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New Frontier in Superconducting Devices

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The study is made on the physical conditions of the appearance of Josephson effect and single charge effect in the junctions of superconductor and normal metal. When the electrodes of a bridge junction are made of the high T_c oxide superconductors, and the bridge part is made of the highly resistive material of a kind of oxide similar to the superconductor, a single charge-quantum devices with working temperature up to T_c could be realized in relatively large sample size.

I. Introduction

There have been proposed and studied several kinds of junctions whose device principles are based on quantizing effects of magnetic flux or electron charge. They are classified in the following categories. (1) Superconductor junctions: (1-a) tunneling type Josephson junction, (1-b) bridge type Josephson junction, (1-c) Bloch oscillation in small tunneling junction.[1] (2) Normal junctions: (2-a) SET effect in small tunneling junctions.[2] (3) Super or normal junction: (3-a) an effect in highly resistive bridge junction dual to tunneling type Josephson effect.[3] As is seen below, these are explicable as the macroscopic quantum effects (MQE) where the quantization of flux and charge is observable with macroscopic means. We have been making unified study of (1-c), (2-a) and (3-a) in the name of phase-quantum tunneling (PQT) effect.[4] We will discuss the junction conditions for these quantum devices. After that, we refer to a new device using high T_c oxide superconductor.

II. Junction Parameters concerning the Transition of Charge and Flux

II-1. Property of Charge and Flux in Junctions

Suppose a process of a charge particle which emits energy quantum $\pm\hbar\omega$ interacting with environment in a conductor. We consider the surface integral of Poynting vector $\Pi=\int E(z)\times H(x,y)\cdot ds$ on the cylindrical surface enclosing the region of the quantum emission. Then we have $\pm\hbar\omega=\int\Pi dt=\int dt\int E(z)dz\int H(x,y)dl$, where $\int\int dzdl$ is the surface integral on the cylindrical surface. Putting $\int E(z)dz=d\Phi/dt=\omega\Phi$ and $\int dt\int Hdl=\int dtdQ/dt=e^*$, these relations lead to $\Phi=\pm\phi^*$, where Φ is flux, $\phi^*=h/e^*$ is the flux quantum, Q is charge, and e^* is the charge quantum. The above relation shows that the transition process of the charge quantum interacting with the origins of resistance or "loss oscillators" (such as phonons and photons) can be replaced with the the process where a flux quantum traverses the wave function of the charge quantum. We will call in the following the flux-traverse process (including the equivalent one) "cross process". The phase change of the charge wave function per each flux-quantum traverse is 2π.[4] In the process a charge particle has the freedom of transition mode corresponding to the mode number of the wave function of charge inside the junction region. We will call by the name of "parallel mode number" the maximum charge mode number g_p in a cross process of charges with a flux quantum. On the other hand, the (equivalent) flux making the cross process has the freedom of mode corresponding to the mode number of the loss oscillators interacting with the charge. We will call by the name of "series mode number" the maximum mode number g_s in a cross process of flux quanta interacting with a charge quantum. As is known by the discussion using the Poynting vector, the effect of loss oscillators and magnetic flux in the cross processes in a junction can not be distinguished from the observer outside the junction.

Our study given below is restricted to the junctions where 1 mode or multiple modes of charge quanta make transition from the initial state in one electrode of a junction to the final state in the other electrode.[4] Since a charge quantum makes the transition between two electrodes in a short time Δt, the energy broadening $\Delta E\sim h/\Delta t$ is inevitable. The relation is formally rewritten $\Delta E/e^*\sim\phi^*/\Delta t$, and is plausibly interpreted that ΔE is caused in the cross process as the result of the disturbance of the energy level of the charge caused by the traverse of a flux quantum.

When the average interval ΔW between the energy levels of charges in the junction region is smaller than ΔE, we may put $g_p=\Delta E/\Delta W$. In this case g_p charge quanta can make interaction with a flux quantum in a cross process. In case $\Delta W>>\Delta E$ and g_s flux quanta interact with one charge quantum in a cross process, we may put $g_s=\Delta W/\Delta E$.

