PCP7-1

AC Resistivity of Driven Vortices of a Superconductor Measured by Mirowave technique

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Driven vortices of a superconductor have been investigated both extensively and intensively because of the importance in their industrial application and the interests in their fundamental properties. Vortex movements are described by the force balance equation consisted of driving force, viscous drag force, pinning force and thermal fluctuation. Dissipation of moving vortices arises from both viscous force and dynamic pinning force. However, microscopic nature of this dynamic pinning force is still poorly understood because of its nonlinearity and randomness. While some theories attribute dynamic pinning force to the elastic deformation of a vortex lattice[1][2], experimental verification is open to further studies.

So far, measurements of I-V characteristics are widely used to investigate the driven vortices. In addition, other measurement techniques, such as velocity noise[3], interference effect[3] and small angle neutron scattering[4] were employed to study the driven vortex lattice. Among those, we believe that the ac response of moving vortices is one of the most essential quantity to understand them, because moving vortices always feel time-dependent force due to the pinning. However, there have been almost no experiments focusing on this subject. Thus, we started to measure the ac response of vortex lattice under dc driving force.

We fabricated transmission line resonators made of Nb to observe the ac response of vortices under dc bias current. With these devices, we can measure complex resistivity as a function of dc driving force. As a result, a peak in Q-1 was observed around 30 mA (Fig. 1). This change was observed only under magnetic field, suggesting the vortex dynamics origin. We will discuss this phenomenon in more detail, including the frequency dependence, and also discuss these in terms of the complex resistivity.

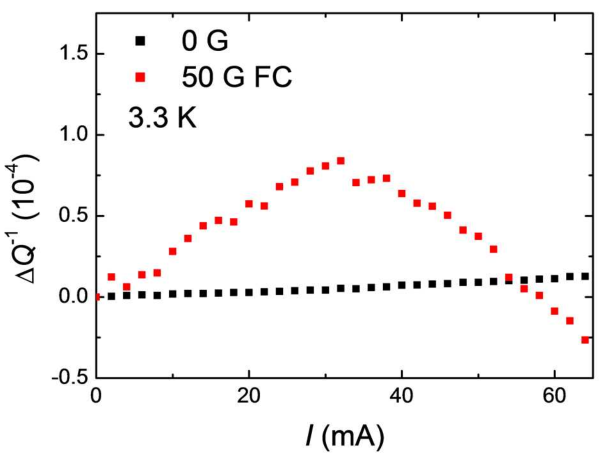

Fig.1 Current dependence of Q-1 with and without magnetic field.

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Keywords: Driven vortices, Pinning, Microwave response, Superconducting resonators

PCP7-2

Estimation of the size of the pinning potential from ac current-voltage characteristics

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An experimental determination of the pinning potential is of great importance from the practical as well as fundamental point of view. While much effort has been devoted to controlling and improving the pinning properties of superconductors, to the best of our knowledge, there has been no suitable experimental method to estimate the size of the pinning-potential well in actual materials. Here, we present a convenient method to estimate the mean diameter of the pinning potential d_p in amorphous superconducting films with weak random pinning from ac current-voltage (I_{ac}- V_{ac}) characteristics [1].
The $I_{ac,e}$- $V_{ac,e}$ curves at various frequencies f are measured in the vortex solid phase of amorphous Mo_xGe_{1-x} films, where $I_{ac,e}$ and $V_{ac,e}$ are the effective ac current and voltage, respectively. We clearly identify the frequency(f)-dependent effective current $I_{ac,es}$ and voltage $V_{ac,es}$ separating the linear regime where the vortices oscillate inside the pinning-potential well from the nonlinear regime where the vortices are depinned from the pinning potential. These features are qualitatively the same as those found numerically [2]. From the $V_{ac,es}$-f relation, d_p is estimated to be about 28 nm, which is comparable to the size of the vortex core. The result is consistent with the intuitive belief based on structural studies of amorphous films and other indirect experimental evidence that the amorphous films contain point-like pinning centers. The critical behavior associated with the transient dynamics of vortices near the depinning transition is also observed for the ac drive [1], which is similar to that for the dc drive [3]. The results further demonstrate the universality of the nonequilibrium depinning transition.

