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Single-Electron Tunneling and Mesoscopic Devices

Proceedings of the 4th International Conference
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Preface

Single-electron tunneling (SET) and related phenomena have recently come to be considered as "hot topics". This also became apparent when we organized the 4th International Conference on Superconducting and Quantum Effect Devices and Their Applications, SQUID'91, which was held June 18–21, 1991, in Berlin, Germany. Impressed by the number of contributions dedicated to the new physics of ultrasmall devices, we deemed it appropriate to devote this volume of the Springer Series in Electronics and Photonics to these specialized proceedings. The other contributions presented at SQUID'91, which are more conventional in character but nevertheless contain excitingly innovative results, are published separately as Volume 64 of the series Springer Proceedings in Physics.

At first glance it seems strange that a conference abbreviated SQUID'91 should attract so many papers on *non*-superconducting devices, and in fact the first SQUID'XX conferences dealt exclusively with the physics and technology of Josephson junctions, SQUIDs and other superconducting devices and their applications. However, many concepts developed for superconducting devices, like tunneling, flux quantization, and flux-charge conjugation, appeared to be suitable for ultrasmall non-superconducting structures as well, and many researchers in the field of superconducting devices extended their activities accordingly. Thus the extension of the conference programme evolved quite informally. Meanwhile, the meetings established themselves as well-known conference series traditionally appreciated by the SQUID community for its balanced mixture of physics and technology, review and preview. SQUID'XX became a kind of a trademark. One may say, the people remained the same but their research topic sometimes underwent a phase transition. So, why change the name?

SQUID'85 was the first international conference at which the concept of single-electron tunneling was introduced: by Averin and Likharev and by Ben-Jacob et al. The first two authors open these proceedings with an overview of the fast expanding field. Their article is followed by up-to-date contributions describing the very recent activities of nearly all leading groups engaged in this extremely interesting research. At the conference an excellent introductory tutorial was presented by Mooij, who heads the very productive research group in Delft. This productiveness prevented him from writing another manuscript. Thus newcomers to the field are referred to the contributions by Ingold and Urbina et al., which exhibit a nice blend of clear tutorial style and scientific depth and topicality.

SET and related phenomenona have been observed in quite different configurations, like sets of tunnel junctions, junction arrays, scanning tunneling microscopes, and one- and two-dimensional electron gas systems all of them covered by the following contributions. Theory and experiment stimulate each other and it was primarily the close collaboration between theorists and experimentalists that initiated the break-through of the field that we now experience. This mixture of theoretical papers and experimental results is reflected by the contents of this book.

In addition, the contributions, particularly in Part IV on low dimensional electron gas systems, demonstrate how these new phenomena influence quite different fields of device physics.

Besides SET, other phenomena of mesoscopic configurations are of growing importance to electronic device physics as the trend to ultra-high packaging densities and miniaturization inevitably leads to dimensions where these quantum phenomena become more and more substantial.

The purpose of this volume is to provide an up-to-date reference book on the status of a field that is just emerging and promises a future of exciting new physics, electronics, and technology.

Only the combined effort of numerous colleagues, co-workers, friends, institutions and of course the authors of all talks, posters and papers made this successful conference and this proceedings volume possible. We greatly appreciate their support. In addition, we gratefully acknowledge the generous sponsorship of the Dr. Wilhelm Heinrich Heraeus and Else Heraeus Stiftung and the very helpful provisions we received from the Japanese-German-Center, Berlin, and from our institute, the Physikalisch-Technische Bundesanstalt.

Berlin
October 1991

Hans Koch
Heinz Lübbig

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Part I

Single-Electron Tunneling

Single-Electronics – Recent Developments

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Abstract. We present a brief review of the recent results in physics and possible applications of the correlated transfer of single electrons and Cooper pairs in ultrasmall tunnel junctions and systems. In this context we give an overview of the related papers published in this volume.

1. Introduction

A considerable attention of the participants of the SQUID'91 meeting was attracted to the so-called single-electronics. This new field of physical and applied electronics emerged right after the preceding SQUID'85 conference. Actually, a short paper [1] presented at that conference had served as a sort of a seed for this field.

