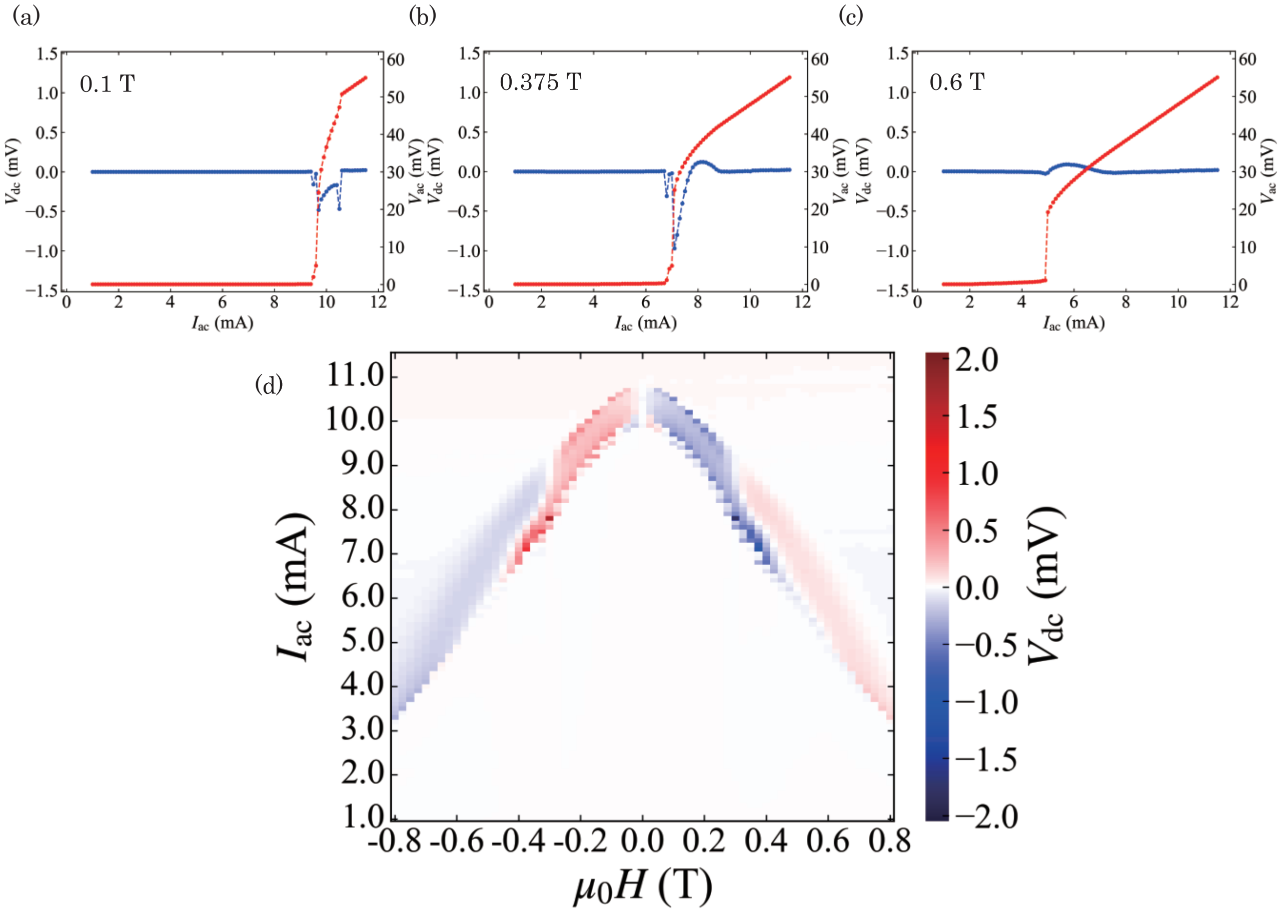

Fig. 2 (a-c) AC current dependence of rectification voltage (blue dots) and AC voltage (red dots) when in-plane magnetic field was applied orthogonal to current direction. (a) 0.1 T, (b) 0.375 T, and (c) 0.6 T were applied. (d) Color plot of rectification voltage with respect to AC current and magnetic field. Temperatures in (a)-(d) are all 2 K.