II-2. The Condition of Junctions for the Observation of MQE

The junctions treated in our discussion is restricted to the following two types which are interesting in connection with MQE.

II-2-1. Type 1 Junction

In order to observe "flux" quantization phenomenon, the mode numbers related to the cross process must be $g_P=\Delta E/\Delta W>>1$. Since the conductance caused by the cross process between single charge quantum and and single flux quantum is $G_c=e^*/\phi^*$, the junction condition in question corresponds to g_P parallel connection of G_c. Therefore the junction conductance is $G_J=g_PG_c$.

II-2-2. Type 2 Junction

In order to observe the charge quantization phenomenon, we need $g_s=\Delta W/\Delta E>>1$. The junction resistance in this state corresponds to g_s series connection of the resistance $R_c\equiv G_c^{-1}$.

II-2-3. Correspondence to Scaling Theory

Edwards and Thouless[5] and Licciarderllo and Thouless[6] theoretically investigated the change of the electronic wave functions in the scaling-up process. They showed that i) electron diffusion takes place when $\Delta E/\Delta W>>1$, that ii) electrons localize when $\Delta E/\Delta W<<1$ (Anderson localization), and that iii) the conductance is given by $G=G_c(\Delta E/\Delta W)$. These general result agrees with our discussion on the behavior of charge and flux in the junction region. When $\Delta E/\Delta W>>1$ is satisfied in the junction region, the charge does not localize there, but passes there as wave with definite phase with "flux localization". On the other hand, when $\Delta E/\Delta W<<1$, the charge localizes in the junction region with large uncertainty of phase with no "flux localization".

III. MQE in Junctions

III-1. The Coherent State and MQE in Junctions

III-1-1. Uncertainty Relation and Coherent State

Generally speaking, we can not make a definite study of some quantum effect observing two canonically conjugate quantities (X,Y) at the same time due to the uncertainty relation. Only exception is the coherent state where the least uncertainty relation $\Delta X\Delta Y=h/2$ is satisfied.[7] In this state we have $\Delta X/X_0<<1$, $\Delta Y/\langle Y\rangle\sim(Y/Y_0)^{1/2}<<1$, where $(X_0, Y_0\equiv h/X_0)$ are respectively the quantum units of (X,Y), and $\langle\,\rangle$ denotes the statistic average. These relations enables us to observe the quantization phenomenon about X by means of a macroscopic measurement of X and $\langle Y\rangle$. Thus the coherent state is the prerequisite for a MQE concerning the quantization of X.

The properties of a junction is determined by a macroscopic measurement on (q, ϕ). In this situation we know that two kinds of coherent states and MQE's are possible correspondingly to $(X=\phi, Y=q)$ and $(X=q, Y=\phi)$.

III-1-2. The Type of Junction and MQE

In the case of type 1 junction with $g_P>>1$, the fluctuation of charge is large and that of flux is small. Therefore if the charge fluctuation forms a coherent oscillation, $(X=\phi,\ Y=q)$ type MQE with flux quantization is possible. On the other hand, in the case of type 2 junction with $g_s>>1$, $(X=q, Y=\phi)$ type MQE with charge quantization is possible.