The single-electronics is based on a group of physical effects with a common origin: a substantial charging of relatively large conducting objects (containing up to billions of free electrons) by addition/subtraction of one of the electrons (for the case of superconductors, a single Cooper pair or a electron-like quasiparticle). These effects are possible because the negative electric charge of the background electrons is completely compensated by the positive charge of the nuclei, but the charge of the new electron is not. Therefore, transfer of the electron causes a change

$$\Delta\mu = e^2/C \tag{1}$$

in the electro-chemical potential of the conductor, where C is its electric capacitance. For a ball with the radius of 1 μm in air, C is of the order of 10^{-16} F, so that $\Delta\mu$ is of the order of 1 meV. Thus, if the scale of thermal fluctuations k_BT is well below $\Delta\mu$ ($T \ll 10$ K in the above example) the single-electron charging can have profound effects on the electron transport properties of systems including small conductors.

Particularly interesting properties were predicted for (and observed in) systems of small conducting particles separated by tunnel barriers - for reviews, see Refs. 2-5, as well as papers by Ingold and Urbina *et al.* in this volume. Here, tunneling of a single electron (or Cooper pair) can essentially influence tunneling of other electrons through the system. The most general term embracing these effects is *correlation* of the single tunneling events. Concrete type of this correlation strongly depends on the type of the system under

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study. In what follows below we will pass through the basic systems of small tunnel junctions, and discuss the most important predictions and observations.

In this discussion we will mostly rely on the so-called "orthodox" theory of the correlated tunneling [2] which is generally in a very good agreement with experiments on metallic samples. In semiconductor samples, considerable deviations from the orthodox theory were revealed, and we will discuss recent extensions of the theory in Sec. 7.

2. Isolated tunnel junction ("Single-Electron Box")

For the simplest system of two small conductors separated by a tunnel barrier the orthodox theory gives a very simple prediction [1]: if the capacitance C of the system as a capacitor and the tunnel conductance G of the junction are small enough

$$C \ll e^2/k_BT, \tag{2}$$

$$G \ll e^2/\hbar, \tag{3}$$

the tunneling is vanishing within the following range

$$-\frac{e}{2} < Q < \frac{e}{2} \tag{4}$$

of the initial electric charge of the system. Physics of this so-called "Coulomb blockade of tunneling" [6] is very simple: if condition (3) is satisfied, the dominating term in the system energy is just the charging energy $Q^2/2C$. It is straightforward to get convinced that within the Coulomb blockade range (4) tunneling of an electron (i.e. the change $Q \rightarrow Q \pm e$) is energy-unfavorable, so that at low temperatures (3) this process is impossible.

The Coulomb blockade manifests itself not only in this particular (simplest) system, but in more complex systems as well. Historically, this effect was noticed in several random systems of metallic grains (for references, see Sec. 4 below). However, until recently, there were no direct experiments with a single "box", because of problem of measurement of the charge Q with a sub-e precision.

Recently, such experiments were carried out by the Saclay group using single-electron transistor (see Sec. 4) as an instrument measuring the charge. This nice work, described in detail in this volume by Urbina *et al.* allowed not only direct observation of the Coulomb blockade, but also detection of a more subtle phenomena, the macroscopic quantum tunneling of electric charge [7], observed earlier by Geerligs *et al.* [8] in more complex systems.

3. Single tunnel junction in an external circuit

If the single tunnel junction is attached to an external circuit, a wider variety of effects is possible. Here impedance $Z(\omega)$ of the external circuit (as seen by the junction) is of a core importance.

If the impedance is low

$$| Z(\omega) | \ll R_Q, \qquad R_Q \equiv \pi\hbar/2e^2 \simeq 6.5\text{k}\Omega \tag{5}$$

at the most important frequencies $\omega \sim e^2/C\hbar$ the quantum fluctuations of charge are much larger than e,

$$< Q^2 > \sim \frac{\hbar}{|Z(\omega)|} \gg e^2, \tag{6}$$

and all correlation effects (including the Coulomb blockade) are completely suppressed. This basic conclusion of the theory [2] is in agreement with the whole body of experimental data accumulated by now, with a single exception of those claimed by the Brighton University group (see the paper by Clark *et al.* in this volume, as well as more detailed descriptions [9,10] of their experiments). We believe that their data are in a need of independent confirmation before they can be taken into account in a meaningful discussion.