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Keywords: Vortex pinning, AC transport properties, Non-linear phenomena, Amorphous films

PCP7-3

Partial reordering of dc plastic flow by superimposing ac drive

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When a small ac force is applied to many particle systems with a random distribution and the number of cycles is increased, the particles gradually transform into an organized configuration called random organization. To obtain the information on how random organization evolves with the cycle number, we have recently conducted two-step measurements of time-dependent voltage $V(t)$ in response to the ac drive for vortices in amorphous Mo_xGe_{1-x} films with weak random pinning. In the first input experiment, we observed random organization, while in the second readout experiment, we found that the transient vortex configuration formed during random organization is not microscopically homogeneous but consists of disordered and organized regions [1]. It is well known, on the other hand, that when the vortices with organized configuration are driven by a small dc force slightly above the depinning threshold, they are gradually pinned by random pinning centers, indicative of dynamic disordering. Thus, it is interesting to examine how dynamic ordering emerges in plastic flow when an ac drive is superimposed with the dc drive, and what configuration such a vortex system takes.

To answer the question, here we again conduct two-step measurements of $V(t)$. In the first experiment, we find that random organization by ac drive is suppressed with an increase in the superimposed dc drive, and finally vanishes as the dc voltage is equal to the amplitude of the ac voltage in the steady state, where the vortices move in the forward direction only without retracing the path they just traveled. From the second readout experiment, we find that even in the steady state, the vortex configuration created with dc and ac drives is not microscopically homogenous but consists of two regions: a disordered region characterized by plastic flow by dc drive and an organized region characterized by ac drive without dc drive. The ratio of the ordered region to the total area decreases monotonically from 1 to 0 with superimposed dc drive, and finally falls to zero, where random organization in the first experiment disappears.

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Keywords: Plastic flow, Vortex structures, Nonequilibrium phenomena, Amorphous film

PCP7-4

Blocking phenomenon in a vortex system

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When a vortex lattice is driven by a dc current in a random pinning potential, fluctuating plastic flow (PF) occurs at small drives. PF changes to coherently moving flux flow (FF) at larger drives. While much effort has been devoted to understand the moving lattice states or dynamic transitions, PF is poorly understood at least experimentally. The study of PF would lead to interesting general problems: e.g., the system that exhibits PF displays liquidlike and solidlike properties at the same time [1].

We investigate the vortex configuration in PF using an amorphous Mo_xGe_{1-x} film with weak random pinning. First, we prepared steady-state PF by applying a small dc current I_{inp}, and then froze its vortex configuration by switching off I_{inp}. Subsequently, we applied a dc current I of the same amplitude as I_{inp} at time zero ($t = 0$), but the direction of I is either the same or opposite to the direction of I_{inp}, and measured the time evolution of voltage V(t). When I is applied in the opposite direction to that of I_{inp}, V(t) shows a sharp rise at $t = 0$ and a subsequent decay toward a steady-state voltage. By contrast, when I is applied in the same direction as that of I_{inp}, no relaxation of V(t) was observed. These results indicate that in the former case, a greater number of vortices are mobile at $t = 0$ than in the latter case. We attribute its origin to the blocking effect for free vortices by pinned vortex bundles. That is, since there are regions in the sample where the distribution of pinning centers is slightly denser, vortices are pinned to them and form vortex bundles. When I is applied in one direction, some free vortices are blocked by the pinned vortex bundles. However, once the direction of I is reversed, the blocked vortices move abruptly, giving rise to a sharp additional voltage. In the FF regime, by contrast, V(t) is found to be independent of the direction of I. This is reasonable, because in the FF state the pinning effects are so small that the blocking is no longer effective. The blocking effect observed here may be analogous to the clogging effect reported in the simulation for a two-dimensional bidisperse disk system with random pinning [2].

