Z. Phys. B – Condensed Matter 85, 319–325 (1991)

Zeitschrift für Physik B Condensed Matter

Single charge tunneling: a brief introduction

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Received August 12, 1991

The field of single charge tunneling comprises of phenomena where the tunneling of a microscopic charge, usually carried by an electron or a Cooper pair, leads to macroscopically observable effects. The basic principles governing this area of research are briefly outlined and the present state of the art is discussed.

1. Introduction

The importance of Coulomb charging effects for charge transfer through small systems was first noted several decades ago [1–5]. At that time, Coulomb blockade phenomena could only be observed in granular metallic materials, in which single electron effects and random media properties interplay. Nowadays, modern lithography allows for the controlled fabrication of submicron structures, where metallic islands with capacitances C in the fF range or below are separated by tunneling barriers with resistances R_T well above the resistance quantum $R_K = h/e^2 \simeq 25.8\ \mathrm{k\Omega}$. In such systems, the charging energy $E_c = e^2/2C$ of a single excess electron on the metallic island exceeds the energy $k_B T$ of thermal fluctuations at sub Kelvin temperatures. As a consequence, a Coulomb blockade of tunneling arises [6, 7] which can be exploited to transfer single charges from one island to another in a controlled way [8, 9].

The paragraph above indicates the basic requirements for Single Charge Tunneling (SCT) phenomena to occur. Leaving aside for the moment the special case of a single tunnel junction which will be discussed in the following section, these conditions are as follows. Firstly, the system must have metallic islands that are connected to other metallic regions only via tunnel barriers with a tunneling resistance that exceeds the resistance quantum, i.e.,

$$R_T \gg R_K. \tag{1}$$

This condition ensures that the wave function of an excess electron or Cooper pair on an island is basically localized there. In systems with lower tunneling resistances, charges can be transferred through small islands without paying the charging energy as a penalty, since delocalized states with lower Coulomb energy are available for the transport. Secondly, the islands have to be small enough and the temperature has to be low enough so that the energy required to add a charge carrier to an island exceeds the mean thermal energy of the charge carriers, i.e.,

$$E_c \gg k_B T. \tag{2}$$

This ensures that the transport of charges is in fact governed by the Coulomb charging energy. With the use of externally applied voltages, the charging energy can then be influenced in order to manipulate the charge carriers.

At present, two main types of systems where SCT effects arise are being explored. Much of the work done in the last few years has used lithographically patterned tunnel junction circuits, where metallic islands (mostly made from Al) are separated by oxide layer tunnel barriers. In this case, three-dimensional electron gases confined to small regions are weakly coupled by the tunnel effect. These systems also allow one to explore charging effects involving Cooper pairs since the metals used to fabricate the circuits are superconductors. At the temperatures required to satisfy (2), one must apply a magnetic field to keep the metals in the normal state. Specific examples for such circuits are given in the articles by Haviland et al. [10], Lafarge et al. [11] and Geerligs et al. [12].

Single electron effects also arise when the two-dimensional electron gas of a GaAs/AlGaAs heterostructure is confined to small islands by means of Schottky gates. In this case the tunneling resistances of the constrictions separating the islands can be tuned by changing the gate voltages. Further, the islands may be quantum dots with a discrete energy spectrum. Such semiconductor circuits are presented in the articles by Meirav et al. [13], Kouwenhoven et al. [14, 15], and Glattli et al. [16]. A different structure where electrons tunnel vertically to the plane of the two-dimensional electron gas is discussed by

Ramdane et al. [17]. Apart from these lithographically patterned systems, single charge tunneling phenomena are observed in a number of other cases. There is a large body of work on disordered systems such as granular films [1–5], small metal particles embedded in an oxide layer [18], or disordered quantum wires [19]. Also, one of the tunneling barriers may be formed by a scanning tunneling microscope [20]. Detailed lists of references to earlier studies may be found in the review articles by Averin and Likharev [6] and Schön and Zaikin [7].

This article is not intended to review the field of single charge tunneling: rather, the main issues will be briefly discussed with particular emphasis on subjects covered in this Special Issue. A detailed introduction to this field and a survey of recent activities is given in Ref. 21. In Sect. 2, we discuss single tunnel junctions. The main predictions of the conventional theory are summarized and the disappearance of the Coulomb barrier due to the leads attached to the junction is discussed. Then, in Sect. 3 the basic components of circuits where SCT occurs are described, and possible applications are discussed. Finally, in Sect. 4, we give a short summary.