If the external circuit impedance is in the intermediate range,

$$R_Q \ll | Z(\omega) | \ll G^{-1} \tag{7}$$

the junction exhibits the Coulomb blockade within the corresponding dc voltage range ($| V | < V_t = e/2C$), but at larger voltages ($| V | < V_t$) there is no correlation between the single-electron tunneling events [11].

The transitional regime $| Z(\omega) | \sim R_Q$, which has been first analyzed by Nazarov [12], and recently attracted much theoretical attention (see Refs. 13-15, as well as the review by Ingold in this collection). Moreover, due to recent advances in fabrication of small-size high-ohmic thin-film resistors, this transitional range is within experimental reach, and several experiments [16-18] gave results which are in fair agreement with the theory, for tunneling both of the single electrons [12-17] and Cooper pairs [15-18].

Note the recent efforts to solve a related problem of the Coulomb blockade destruction due to increase of the junction conductance to $G \sim R_Q^{-1}$ (while $| Z(\omega) | \gg R_Q$). Here theoretical results obtained by various authors (cf., for example, Ref. 19 and the paper by Falci *et al.* in this collection) contradict each other, and no definite experimental results have been obtained so far.

Finally, in the case of large impedances

$$| Z(\omega) | \gg G^{-1} \gg R_Q \tag{8}$$

the external circuit can be approximated as a source of fixed dc current I. This current causes a simple recharging of the junction (i.e. a linear change of Q in time with the derivative $\dot{Q} = I =$ const) inside the Coulomb blockade range. Reaching of the blockade range edge results in tunneling of a single electron (or of a Cooper pair in Josephson junctions with low quasiparticle tunneling rate). As a result of the tunneling, the system finds itself again inside the Coulomb blockade (near its opposite edge) and the whole process repeats. Due to charge conservation, frequency of such a correlated tunneling is fundamentally related to the current I as

$$f_{SET} = I/e \quad \text{for single electrons} \tag{9}$$

$$f_{BLOCH} = I/2e \quad \text{for Cooper pairs} \tag{10}$$

These so-called "Single-Electron-Tunneling" (SET) and "Bloch" oscillations were predicted in the first half of the 1980s (see Refs. 1 and 20-22, respectively), but evaded observation until recently, mainly because it is hard to implement the regime (8) experimentally.

The SET oscillations have been observed in 1989 in more complex multi-junction structures (see below), but not yet in a single junction. Very recently, Kuzmin and Haviland have got quite a convincing evidence of the Bloch oscillations in a single junction (see their paper in this volume). This remarkable work has already led to an interesting controversy concerning interpretation of this phenomenon.

Originally (see, e.g., Ref. 21) the Bloch oscillations were derived as a result of the quantum coherence of states corresponding to various minima of the Josephson coupling energy as a function of the Josephson phase difference φ: $U = -E_J \cos\varphi$. Thus, observation by Kuzmin and Haviland can be interpreted as the first experimental observation of the quantum coherence in macroscopic objects - the fact which is sometimes believed [23] to be of a core significance for foundations of the quantum mechanics.

On the other hand, in a paper being published in this volume, Nazarov and Odintsov argue that the same observation can be interpreted in a completely different way, as an "incoherent" photon-assisted macroscopic quantum tunneling of the Josephson phase.

Our point of view on this subject is that the terms "coherence" and "incoherence" should be better defined, not to be ambiguous in application to this particular problem. Simple mathematics (see, e.g., Sec. 6.3 of Ref. 4) shows that the *both* interpretations of the Bloch oscillations are correct, and the difference between what could be called coherent and incoherent regimes correspond, respectively, to small and large line width $\Delta\omega$ of the oscillations in comparison to the average frequency (10).