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Keywords: Vortex pinning, Nonequilibrium phenomenon, Plastic flow, Amorphous film

PCP7-5

Random organization and reversible-irreversible transition of vortices in tilted field

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When a periodic shearing force is applied to a many particle system with random configuration, particles self-organizes to avoid the next collision. This is called random organization. A relaxation time to reach the steady state exhibits a power-law divergence at the critical displacement of the reversible-irreversible transition (RIT). Random organization and RIT were first observed in colloidal suspensions [1] and later in a vortex system [2]. However, the nature of random organization remains still unclear, and there are interesting problems, which include how the configuration evolves associated with random organization and how anisotropy in the system affects random organization. Regarding the latter, we have recently studied random organization in the vortex system under the tilted field, where an anisotropic vortex-vortex interaction as well as an anisotropic vortex configuration is introduced [3]. The relaxation time of random organization for the vortices driven in the tilt direction was found to be much smaller than that in the untilted field [4]. The results indicate that the anisotropy introduced by the tilt field significantly limits possible configurations of vortices and expedites random organization.
Here, we extend this experiment to include random organization for the vortices driven *perpendicular* to the tilt direction. As a result, the relaxation time is found to be further decreased, approximately, an order of magnitude smaller than that for the vortices driven in the tilt direction. The vortex-vortex interaction along the flow direction is stronger when the vortices are driven in the direction perpendicular to the tilt direction than in the tilt direction. Therefore, the decreased relaxation time observed here is explained in terms of the enhanced vortex-vortex interaction for the vortices moving in the direction perpendicular to the tilt direction. The critical behavior of RIT is observed irrespective of the flow direction.

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Keywords: Nonequilibrium phenomenon, Vortex dynamics, Dynamic transition, Amorphous film

PCP7-6

Configuration of vortices in dc flow interacting with random pinning

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It is interesting how elastic objects interacting with a random substrate escape from a pinning potential and exhibit dynamical flow phases with an increase in a driving force. The phenomena appear in a wide variety of systems and have attracted broad attention. A vortex system with pinning is a suitable system to study such phenomena. It is well known that vortices driven by a small dc current, *I,* exhibit pinning-dominated plastic flow, while at large *I*, dynamic ordering of driven vortex lattices occurs. The dynamic transitions among different dynamical phases have been predicted numerically [1], and evidence of dynamic ordering has been obtained experimentally [2,3]. However, it has not been fully clarified how plastic flow at low *I* becomes ordered with an increase in *I*. Recently, we have proposed a novel method for detecting the configuration of vortices subjected to an ac drive in the transient as well as steady state for amorphous Mo_xGe_{1-x} films with weak random pinning [4]. In this method, after freezing the vortex configuration by cutting off the ac current, we conducted readout measurements of the time-dependent voltage $V(t)$ in response to the ac drive with various amplitudes, thus obtaining the information on the frozen vortex configuration.

In this work, we employ this method to study the change in the configuration of dc driven vortices in the steady state as a function of *I*. First, we freeze the configuration of the moving vortices in the steady state driven by *I*. Then, we perform the readout measurements of $V(t)$ for the frozen vortex configuration in response to the ac drive. As a result, we find that in the intermediate *I* regime between the plastic-flow and moving-lattice states, the vortex configuration is not microscopically homogeneous but consists of two regions: a highly disordered region characterized by plastic flow at small *I* and an ordered region characterized by flux flow or moving lattices at large *I*. With increasing *I*, the ratio of the ordered region to the total sample area increases monotonically from zero to unity.

