Superconducting Diode Using Semiconductor Quantum Dots

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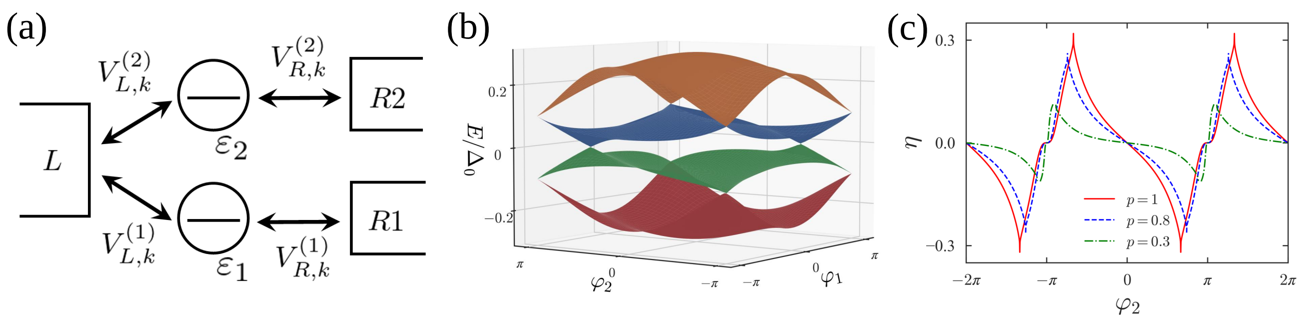
Quantum dots (QDs) fabricated on semiconductors are useful devices to examine various transport phenomena due to their tunability. In double quantum dot (DQD) in parallel, the tunneling to a common lead results in the coherent coupling between the QDs even in the absence of direct tunneling between them. In the DQD and two leads forming a closed loop, we observe the Aharonov-Bohm effect in a magnetic field and Fano or Fano-Kondo resonance as a function of energy level in one of the QDs when the Coulomb interaction U is irrelevant or relevant, respectively [1, 2]. In this work, we examine the connection of the DQD to three superconducting leads, as depicted in Fig. (a): Lead L is commonly connected to the two QDs (denoted by QD1 and QD2) while lead $R1$ ($R2$) is connected to QD1 (QD2) only. The phase difference between leads $R1$ ($R2$) and L is φ_1 (φ_2). We show the superconducting diode effect (SDE) for the critical current from lead L to $R1$ when $\varphi_2 \neq 0$, π [3], which is ascribable to the coherent coupling between the DQD by the crossed Andreev reflection.

We assume that the energy levels ε_j in QDj, level broadening $\Gamma_{\alpha,j}$ by the tunnel coupling to lead α, and U are smaller than the superconducting gap Δ, where the Andreev reflection takes place between the QDs and leads; an electron is reflected to a hole and *vice versa*. The tunnel coupling to lead L is characterized by the linewidth functions, $\Gamma_{ij} = \pi \sum_k V_{L,k}^{(i)} V_{L,k}^{(j)} \delta(\varepsilon - \varepsilon_k)$ at $\varepsilon \approx \varepsilon_{\rm F} = 0$, with tunnel amplitude $V_{L,k}^{(j)}$ between QDj and state k (energy ε_k) in the lead. $\Gamma_{jj} = \Gamma_{L,j}$, whereas the coherence between the QDs is determined by $p = \Gamma_{12}/\sqrt{\Gamma_{11}\Gamma_{22}}$ ($0 \le p \le 1$). p is equivalent to the overlap integral between the wavefunctions coupled to QD1 and QD2.

The multiple Andreev reflections make the bound states as a function of φ_1 and φ_2. Their energy levels are plotted in Fig. (b) for $\varepsilon_1 = \varepsilon_2 = 0$, $\Gamma_{L,1} = \Gamma_{L,2} = \Gamma_{R1,1} = \Gamma_{R2,2} \equiv \Gamma_0$, and $p = 1$. For $p \neq 0$, empty and doubly occupied states in QDj ($|0\rangle_j$, $|\uparrow\downarrow\rangle_j$; $j = 1, 2$) with $(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2)/\sqrt{2}$ are coherently coupled by the crossed Andreev reflection. The energy levels have two zero-points forming Dirac cones around them, which exist if $\varepsilon_1 = -\varepsilon_2$ and $|\varepsilon_1| < \Gamma_0 p$ are satisfied. From the Andreev bound states, we evaluate the positive and negative critical currents $I_{\rm c}^{\pm}$ from lead L to $R1$, which are defined by the absolute values of the maximum and minimum supercurrents as a function of φ_1, respectively, for a given φ_2. Figure (c) presents the efficiency of the SDE, $\eta = (I_{\rm c}^{+} - I_{\rm c}^{-})/(I_{\rm c}^{+} + I_{\rm c}^{-})$, for $p = 1$, 0.8, and 0.3. η is markedly enhanced around the Dirac points. The tunability of the QDs could realize a large SDE compared with other systems [3].



References

[1] Y. Zhang, R. Sakano, and M. Eto, J. Phys. Soc. Jpn. **91**, 014703 (2022).

[2] Y. Zhang, M. Kato, R. Sakano, and M. Eto, J. Phys. Soc. Jpn. **93**, 024702 (2024).

[3] The SDE was reported in a similar geometry using a quantum well; S. Matsuo, T. Imoto, T. Yokoyama, Y. Sato, T. Lindemann, S. Gronin, G. C. Gardner, M. J. Manfra, and S. Tarucha, Nat. Phys. **19**, 1636 (2023).