4. Two-junction system ("Single-Electron Transistor")

In contrast to the single junction, a system of two small tunnel junctions connected in series can exhibit a considerable correlation of the single-electron tunneling even in the case of small external impedance (5). The reason is that electric charge Q of the middle electrode of this system (common for the both junctions) is not perturbed by quantum fluctuations of charge of the external electrodes. However, these fluctuations destroy the *auto*-correlation of the tunneling events (i.e., destroy the SET/Bloch oscillations in the system), and what remains is just the *mutual* correlation of the tunneling events in the neighboring junctions [4, 24].

According to the orthodox theory, this correlation should manifest itself by several features in the dc $I - V$ curve of the junction:

- Coulomb blockade with a vanishing dc current within some dc voltage range near the origin;
- periodic oscillations of the dc current as the function of the bias voltage V (so-called *Coulomb staircase*) with each period corresponding to injection/removal of one electron to/from the middle electrode;
- linear shift of the Coulomb staircase with respect to the origin in the result of injection of additional electric charge Q into the middle electrode, with $\Delta Q = e$ resulting in the shift by one period.

The first of these features was observed and correctly identified with the single-electron charging in seminal experiments [25,26] carried out in the end of 1960s with granular structures which can be understood as a parallel connection of many two-junction systems with random parameters. (Unfortunately, this randomness did not allow an explicit observation of other two features listed above.) We should again note a remarkable theoretical work by Kulik and Shekhter [27] where two first features of the above list were described quantitatively.

The last feature of the list, which is the most important for applications (see below), remained unnoticed until the more recent work [6]; after that several experimental confirmations of this prediction appeared soon [28,29]. Since then, similar experimental observations were carried out for various physical implementations of the two-junction system.

Of those, notorious are scanning-tunnel-microscope (STM) experiments where the role of the middle electrode is played by small conducting particles (say, metallic droplets) located on a conducting surface. Especially interesting are works where the particles are not intentional but are rather revealed by the STM experiments. In this volume, the paper by Takeuchi *et al.* complements earlier evidence (for its reviews, see Ref. 32 and Sec. 4.2 of Ref. 4) that the high-T_c superconductors are especially apt to forming loose fragments on apparently clean surfaces.

One observation described in this paper, namely microwave-induced steps in the dc $I - V$ curves, at quantized values of the dc current $I = nef$ deserves a special comment. According to the orthodox picture, of the correlated tunneling such steps (which may arise due to phase-locking of the SET oscillations by external signal [2-4]) can appear only in long arrays of tunnel junctions (see below), but not in the two-junction system. It is highly unprobable that such an array could be occasionally formed on the surface of any material. Another way to realize the SET oscillations in the two-junction system is to embed it into a high-ohmic electrodynamic environment (see, e.g., paper by Odintsov *et al.* in this volume), with impedance satisfying the condition (8). However, according to simple electrodynamic estimates, in the STM experiments the external impedance should be of the order of $10^2\ \Omega$, i.e. much *less* than

$R_Q \simeq 10^4\ \Omega$. Presumably, this observation by Takeuchi *et al.* (made on just one sample) should be confirmed in other experiments before it is used as an argument against the orthodox theory.

We should mention also the paper by Krech and Seume of this volume, where the theory of the macroscopic quantum tunneling of charge [7] is reviewed, and a master equation taking this effect into account, is suggested.

5. 1-D arrays

The main characteristic feature of one-dimensional arrays of small tunnel junctions (connected in series) is that they can exhibit *both* mutual ("space") and auto ("time") correlation of the single-electron tunneling events, even if the impedance of the external circuit is much smaller than R_Q and G^{-1} [33]. In particular, it means that at certain conditions the array can exhibit narrow-band SET oscillations (implementation of the Bloch oscillations in arrays is somewhat more tricky [34,35]). Applying an rf drive of frequency f to the array, one can phase lock these oscillations and as a result get a series of "voltage steps" in the dc $I-V$ curve of the system, at quantized values of the dc current I:

$$I = nef \tag{11}$$

This experiment was carried out successfully in 1989 by Delsing *et al.* [36]. In this collection, one can find a description of the further experiments of this group. They have shown that arrays of a slightly different layout exhibit much larger steps than in the first experiments. Theoretical analysis has shown that the most probable reason for this behavior is that the electric field of the external rf drive is partly applied across the array rather than exactly along it. As was shown earlier in experiments [37] (see also the review by Urbina *et al.* in this collection), such perpendicular electric field can provide a more exact fixation of the number of electrons passing along the array during each period, and hence more flat voltage steps (11).

