From Maxwell's displacement current to superconducting current

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We investigate the nature of the superconducting current from the Maxwell's displacement current. We argue that the conduction current density term of the Maxwell's equations is physically untrue, and it should be eliminated from the equations. Essentially, both the superconducting current and conduction current are originated from the Maxwell's displacement current characterizing the changes of electric field with time or space. Therefore, there are no electrons tunnel through the insulating layer of the Josephson junction. It is shown that the conventional static magnetic field is, in fact, the static electric field of the intrinsic electron-ion electric dipoles in the materials. The new paradigm naturally leads to unification of magnetic and electrical phenomena, while at the same time realizing the perfect symmetry of the Maxwell's equations. Moreover, it is well confirmed that the Dirac's magnetic monopole is indeed the well-known electron. This research is expected to shed light on the high-temperature superconductivity.

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I. INTRODUCTION

The copper oxide-based superconductors were discovered in 1986 [1], 26 years later, the condensed matter physicists are still unable to identify the exact mechanism that can result to the superconductivity as high as 164 kelvin [2–4]. It is widely believed that the cuprate superconductors also conduct the superconducting current via Cooper pairs like conventional superconductors. Hence, it is a primary task of the researchers to look for the "glue" binding Cooper pairs together. In addition to the conventional BCS electron-phonon glue [5], many new "glues" and models have been proposed to create and maintain the Cooper pairs, including resonating valence bonds [6], confined loops of current [7], spin fluctuations [8], interlayer tunneling, gauge theories, etc. But the search for a magic "glue" has turned out to be an unsuccessful research strategy. So far, the high-temperature cuprate superconductors remain unknown despite tremendous efforts from both experimental and theoretical research communities.

In 2007, Anderson pointed out that many theories about electron pairing in cuprate superconductors may be on the wrong track [3]. We completely agree with his opinion that there is no "glue" for cuprate superconductors. So the key point right now is: What is the right track to unveiling the truth behind the high-temperature superconductivity?

In the framework of the standard theory of superconductivity [5], it is assumed that the paired electrons can flow freely through the superconductors in a way that individual electrons are unable to do. This physical picture suggests that the superconducting current as a conduction current of Cooper pairs. Here, we will show that the conduction current, as a starting point for investigation into the superconducting phenomena, is the root cause of the difficulties in establishing the microscopic theory of superconductivity. We argue that the Maxwell's displacement current is the right track to uncover the superconducting mystery. In other words, the entire paradigm of the superconductivity developed over the past several decades must be reexamined.

In 2008, we achieved the unification of electricity and magnetism based on the electric-magnetic duality symmetry [9]. We found that the static magnetic field of a bar magnet, in fact, is the static electric field of the periodically quasi-one-dimensional electric-dipole superlattice. In this paper, it will be demonstrated that this new paradigm may directly lead to the final solving of the superconducting puzzle. In Section II, we compare the conduction and displacement current of a classical capacitor with the superconducting current of a quantum Josephson junction. It is thought that the superconducting current might intrinsically be the displacement current, while perhaps the traditional concept of the conduction current is physically untrue. In Section III, we concentrate our attention on studying the symmetry of Maxwell's equations. To ensure the electric-magnetic duality symmetry, obviously, the concept of conduction current has to be abandoned. In Section IV, the microelectronic structures of the conduction current, the displacement current and the superconducting current are illustrated. In the final section, we provide a brief summary and conclusion.

II. JOSEPHSON JUNCTION AND CAPACITOR

In 1962, Josephson made a remarkable prediction that two superconductors separated by a thin insulating barrier (about 5 to 30 Angstroms) should give rise to some new quantum effects [10]. As shown in Fig. 1(a) ,

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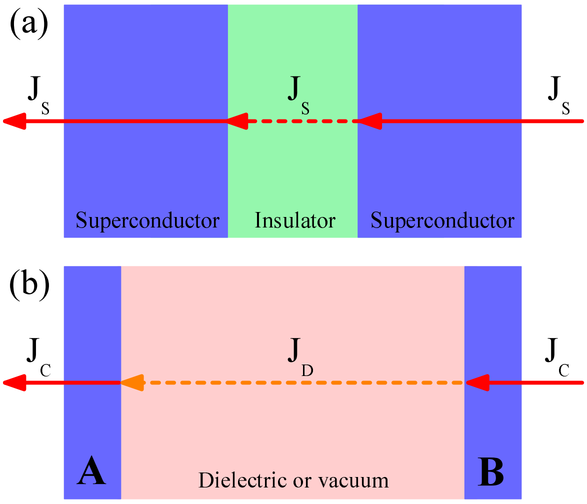