(Yokogawa7651). The temperature and magnetic field were controlled using a commercial refrigerator (Quantum Design, Physical Property Measurement System). The superconducting transition temperature was 3.3 K under a zero magnetic field. We measured the critical current by increasing the current under a constant in-plane magnetic field orthogonal to the current direction. Figure 1(b) shows the magnetic field dependence of the critical current. The critical current were different whether the applied currents were positive or negative. Here, the nonreciprocal critical current ΔI_c, is defined as the difference between the critical current in the positive direction (I_c+) and that in the negative direction (I_c−). Figure 1(c) presents the magnetic field dependence of the nonreciprocal critical current. In the positive field region, the sign of the nonreciprocal critical current was negative below 0.275 T, positive between 0.275 and 0.375 T, and negative again above 0.375 T. This oscillating behavior of the nonreciprocal critical current is consistent with our previous report[20].

2.2 Rectification Effect

To probe the rectification effect, we investigated the magnetic field dependence of the rectification voltage under a sinusoidal AC current of 100 kHz. We injected AC currents into the device with an AC current source (Keithley 6221 AC and DC current source), and measured DC voltages with a nanovoltmeter (Keithley 2182A) and AC voltages with a multimeter (Keithley 2000). Figure 2(a) shows the change in DC voltage (blue dots) and AC voltage (red dots) as the AC current amplitude was increased under an in-plane magnetic field of 0.1 T. The rectification voltage appeared in close vicinity to the superconductor-to-metal transition. Figures 2(b) and 2(c) show the rectification voltage when magnetic fields of 0.375 T and 0.6 T were applied, respectively. We observed negative rectification voltage at 0.1 T, both positive and negative rectification voltage at 0.375 T, and positive voltage at 0.6 T. Furthermore, dip structures were observed in Fig. 2(a) and Fig. 2(b). Although the origin of the dip structures was not clear at this stage, one possibility can be the vortex ratchet motion reported in Ref. 2. To investigate the rectification effect in detail, we plotted the rectification voltage as a function of magnetic field and AC current amplitude in Fig. 2(d). Comparing Fig. 2(d) with Fig. 1(c), between 0 and 0.275 T, the sign of the rectification voltage was the same as that of the nonreciprocal critical current. At 0.325 T, where the sign of the nonreciprocal critical current was reversed to be positive, both positive and negative rectification voltages were observed. As the magnetic field was further increased to 0.6 T, where the sign of the nonreciprocal critical current was reversed again, the polarity of the rectification voltage was opposite to that of the nonreciprocal critical current. The inconsistency between the signs of the superconducting diode effect and the rectification voltage observed here could be due to the additional contributions of the dynamics of vortex or non-equilibrium quasiparticles driven by AC current. To elucidate the mechanism, it is necessary to further investigate the frequency dependence of the rectification effect.[21)-23)]

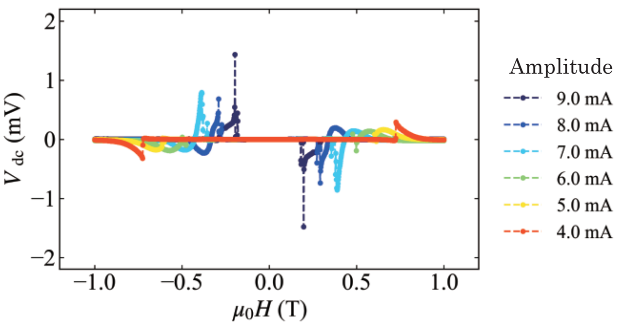

Fig. 3 Magnetic field dependence of rectification voltage when AC current amplitude was constant at 2 K.

In Fig. 2(d), we examined the rectification voltage when an AC current amplitude was increased under a constant magnetic field. To check the reproducibility, we also investigated the rectification voltage when a magnetic field was increased under a constant AC current amplitude. Figure 3 shows the magnetic field dependence of the rectification voltage when an AC current amplitude was increased from 4 to 9 mA. The polarity of the rectification was reversed as the AC current amplitude was increased, which was consistent with the experimental result of Fig. 2. We have reconfirmed the polarity reversal of the rectification effect induced by the magnetic field.

3. Conclusion

We have demonstrated the rectification effect of the Nb/V/Ta artificial superlattice superconductor. The rectification effect obtained here is expected to be observed in other non-centrosymmetric materials exhibiting the superconducting diode effect.

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