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Keywords: Moving vortex phase, Dynamic transition, Non-equilibrium phenomena, Amorphous films

PCP7-7

Observation of Vortex Motion Using Scanning Tunneling Spectroscopy

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Investigation of vortex dynamics is important for the practical applications of superconductivity. It is also of fundamental importance, because a vortex system is a suitable system to study novel nonequilibrium phenomena and phase transitions. We have studied the dynamics of vortices driven by applied currents using various transport measurements, where we probe the mean velocity of vortices moving over the whole sample. However, it is also important to trace individual vortex motion and determine the time evolution of the vortex configuration. For the purpose, we have constructed a measurement system that enables to perform scanning tunneling microscopy and spectroscopy (STM/STS) measurements simultaneously with the transport measurements.
High-quality films of amorphous Mo_xGe_{1-x} with weak pinning have been prepared using an RF sputtering system installed in an ultra-high vacuum chamber. To prevent slight surface oxidation that might hinder the visualization of vortices, a thin film of gold was evaporated in situ onto the surface of the Mo_xGe_{1-x} film. In our STM/STS system, we drive the vortices by applying a current, and a voltage generated by vortex motion is measured. After freezing the configuration of moving vortices at a desired time by abruptly switching off the current, we acquire its image by STS. Thus acquired snapshot images of vortex configuration provide useful information, complementary to the transport data, in elucidating the vortex dynamics. This will help complete a dynamic phase diagram for dc-driven vortices in random potential, and to explore the nature of random organization [1] and novel nonequilibrium transitions [2,3].

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Keywords: STM/STS, Vortex structure, Vortex flow, Amorphous film

PCP7-8

Microscopic theory of the vortex-core charging in superconductors

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A number of studies on vortex-charging have been carried out based on the mean field theory of supercon- ductivity such as the Bogoliubov–de Gennes (BdG) equations [1,2]. However, the BdG equations cannot clarify mechanisms of charging explicitly. In addition, it is difficult to incorporate Fermi-surface and gap anisotropies in this approach.

Recently, studies on the flux-flow Hall effect have been carried out by using the augmented quasiclassical equations in the Keldysh formalism, incorporating the Lorentz and pair-potential gradient forces which are first order in quasiclassical parameter [3]. In addition, we have transformed the augmented quasiclassical equations into the Matsubara formalism, so that charging in superconductors can be calculated microscopically and quantitatively [4,5]. However, little study has been done on the valid parameter region of the quasiclassical equations.

We study the validity of the augmented quasiclassical equations by calculating the vortex-core charging of a two-dimensional s-wave superconductor in comparison with the result based on the BdG equations.

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Keywords: vortex charge, quasiclassical equations, BdG equations

PCP7-9

Paramagnetic and Glass States in YBCO Film Containing Nanorods at Low Magnetic Fields

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Recently, multilayered films comprised of $YBa_2Cu_3O_{7-x}$ (YBCO) layers containing nanorods have been extensively studied for flux pining properties in the strong magnetic field. Flux pinning properties of YBCO are strongly enhanced by columnar pins, which are produced by introduction of compound defects such as $BaHfO_3$ (BHO) nanorods.[1]
However, few experimental studies on magnetic glass properties have been investigated at low fields below the lower critical field H_{c1}. Magnetic flux disorder due to the random locations of nanorods in the YBCO film corresponds to that in the ceramic YBCO composed of sub-micron size grains, which showed the chiral-glass transition with the novel glass behavior at low fields.[2]
We have investigated magnetic-glass properties of YBCO multilayered film containing BHO nanorods at zero and small fields. The multilayered film comprising of BHO containing YBCO layers and pure YBCO layers was prepared on $SrTiO_3$ substrate by alternating ablation of YBCO-BHO mixed target and stoichionmetric YBCO target. The dc magnetization and the ac susceptibility were measured with a SQUID magnetometer. In the zero-field-cooling, the diamagnetism due to the Meissner effect is observed. On the other hand, the paramagnetic magnetization is shown in the field-cooling lower than $H = 2.5$ Oe below Tc= 87 K. The nonlinear susceptibility has the large peak at Tc, which reflects a glass-transition. The aging effect observed in spin glasses and chiral glasses occurs in the relaxation of zero field-magnetization below Tc.
In conclusion, paramagnetic Meissner behavior and magnetic-glass properties are observed in YBCO multilayered film containing BHO nanorods. The results suggest that the YBCO multilayered film is the novel magnetic-glass system at low fields.