2. Single tunnel junctions

Charging effects in small capacitance tunnel junctions became a main topic of low temperature physics a few years ago when several new effects due to the quantization of the charge were predicted to arise in both superconducting [22, 23] and normal tunnel junctions [24, 25]. In particular, Likharev and coworkers have expanded the theory of Coulomb blockade phenomena and have proposed various applications of the new effects [6].

The conventional treatment of charging phenomena in ultrasmall junctions starts out from the current-biased tunnel junction [6, 7]. Charging effects result from an interplay between the continuous nature of the charge Q on the junction capacitor and the discrete nature of charge tunneling across the junction. On the one hand, the current I increases the charge Q in a continuous way, i.e., $\dot{Q}=I$, since the charge transferred from the external circuit to the capacitance C is a continuous variable. In fact, Q may be an arbitrarily small fraction of the elementary charge e, caused by a small shift of the electrons in the junction electrodes with respect to the positive ionic background. On the other hand, tunneling through the junction results in a sudden discharge by e or $2e$, depending on whether an electron or a Copper pair is tunneling. For a normal junction, the reduction of the Coulomb energy $Q^2/2C$ by a tunneling event is

$$\Delta E=\frac{Q^2}{2C}-\frac{(Q-e)^2}{2C}=\frac{e\left(Q-\frac{e}{2}\right)}{C}. \tag{3}$$

Now, at zero temperature tunneling can only occur if ΔE is positive, which implies a Coulomb blockade of tunneling for $Q<e/2$. Hence, the current-voltage characteristic of the junction should show a Coulomb gap, i.e.,

$$I=0 \quad \text{for} \quad -\frac{e}{2C}<V<\frac{e}{2C}. \tag{4}$$

Furthermore, the current source will charge the capacitor until the threshold charge $e/2$ is reached. Then, a tunneling transition occurs, leading to $Q=-e/2$, and a new charging cycle starts. This leads to Single Electron Tunneling (SET) oscillations [25] of the voltage with the fundamental frequency

$$f_{\text{SET}}=I/e. \tag{5}$$

By a similar kind of reasoning one predicts for a Josephson junction a Coulomb blockade of Cooper pair tunneling and so-called Bloch oscillations [23] with the frequency

$$f_{\text{Bloch}}=I/2e. \tag{6}$$

This analysis assumes that the tunnel junction can be considered as being independent of its electromagnetic environment, which is represented by an ideal current source. As already mentioned, a charging energy $E_c=e^2/2C$ well above k_BT is only attainable for junctions with capacitances in the fF range or below. However, such ultrasmall junctions are strongly affected by the leads attached to them [26–28]. Firstly, the leads have capacitances that always exceed the junction capacitance by several orders of magnitude. These parasitic capacitances are polarized by the average voltage across the junction and act as an effective voltage source. Secondly, the electromagnetic modes of the leads and external circuit are coupled to the electric field in the junction. As a consequence, the environmental modes influence the charge tunneling rates. Since the typical frequency of tunneling transitions is in the GHz range, the leads can usually be described in terms of a circuit model [29]. The electromagnetic environment is then characterized by the impedance $Z(\omega)$ seen from the location of the junction. These considerations lead to the more realistic junction model of Devoret et al. [27] depicted in Fig. 1.

When charge tunneling rates are calculated for the coupled system formed by the junction and its electromagnetic environment, one finds that no Coulomb blockade occurs under standard experimental conditions. Typical environmental impedances $Z(\omega)$ are of the order of the impedance of free space ($Z_V \simeq 377\ \Omega$), which is small compared to the resistance quantum $R_K \simeq 25.8\ \text{k}\Omega$. The influence of the environment on electron tunneling rates in normal junctions can be described in terms of a function $P(E)$ which gives the probability that the tunneling electron transfers the energy E to the electromagnetic modes of the circuit [27]. For impedances $Z(\omega)$ with $|Z(\omega)| \ll R_K$, one finds $P(E) \simeq \delta(E)$, which means that most tunneling transitions are basically elas-