Figure 1: What are the differences among the conduction current ($\mathbf{J}_C$), the displacement current ($\mathbf{J}_D$) and the superconducting current ($\mathbf{J}_S$)? According to the current continuity of (a) microscopic quantum Josephson junction and (b) macroscopic classical capacitor, we argue that any kinds of currents should share an exactly the same physical reason. In other words, they must have a definite physical meaning. In our view, the electric current is the physical quantity characterizing the changes of electric field with time or space. Hence, it is physically unreasonable to assume that the conduction current originates simply from the flow of charged particles.

this superconductor-insulator-superconductor sandwich has been called a "Josephson junction". There are three main effects predicted by Josephson for the junction. First, the DC Josephson effect

$$\mathbf{J}_S = \mathbf{J}_0 \sin \Phi, \tag{1}$$

where $\mathbf{J}_S$ is the current density across the Josephson junction, $\mathbf{J}_0$ is called the Josephson critical density current, and Φ is the "phase difference" across the junction.

The DC Josephson effect refers to the phenomenon of a direct quantum tunneling of the paired electrons through the insulating barrier in the absence of any external electromagnetic field. Second, the AC Josephson effect which is induced by a fixed voltage across the junctions. The AC Josephson effect tells us that the phase will vary linearly with time, and the corresponding current will be an AC current with a frequency

$$f = \frac{2e}{h} V, \tag{2}$$

where e is the elementary charge, h is the Planck constant, and V is the voltage across the junctions.

The Josephson effects are universal for any superconductors and have some important applications, such as SQUIDs, radiation detection, frequency measurement and superconducting qubits. It is commonly believed that the Josephson effect is one of the strongest supports for pairing picture of the BCS theory. However, we would like to raise one question: Is it real that the paired electrons indeed pass through the insulating layer?

In fact, the current tunneling is not the unique phenomenon of the microscopic Josephson junctions, it may happen in some macroelectronic devices, such as the capacitor. As shown in Fig. 1(b), the conduction current J_C is interrupted between two plates of the capacitor. Although current is flowing through the capacitor, no actual charges are transported through the dielectric (or vacuum) between plate A and B. In order to ensure the continuity of the conduction current, Maxwell postulated the following displacement current

$$\mathbf{J}_D = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}, \tag{3}$$

where $\mathbf{E}$ is the electric field and ε_0 is the permittivity of free space.

Of course, the displacement current is not a conduction current at all. It is interpreted as a changing electric field makes a changing magnetic field. The hypothesis of the existence of the displacement current is now generally accepted as a historical landmark in physics. Motivated by the significance of the displacement current, an interesting question arises: Is it possible that the conduction current and the superconducting current are also the displacement currents? In our view, the electric current (whether it is the conduction current or the superconducting current) is the physical quantity characterizing the changes of electric field with time or space. Thus, Eq. (3) can be expressed in the form of spatial variation

$$\mathbf{J}_D = \sqrt{\frac{\varepsilon_0}{\mu_0}} \left(\frac{\partial E}{\partial x}\mathbf{i} + \frac{\partial E}{\partial y}\mathbf{j} + \frac{\partial E}{\partial z}\mathbf{k} \right), \tag{4}$$

where $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$ are the unit vector in x-, y-, and z-axis, respectively, μ_0 is the vacuum permeability, and the speed of light in free space satisfies $c = 1/\sqrt{\varepsilon_0 \mu_0}$.

With this idea in mind, the conventional concept that electric current is a flow of electric charge through a medium will no longer be available. Consequently, the physical properties of the quantum Josephson junctions and the classical capacitors can be explained under a unified current scheme. In the following two sections, we will provide some solid evidence supporting the new postulation.