III-2. MQE's in Tunnel Junction

III-2-1. Josephson Effect in Superconductor Tunnel Junction

The property of the junction is as follows. i) The electrodes are occupied by charge with no intrusion of flux (no flux path). ii) The outside of the electrodes are occupied by flux with no charge (no charge path). iii) Type 1 junction. iv) The fermion charge system are in a coherent state due to superconductivity. v) Tunneling electron pairs have energy uncertainty $\sim2\Delta$. The condition that electrostatic energy is negligible at the tunneling is $e^{*2}/2C_J<2\Delta/g_P$. vi)The flux in the junction must make the zero-point oscillation state in the lowest level. In order that the flux fluctuation with energy loss is forbidden, we need $C_J[\phi^*(G_J/C_J)]^2/2>>kT$. vii) When current I is present in the junction, the energy of the junction charge system increases $\sim I\phi^*$ in the cross process with a flux quantum. The increase per one charge is $\sim I\phi^*/g_P$, resulting in the increase of ΔW. When the critical current I_c is determined by the criterion that the increase reaches $\sim\Delta E$ to destroy the condition of type 1 junction, we find $I_c\sim(\Delta/e)G_J$. This value nearly agree with the result of Ambegaokar and Baratoff.[8] viii) Based on the coherent state of charge fluctuation caused in connection with the small zero point fluctuation of flux, the junction current is calculated to be $I=I_c\sin\theta$, where θ is flux quantum number N_ϕ multiplied by 2π.[9]

III-2-2. Bridge Type PQT Junction

The property of the junction is as follows. i) The electrodes have no flux path, and outside of them has no charge path (superconductor electrodes are ideal). ii) Type 2 junction. iii) The charge in junction is the zero-point oscillation state. The flux crossing the charge in the junction is quantized in ϕ^*N $(N=1,2,3,\ldots)$. iv) The condition that many flux quanta exist in the junction is $\phi^{*2}/2L_J<h\Omega_{min}/g_s$, where Ω_{min} is the minimum frequency of the loss oscillators interacting with a charge quantum in the bridge region. v) The condition to suppress the lossy charge fluctuation $L_J[e^*(R_J/L_J)]^2/2>>kT$. When the electrodes are superconductor and the charge quantum is the electron pair, the charge quantum may not make the fluctuation with thermal excitation, so long as it is under the influence of the coherence of electrode charges. vi) When voltage V is applied to the junction, the ΔE may increase by $\sim e^*V$. If we determine the critical voltage with the criterion that the condition of the type 2 junction is destroyed due to the increase, we get $V_c\sim\Delta W/e^*\sim h\Omega_{min}/e^*$. vii) When a calculation similar to the tunnel type Josephson junction is made with the use of the tunnel Hamiltonian for flux quanta, the junction voltage is found $V=V_c\sin\gamma$, where $\gamma=N_q\times2\pi$.[4]

III-3. MQE Caused by the Interference of Coherent Wave Fields

III-3-1. Josephson Effect in Bridge Junction

In the case of superconducting bridge junctions, the phase difference between two macroscopic wave fields in electrodes is modified by the flux quantum in the junction, resulting in periodic current change by the interference of macroscopic fields.[3] Junction conditions are as follows. i) Type 1 junction. ii) The coherence of the fermion charge system due to superconductivity ($e^*=2e$). iii) The junction current is saw-teeth like. iv) In order that the charge system in the junction region can be treated by macroscopic wave equation, many charge quanta must exist in the bridge region, which requires $L_J[e^*/(L_J/R_J)]^2 << 2\Delta/g_P$. v) The suppression of flux fluctuation by thermal disturbance requires $\phi^{*2}/2L_J >> kT$.

III-3-2. PQT Effect in Tunnel Junction (SET Effect)[3]

i) Type 2 junction. ii) With the use of the minimum free energy δF_{min} of the magnetic field around the junction, the (saw-teeth like) periodic junction voltage is obtained. iii) In order that flux in the junction region is treated with macroscopic wave equation, many flux quanta must exist there, which requires $C_J[\phi^*/(C_J/G_J)]^2/2 << (e^{*2}/2C_J)/g_s$. This relation is always satisfied in type 2 junctions. iv) The suppression of the charge fluctuation caused by the thermal disturbance requires $e^{*2}/2C_J >> kT$. The charge satisfying this condition makes transition on the lowest energy level, and does not interact with incoherent flux. v) The level separation $\Delta W \sim e^{*2}/2C_J$. The existence of junction voltage V increases ΔE by $\sim e^*V$. If the critical voltage is determined from $\Delta W \sim e^*V$, we have $V_c \sim e^*/2C_J$.