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Keywords: YBCO film, flux pinning nanorod, ageing effect, paramagnetic magnetization

PCP7-10

Effects of chirality of a helical magnetic field on a superconductor

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A chiral helimagnet has a helical magnetic structure along one direction. This helical rotation in the chiral helimagnet comes from chirality of its crystal structure. Under a magnetic field, this helical structure changes into a periodic soliton structure, which called a chiral soliton lattice. The chiral helimagnet has many interesting physical features such as a giant magnetoresistance.
We focus on effects of the chiral helimagnet on a superconductor. It is known that a vortex state in the superconductor is affected by a ferromagnet in a ferromagnet / superconductor bilayer system. We expect novel influences of the chiral helimagnet on the superconductor. Therefore, we investigate effects of the chirality of the helical magnetic field on the superconductor.
We consider a chiral helimagnet / superconductor bilayer system. The effect of the chiral helimagnet on the superconductor is taken as an external magnetic field. On the other hand, we neglect the effect of the superconductor on the magnet. In our previous study, we focused on the effect of the magnetic field normal to an interface of the bilayer. Then, we investigated vortex states in a two-dimensional superconductor under the oscillating magnetic field. However, this two-dimensional system cannot treat effects of the chirality of the helical magnetic field. Therefore, we consider a three-dimensional system and investigate vortex states in the superconductor under the helical magnetic field. In order to obtain vortex states, we calculate the Ginzburg-Landau equations with the finite element method and obtain the order parameter in the superconductor.
In this presentation, we show vortex states in the superconductor under the helical magnetic field and discuss effects of the chirality of the helical magnetic field on the superconductor by comparing vortex states in the three-dimensional and the two-dimensional systems.

Keywords: Superconductor, Chiral helimagnet, Vortex states, Finite element method

PCP7-11

Theoretical Study of Spontaneous Half-quantized Vortices in 3D d-dot model

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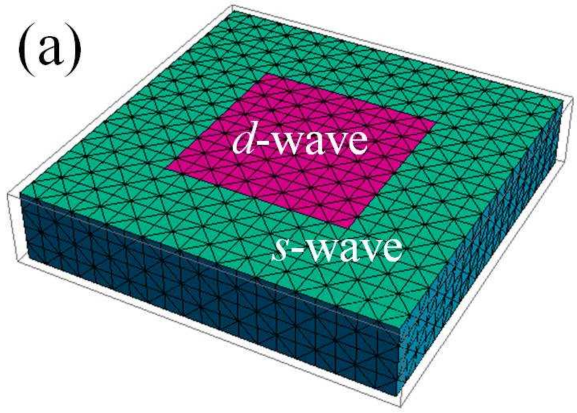
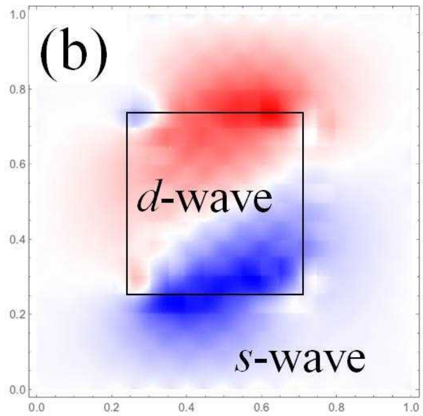
A d-dot is a nano-scaled composite structure that consists of a *d*-wave superconductor (SC) embedded in an *s*-wave matrix. Since the phase of the superconducting order parameter in the *d*-wave SC depends on direction, phase difference appears at the corner junctions between *d*-wave and *s*-wave SCs in d-dot's. Due to quantization of fluxoids including this phase difference, half-quantized vortices spontaneously appear at the each corner. This is a feature of d-dot's [1]. We can use Pb or Nb as *s*-wave SCs and $YBa_2Cu_3O_{7-\delta}$ (YBCO) as *d*-wave SCs.