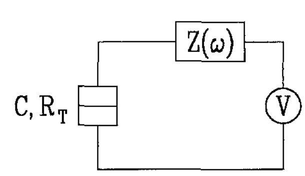

Fig. 1. A realistic model for an ultrasmall tunnel junction and its electromagnetic environment. The junction is attached to a circuit with an impedance $Z(\omega)$ and a voltage source V

tic, i.e., they do not lead to an excitation of the environment. Now, a change of the charge Q on the junction capacitor disturbs the equilibrium between the junction and its environment and thus corresponds to the excitation of electromagnetic modes. Hence, in an elastic transition the electron charge is immediately transferred to the large parasitic capacitances and no change of Q occurs. We thus see that the junction and the leads act like a system with a large capacitance, and the Coulomb blockade is therefore removed. The situation is reminiscent of the Mössbauer effect, where for recoil-less transitions which do not excite the phonon modes, the recoil momentum of the nucleus is transferred to the entire crystal. On the other hand, when the environmental impedance $Z(\omega)$ is of the order of R_K, low-frequency electromagnetic modes are more abundant and they can be more easily excited by a tunneling electron. For an impedance satisfying $|Z(\omega)| \gg R_K$ for all frequencies $\omega \lesssim E_c/\hbar$ one finds at zero temperature $P(E) \simeq \delta(E - E_c)$ [30]. Hence, an electron can only tunnel when it gains at least E_c from the applied voltage, which leads to a Coulomb blockade of tunneling.

The approach by Devoret et al. [27, 30] can equally well be applied to superconducting junctions [31, 32]. Again, the influence of the external circuit is described by the probability $P(E)$ introduced above, which for Cooper pairs is modified slightly since they carry twice the electron charge. In particular, Schön and coworkers [32, 33] have put forward detailed predictions for Josephson junctions. As for normal junctions, charging effects are found to be observable only for environmental impedances of the order of R_K. However, this limit is very hard to achieve experimentally, since a very high resistance has to be placed very close to the junction without causing substantial heating. Remarkable progress in this direction was made by Cleland et al. [34] for normal junctions and by Haviland et al. [10] for Josephson junctions.

These considerations show that single tunnel junctions are not particularly simple systems as far as SCT is concerned. They are certainly of interest for the foundations of the field, but are not suited for practical applications. Further aspects of the theory on the influence of the environment are presented in the articles by Flensberg et al. [35] and Falci et al. [32], and a survey is given by Ingold and Nazarov [36]. The main insight gained from these studies is that ultrasmall tunnel junctions with ordinary metallic leads are well described by a voltage bias except for large voltages of the order of $(E_c/e)|R_K/Z(E_c/\hbar)|$, where a crossover to predominately inelastic tunneling transitions occurs [27, 30]. The corresponding offset of the current-voltage characteristic at large voltages is the principal charging effect observable for single junctions with standard current and voltage leads [37]. Recent theoretical work on single junctions also includes a study of thermoelectric effects by Amman et al. [38]. Conductance anomalies arising from electronic excitations caused by the tunneling of localized charges are predicted in the article by Ueda and Guinea [39]. This last prediction has been questioned, since a charge disturbance due to tunneling is not necessarily localized like the core-hole in the x-ray edge problem.

3. Tunnel junction circuits

As we have seen, charging effects are usually not very important for single tunnel junctions. The leads effectively provide a voltage bias and cause large zero-point fluctuations of the charge Q on the junction capacitor that wash out single charge effects. For multijunction systems the effect of the environment on SCT was studied by Grabert et al. [40], and detailed predictions for several cases were made in subsequent articles by Grabert et al. [30], Maasen van den Brink et al. [33] and Ingold et al. [41]. Provided that the tunneling resistances of the junctions satisfy (1), pronounced charging effects arise in multijunction circuits even for a low impedance environment as a consequence of the charge quantization on the islands between the junctions.

The simplest system showing this quantization of an island charge is the Single Electron Box (SEB) studied both experimentally and theoretically by Lafarge et al. [11]. The island lies between an ultrasmall tunnel junction with capacitance C and an equally small gate capacitance C_G, and the device is controlled by a gate voltage U. The corresponding circuit diagram is shown in Fig. 2. Because of the low impedance leads from the battery to the box, the charges Q and Q_G on the junction and gate capacitors undergo large quantum fluctuations. However, since the two capacitances in series couple to the leads like one capacitance $C_\parallel = CC_G/(C+C_G)$, carrying the charge $Q_\parallel = (C_G Q + CQ_G)/(C+C_G)$, only this linear combination of Q and Q_G is affected by the electromagnetic environment [30], while the island charge