III. SYMMETRIES OF MAXWELL'S EQUATIONS

The principle of symmetry is crucial to the study of physics. As is well known, the behavior of electric and magnetic fields can be well described by the following

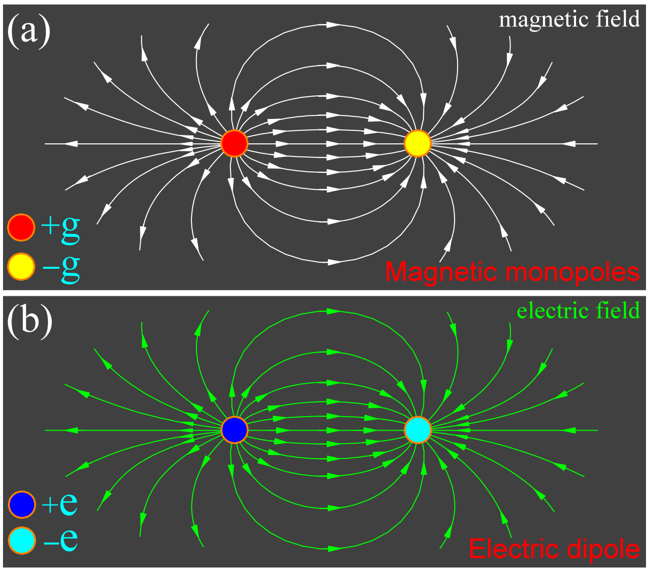

Figure 2: A comparison of the static magnetic field and the static electric field. (a) The theoretical magnetic field lines (the white curves) of a pair of hypothetical monopoles ($+g$ and $-g$), (b) the static electric field lines (the green curves) of the simplest electric dipole consists of one proton ($+e$) and one electron ($-e$). It should be noted that they looked the same. Does this imply that the Dirac's magnetic monopole is actually the well-known electron?

Maxwell's equations

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 4\pi\rho_e, &(5)\\ \nabla \cdot \mathbf{B} &= 0, &(6)\\ \nabla \times \mathbf{E} &= -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, &(7)\\ \nabla \times \mathbf{B} &= \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{J}_e, &(8)\end{aligned}$$

where $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic field, ρ_e is the electric charge density, $\mathbf{J}_e$ is the electric current density and c is the speed of light in a vacuum.

Without electromagnetic sources ($\rho_e = 0$; $\mathbf{J}_e = 0$), it is easy to find that the set of Eqs. (5)-(8) will remain invariant under the following duality transformations

$$\mathbf{E} \rightarrow \mathbf{B}; \quad \mathbf{B} \rightarrow -\mathbf{E}. \tag{9}$$

When $\rho_e \neq 0$ (or $\mathbf{J}_e \neq 0$), the electric-magnetic duality symmetry of Eq. (9) will be destroyed. However, Dirac believed that the electromagnetic laws should keep the "dual nature" under any circumstances. In 1931 [11], Dirac introduced the magnetic monopole (a basic unit of magnetic charge) into the Maxwell's equations. In the Dirac's monopole theory, the relation between an electric charge (e) and magnetic charge (g) is given by

$$eg = \frac{hc}{4\pi}n = \frac{\hbar c}{2}n, \quad (n = 1, 2, 3, \cdots) \tag{10}$$

where h is the Plank's constant ($\hbar = h/2\pi$) and c is the speed of light.

Does the hypothetical magnetic particle exist in the natural world? Since then, the numerous attempts of experimental search for these magnetic monopoles have been done. Unfortunately, up to now, no positive evidence for its existence has been found. In our previous paper [9], we argued that the concept of the magnetic monopole is physically untrue. Furthermore, we pointed out that the Dirac's monopole is, in fact, the well-known electron. Interestingly, this argument can be verified by Eq. (10) of the Dirac's monopole theory. The fine-structure constant is a fundamental physical constant which is defined as

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \approx \frac{1}{137}, \tag{11}$$

where e is the elementary charge, ε_0 stands for the permittivity of free space, c is the speed of light in a vacuum and $\hbar = h/2\pi$ is the reduced Planck constant.