IV. New Possibility of High Temperature Superconductor (HTS) Junction

IV-1. Unusually Long Coherence Length of HTS Junction

Recently long range coherence length is observed in all-oxide junctions.[10] The most simple definition of the coherence length is the size of a pair. According to the definition we may say that i) in a superconducting oxide material with high density carriers the size of hole pairs is several nm, and that ii) in a highly resistive oxide material with small carrier density the pair size reaches as large as hundreds nm.

IV-2. Anomaly of Resistivity and Hole-Pair State[11]

The size-variation model of the hole-pairs depending on carrier density x' also explains the anomalous phenomenon found in the carrier density dependence of the resistivity ρ of HTS. Studying the experimental ρ–x' relation,[12] we found that ρ has dips at $x'=4^{-N}$ (N=1,2,3,...). The result is explicable supposing the existence of hole pairs with size $\sim\sqrt{2}a\times2^{N-1}$ (a, lattice constant of CuO_2 square array) in the range $4^{-N}>x'>4^{-(N+1)}$.

IV-3. "Hole-Pair" Electronics Using HTS

Making use of the property of hole pairs in HTS, there is a possibility of realizing "single hole-pair electronics" based on bridge junctions with a sample size much larger than that of SET junctions, and at much higher temperature ($T<T_c$). As one characteristic of HTS, it is very difficult for 2 holes to occupy the same place due to strong Coulomb repulsion. Therefore a bridge device with HTS electrodes and with bridge part made of similar oxide material of small carrier density may have the characteristics of single charge-quantum device, when the bridge part is constricted in the size less than the size of the hole pair in the low carrier density material. Superconductive oxides have carrier density $\sim10^{27}m^{-3}$. If carrier density of bridge part is 10^{19}-$10^{20}m^{-3}$, the size of a hole pair is $\sim1\mu m$. Making the bridge size less than $1\mu m$, we will have the device described in III-2-2, which will work at temperature up to T_c of electrode HTS.

V. Conclusion

Study is made on the conditions of the physical parameters of the junctions to realize Josephson effect or single charge quantum effect. It is found that a tunnel type Josephson junction and a bridge type single charge junction have dual relation. The latter may be operated at temperature up to T_c, when the electrodes are made of superconductor. On the other hand a bridge type Josephson junction and tunnel type single charge (SET) junction are found to have dual character. When HTS electrodes and a highly resistive oxide bridge are used to compose a single charge junction, it will work i) at a device size much larger than SET junction, and ii) at temperature up to T_c of the HTS.

References

1) K. K. Likharev and A. B. Zorin, J. Low Temp. Phys. 59 (1985) 347.

2) D. V. Averin and K. K. Likharev, J. Low Temp. Phys. 62 (1986) 345.

3) M. Sugahara, N. Yoshikawa and J. F. Jian, Proc. 4th Int. Conf.SQUID'91, Berlin, 1991 (Springer-Verlag, Berlin, 1992), p.263.

4) M. Sugahara and N. Yoshikawa, Jpn. J. Appl. Phys, 30 (1991) 263.

5) J. T. Edwards and D. J. Thouless, J. Phys. C5 (1972) 807.

6) D. C. Licciarderllo and D. J. Thouless, Phys. Rev. Lett. 35 (1975) 1475.

7) M. Sargent III, M. O. Scully and W. E. Lamb, Jr., Laser Physics (Addison-Wesley, Reading, Massachusetts, 1974).

8) V. Ambegaokar and A. Baratoff, Phys. Rev. Lett. 10 (1963) 486.

9) M. Sugahara and N. Yoshikawa, J. Appl. Phys. 28 (1989) 1816.

10) U. Kabasawa, Y. Tarutani, T. Fukazawa, A. Tsukamoto, M. Hiratani and K. Takagi, Jpn. J. Appl. Phys. 30 (1991) 1670.

11) M. Sugahara, Jpn. J. Appl. Phys. 31 (1992) L324.

12) S. Uchida, H. Takagi, Y. Tokura, N. Koshihara and T. Arima, Strong Correlation and Superconductivity (Springer Verlag, Berlin, 1989) p.194.