The appearance of SHQVs in d-dots are proved in theoretically and experimentally [2]. But, since the previous simulation models of d-dots [3] are 2-dimensional, using these models we can't investigate effects of 3-dimensional structure of defects in d-dots. So we extend the d-dot models to 3D system using the finite element method (FEM) with volume coordinates. And numerical results using this 3D d-dot models suggest that c-axis anisotropy in *d*-wave SCs are important for appearance of SHQVs.



(a) a 3-dimensinal d-dot model



(b) Magnetic field distribution (top view)

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Keywords: GL equation, d-wave superconductor, Half-quantized vortex, Finite element method

PCP7-12

Impurity effects on critical temperatures for nano-structured superconductors

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The critical temperatures, Tc, of superconductors depend on the superconducting materials. However Tc depends on the size and shapes of superconductors for nano-structured superconductors, theoretically [1]. Parmenter showed that Tc increases with decreasing size of a cubic superconductor [2]. In experimental study, Nishizaki showed that high pressure torsion (HPT) makes many fine grains in a bulk of Nb and HPT makes Tc higher [3]. However Nishizaki also showed that HPT makes Tc lower for a bulk of V. Nishizaki discussed that the bulk of V include impurity, and the impurity in the bulk affects on Tc [4]. However Anderson showed that non-magnetic impurity doesn't affect Tc for bulk [5]. So we should make sure whether impurity effects on Tc or not for nano-structured superconductors.

We are calculating Tc of nano-structured superconductors, using finite element method (FEM) [6]. And in previous study, we showed that smaller and narrower superconductors shows higher Tc [7]. In this conference, we will talk about the impurity effects on nano-structured superconductor, by solving Gor'kov equations and Bogoliubov-de Gennes's (BdG) equations with the FEM. For the calculation of Bogoliubov-de Gennes equations, we introduce the impurity effects as random potentials. We will discus about the impurity effects on Tc, and size and shape effects on impurity effects.

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Keywords: Nano-structured, critical temperature, impurity, theoretical study

PCP7-13

Critical states in superconducting complex structures

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Magnetic flux penetrates into a superconducting strip from its edge when external magnetic field is applied perpendicular to the strip. Under the external magnetic field, there are two types of the flux penetration, which are critical state and a vortex avalanche. If ramping rate of the applied magnetic field is small, a critical state appears. On the other hand, the ramping rate is large, a vortex avalanche occurs.

The critical state is a metastable equilibrium state in which Lorentz force from a local current, and pinning force are balanced. The vortex avalanche is a thermo-magnetic instability phenomenon, in which heat generation due to vortex motion, heat transfer and vortex jump between pinning centers play important roles. In order to clarify conditions for the instabilities, we should first investigate critical states.

For a superconducting strip in the critical state, when critical current density is constant and an external field is applied, a shielding current flows parallel to an edge of superconductor, and magnetic flux density shows a linear distribution approximately.

In this presentation, we show numerical results for the critical states in a thin superconducting plate. Using two and three-dimensional finite element methods, we have solved the Maxwell equations, the heat equation and I-V characteristics for superconductors, and investigated flux density and current in a rectangular superconducting plate. Comparing results from two and three-dimensional calculation, we report detailed structures of the critical states.

Keywords: Vortex avalanche, Critical state, Finite element method

PCP7-14

Review of Quantum Electrical Standards and the Implementation of the 'Revised SI'

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The Josephson effect and quantum Hall effect have been utilized for voltage and resistance primary standards since 1990. And the other electrical standards are derived from the primary standards basically. In 2018, it is planned that the SI will be revised based on the latest measurements results of the Planck constant,
elementary charge, Avogadro constant, and Boltzmann constant. Review of the present quantum electrical standards and the detailed information of adoption of the 'Revised SI' will be presented.

Keywords: Revised SI, Quantum electrical standards, Josephson voltage standard, Quantized resistance standard