Substitution Eq. (11) into Eq. (10), the Dirac's quantized magnetic charges become

$$g = \frac{e}{8\pi\varepsilon_0\alpha}n, \quad (n = 1, 2, 3, \cdots) \tag{12}$$

Eq. (12) indicates clearly that the nature of the so-called Dirac's magnetic monopole is the electron. The equivalence of the electric charge (electron) and the magnetic charge (monopole) is explicitly shown in Fig. 1. As a result, the static magnetic field is essentially the static electric field of a pair of electric-dipole. Hence, the right side of the Eq. (6) of the Maxwell's equations can always be zero in this way. As the magnetic field is no longer relevant to the conventional electric current (or the conduction current), it is quite reasonable that the $\mathbf{J}_e$ of Eq. (8) can be removed from the Maxwell's equations. After these modifications, the standard Maxwell's equations of Eqs. (5)-(8) can be rewritten as follows

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 4\pi\rho_e, &(13)\\ \nabla \cdot \mathbf{B} &= 0, &(14)\\ \nabla \times \mathbf{E} &= -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, &(15)\\ \nabla \times \mathbf{B} &= \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}. &(16)\end{aligned}$$

Now, the overall Maxwell's equations become neat, symmetry and self-consistent. In the next section, we will further illustrate that these improvements on the Maxwell's equations are physically correct and realistic.

IV. WHAT IS THE DISPLACEMENT CURRENT?

In solid state physics, metals are described as an arrangement of positive ions surrounded by a sea of delocalized electrons, as illustrated in Fig. 3(a). It has

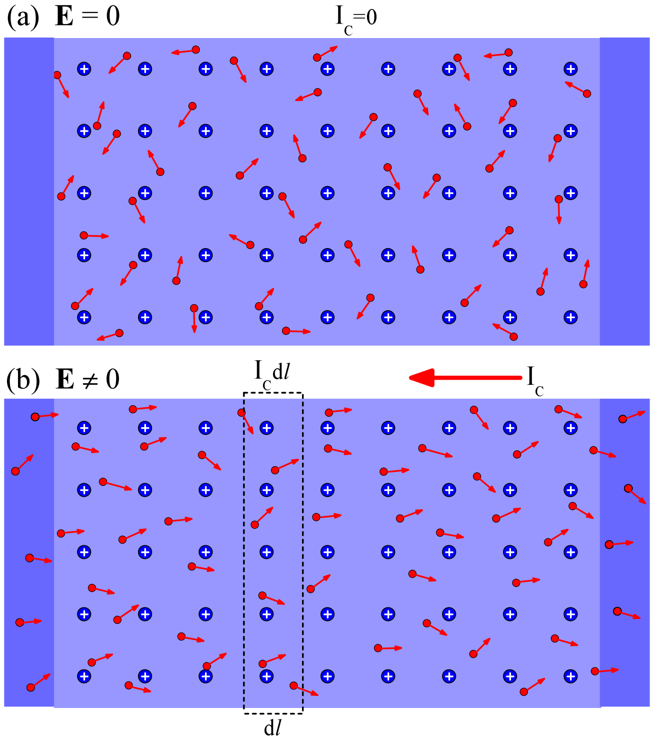

Figure 3: A widely accepted physical picture of the electrons in a metal. (a) Without the external electric field ($\mathbf{E} = 0$), the electrons are in random motion inside the metal, (b) with an external electric field ($\mathbf{E} \neq 0$), the electrons will flow (like the water molecules in a pipe) in the opposite direction of the electric field. Where I_c is the conduction current and $I_c dl$ is a current element. Under an alternating electric field, the electrons will vibrate around the corresponding ions and emit electromagnetic waves.