It is very remarkable that in the limit $GR_Q \rightarrow 0$ such an exact quantization of current can be performed by 1-D arrays of only 4 junctions [37] (or even 3 junctions if two rf drives with shifted phases are used [38]). Unfortunately, at finite GR_Q this quantization is not exact due to the macroscopic quantum tunneling of charge [7, 39]. Presumably the only way to suppress this effect exponentially is to increase the number of junctions in the array.

6. 2-D arrays

There is a deep although incomplete analogy between the correlated transfer of single electrons (or Cooper pairs), and the Josephson effect. The latter effect can be interpreted as the correlated transfer of the single quanta of magnetic flux across the Josephson junctions (see, e.g., the monograph [2]). In small Josephson junctions, the analogy can be refined to exact quantum-mechanical duality between these two groups of effects (for more detailed discussion, see Refs. 2,4).

This duality was the main reason to recent interest in behavior of two-dimensional arrays of Josephson junctions; in certain parameter windows, dynamics of these systems can be interpreted as a result of motion of either the Josephson vortices (single flux quanta) or Cooper pair solitons (single electric charges). In this volume this topic is represented by experimental work of van der Zant *et al.* and theoretical papers by Amman *et al.* and Fazio and Schön.

7. Beyond the orthodox picture

Recently, theoretical and experimental work in the field of single-electronics made the first steps beyond the limits of the orthodox theory. The most important new effects are due to energy quantization in the conducting electrodes (in the orthodox theory, the energy spectrum of the electron excitations was assumed to be continuous). Equations describing both the energy and charge quantization were first derived for the case of the mesoscopic metal particles [40], and later they were applied to the semiconductor quantum wells and dots [41] (for a more detailed version of this theory, see Ref. 42). Most remarkable conclusion of these papers was that the discreteness of charge and energy do not exclude each other, and these two effects can coexist. In particular, the two-junction system (see Sec. 4 above) with a discrete energy spectrum of its middle electrode can exhibit dc $I-V$ curves with a superposition of a structure due to this effect, and a quasiperiodic Coulomb staircase.

In order to observe this superposition, transparency Γ_e of the emitting barrier of the structure should be larger than (or at least close to) that (Γ_c) of the collecting barrier. In quantum wells this fact leads to requirement to have initially asymmetrical barriers which should allow relation $\Gamma_e \geq \Gamma_c$ and hence the coexistence of the two effects at a certain polarity of the dc bias voltage. This idea [41] was experimentally implemented recently by Bo Su *et al.* [43], and coexistence of two structures in the dc $I-V$ curves was really observed.

Another possible configuration of the two-junction system is the quantum dot (see, e.g., the review by von Klitzing in this volume), where one can satisfy the condition $\Gamma_e \simeq \Gamma_c$ even in a symmetric structure. Recent remarkable experiments by McEuen *et al.* [44] have allowed a clear observation of the coexistence of the charge and energy quantization in this system, in a nice agreement with theoretical predictions [40-42]. The paper by Hang *et al.* published in this volume describes similar experiments, but with less conclusive results.

Unfortunately, recent work (see, e.g., Ref. 45) on extension of the ideas of the correlated single-electron transfer to the non-tunnel systems were not reflected in these proceedings. One can envision, however, that this direction may bring many interesting results by the next IC SQUID meeting.

8. Applications

Single-electronics promises several important applications in analog and digital electronics (see Refs. 2-5 as well as the recent review [46]). The possible applications include:

- high-precision dc current standards,
- ultra-sensitive electrometry,
- sensitive infrared detection, and
- digital integration circuits of unparalleled density (up to 10^{10} gates/cm^2).

In this volume, these topics are presented by a short paper by Nazarov and Vyshenskii devoted to the last of them, and contribution of Korotkov *et al.* in which ultimate sensitivity of the single-electron electrometers was calculated. Let us hope that the applied single-electronics will be better presented at the nest IC SQUID meeting, and that by that time we will be able to speak about real (rather than possible) applications of the correlated tunneling.

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