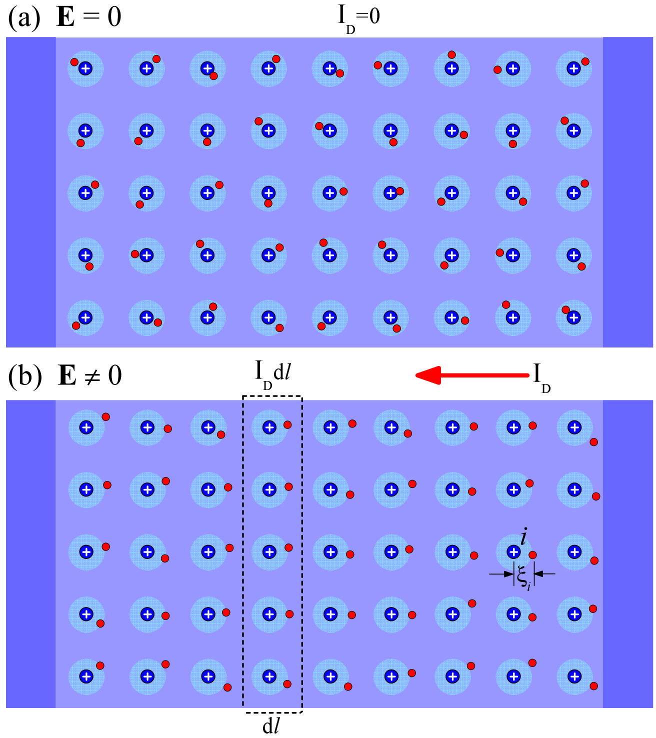

Figure 4: A modified physical picture of the electrons in a metal where the confinement effect of the positive ions to the electrons are taken into account. (a) Without the external electric field ($\mathbf{E} = 0$), the electrons are constrained to move around the corresponding ions, (b) with an external electric field ($\mathbf{E} \neq 0$), all the electrons will drift to the right side of the ions with a electron-ion spacing ξ_i. In this case, the electron-ion pairs will form an electric dipole array which contribute a magnetic field (that is actually an electric dipole field) and a conduction current (in fact, is the displacement-like current $\mathbf{I}_D$). Under an alternating electric field, the electrons will vibrate around the corresponding ions and emit electromagnetic waves.

been the general consensus that the electrical conductivity of metals originates from an overall movement of the nearly free electron gas in a background of positive charge formed by the ion cores, as shown in Fig. 3(b). In this picture, the electric currents (conduction currents) much like water currents flowing in a pipe where a certain number of water molecules leaves the pipe, while at the same time some water molecules enter from the other end of the pipe. This water-like current of electronic may be contrary to the physical reality. Note that this picture of current will inevitably lead to the strong collisions between electrons under the AC current.

When considering the real physical problems, it is necessary to take into account the positive potential caused by the periodic arrangement of the ion cores in crystals, as shown in Fig. 4. Without the applied electric field, the quasi-free electrons are randomly distributed around the positive ions, as shown in Fig. 4(a). With an external electric field, all the electrons inside the metal will shift in the opposite direction of the electric field and "stay" around their quasi-equilibrium positions, respectively. The electron-ion pairs form a ordered electric dipole array which is responsible for the displacement current and electric dipole field, which have been misinterpreted as the conduction current and the magnetic field, respectively. With the above discussions, it is very much clear that the so-called conduction current and displacement current are essentially the electric dipoles of the electron-ion pairs. Then, what is the superconducting current?

Similar to the displacement current, the superconducting current also origins from the electron-ion dipoles in the superconductors. As indicated in Fig. 4(b), the i-th electron-ion pair can be characterized by the electron-ion spacing ξ_i. We define the root mean square deviation (RMSD) of ξ_i as

$$\Omega(\xi) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\xi_i - \bar{\xi}\right)^2}. \tag{17}$$

The parameter $\Omega(\xi)$ may play the role of the order parameter for superconducting phase transition. For the

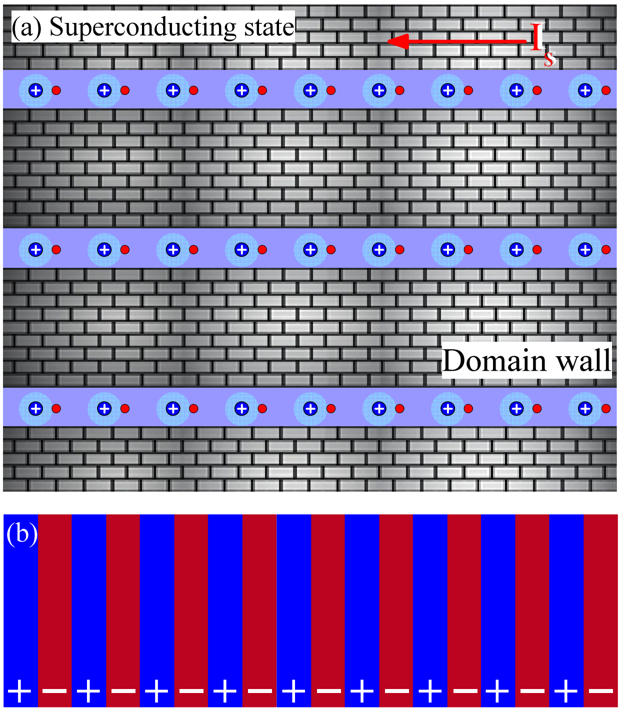

Figure 5: The microscopic electronic structure of the superconducting state. (a) The electron-ion electric dipoles have a same orientation and a same electron-ion spacing. Similar to the case of Fig. 4(b), the electrons will vibrate around the corresponding ions and emit electromagnetic waves under an alternating electric field. This is the most fundamental reason for the AC Josephson effect. Moreover, the high-temperature superconductors usually possess a wide domain wall which is related to the c-axis lattice constant of the crystal. (b) When the sample enter into the superconducting state, the superconductor can be simplified as a quasi-one-dimensional electric-dipole superlattice.

superconducting phase, $\Omega(\xi) = 0$, while for the non-superconducting phase, $\Omega(\xi) > 0$. From the microscopic point of view, the superconducting phase corresponds to an electron-ion dipole state with an identical orientation and spacing [as illustrated in Fig. 5(a)], while for the non-superconducting phase of Fig. 4(b), the orientations of the electron-ion dipoles are not identical. Obviously, the temperature and the dipole-dipole interactions will cause the instability of the dipole orientations, this in turn, reduce the superconducting transition temperature. As shown in Fig. 5(a), the dipole-dipole interactions can be greatly suppressed by increasing the width of the domain wall Δ. Qualitatively, for the layered high-temperature superconductors, the Δ can be significantly increased by decreasing the carrier concentration (or by increasing the c-axis lattice constant of the sample). Further and detailed researches are being conducted.

In the framework of this paper, the nature of the magnetic properties of materials (including the permanent magnet materials and superconductors) are actually the electrical properties of the electric dipoles. As

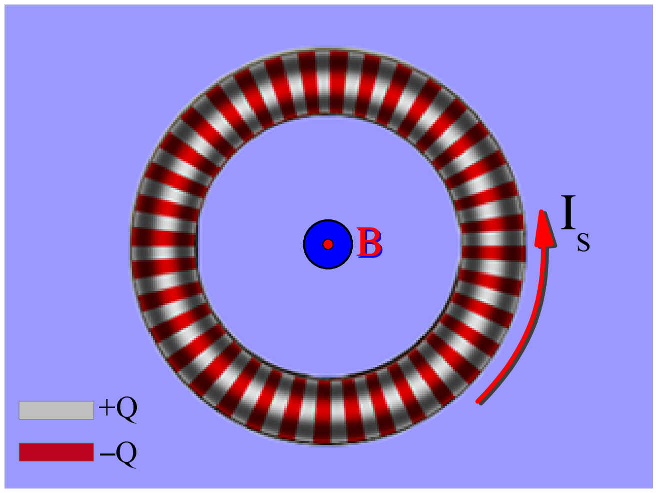

Figure 6: In our theory, the persistent current in a superconducting ring is not physical reality. The observed magnetic field of the “persistent current” is actually the electrostatic field of the electron-ion electric-dipole superlattice ring.

a simplified microscopic model of superconductor, the superconducting state can be presented as a quasi-one-dimensional electric-dipole superlattice, as shown in Fig. 5(b). In the subsequent articles, we will show that this simplified model can explain all experimental phenomena of superconductivity both for conventional and non-conventional superconductors. Such as the experiment of observing a persistent current in a superconducting ring, in fact, there does not exist the so-called the persistent current inside the superconducting ring. As shown in Fig. 6, what the researchers actually observed is the electrostatic field generated by the electron-ion electric-dipole superlattice ring. Hence, from the viewpoint of magnetism, the superconductors are the low-temperature permanent magnets.

V. A BRIEF SUMMARY AND CONCLUSION

Based on the electric-magnetic duality symmetry, we have studied the symmetry of Maxwell's equations. According to the current continuity of the microscopic quantum Josephson junction and the macroscopic classical capacitor, we have argued that the conduction current density term is physically untrue, and it should be eliminated from the Maxwell's equations. We have pointed out that the existing concepts of superconducting current and conduction current are, in fact, the Maxwell's displacement-like current. According to the Dirac's monopole theory, it has been well confirmed that so-called Dirac's magnetic monopole is indeed the electron. Together with our studies, it is clear that the conventional static magnetic field is a misreading of the static electric field of the intrinsic electron-ion electric dipoles in the materials. Interestingly, the new paradigm on the one hand leads to the unification of magnetic and electrical phenomena, and on the other hand realizes the perfect symmetry of the Maxwell's equations. In our theoretical framework, a superconductor is merely a high-quality low-temperature permanent magnet. There is no doubt that the new theory and model may have important implications in physics, especially, in the field of high-temperature superconductivity.

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