$$q = Q - Q_G = -ne \tag{7}$$

decouples from the leads. The charge q is quantized in units of the elementary charge, and is determined by the number n of electrons in the SEB. To change q an electron has to tunnel through the junction. From the Coulomb energy $q^2/2(C+C_G)$ of the island charge and the work done by the voltage source to restore equilibrium after the tunneling event, one calculates that the electrostatic energy is reduced by

$$\begin{aligned}\Delta E &= \frac{q^2}{2(C+C_G)} - \frac{(q-e)^2}{2(C+C_G)} + \frac{C_G}{(C+C_G)} eU \\ &= \frac{e\left(q + C_G U - \frac{e}{2}\right)}{C+C_G}\end{aligned} \tag{8}$$

when an electron tunnels onto the island. This is very similar to (3), except that the junction charge is replaced

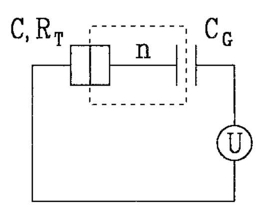

Fig. 2. The single electron box, consisting of a tunnel junction in series with a capacitor. The number n of electrons in the box is controlled by a gate voltage U

by the island charge q which is shifted by the gate voltage. Despite the fact that ΔE depends on the entire circuit, it can be written in terms of the average charge $\langle Q \rangle$ on the tunnel junction. Of course, $\langle Q \rangle$ depends on the applied voltage U. Using simple electrostatics one finds

$$\Delta E = \frac{e}{C}\left(\langle Q \rangle - Q_c\right), \tag{9}$$

where

$$Q_c = \frac{C}{C + C_G}\frac{e}{2} \tag{10}$$

is the so-called critical charge of the junction [8, 30]. As soon as $\langle Q \rangle$ exceeds Q_c an electron can tunnel onto the island. The tunneling rate is given by

$$\Gamma = \frac{1}{e^2 R_T}\frac{\Delta E}{1 - \exp[-\Delta E/k_B T]}, \tag{11}$$

which at zero temperature reduces to

$$\Gamma = \frac{1}{e^2 R_T}\Delta E \quad \text{for } T = 0 \text{ and } \Delta E > 0. \tag{12}$$

According to this simple formula the tunneling rate is determined by the change (8) of the electrostatic energy of the entire system caused by the transition. This so-called global rule rate [42, 43] is found to be very accurate when the tunneling resistance R_T satisfies (1) and the electromagnetic environment is of low impedance [30]. From (12) we see that at zero temperature a transition from n to $n+1$ only occurs for $C_G U > e(n+\frac{1}{2})$. Likewise, one finds for transitions from n to $n-1$ the condition $C_G U < e(n-\frac{1}{2})$. Hence, for sufficiently low temperatures and gate voltages U in the interval

$$e(n-\tfrac{1}{2}) < C_G U < e(n+\tfrac{1}{2}), \tag{13}$$

the state with n electrons in the box is stable. By changing U electrons can thus be added one-by-one to the box. Hence, the SEB is a simple device allowing for the manipulation of a single charge. Further details on this system are given in the articles by Lafarge et al. [11] and Esteve [44]. At the time of this writing, a box for Cooper pairs could not be operated successfully. Since for quasiparticles the threshold voltage for tunneling is always lower than that for Cooper pairs, an island between a Josephson junction and a capacitance will behave like an electron box even when the density of quasiparticles is small.

Another basic device with just one island is the double junction driven by a transport voltage V. Very often a gate capacitor with a gate voltage U is coupled to the island between the junctions. This is the Single Electron Tunneling (SET) transistor [6] with the circuit diagram depicted in Fig. 3. The first observation of SCT in microfabricated samples by Fulton and Dolan [45] was made with this device. SET transistors are also part of more elaborate devices fabricated with oxide layer tunnel junctions [8, 11, 12], and most of the studies on charging effects in semiconductors [13–16] have used this type of circuit.

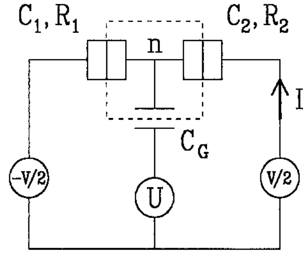

Fig. 3. The SET transistor consists of two tunnel junctions and a gate capacitor with a common electrode. The current I caused by the transport voltage V is controlled by the gate voltage U

In the SET transistor the island can be charged by tunneling across one junction and discharged by tunneling across the other junction, which leads to a net current through the device. If the tunneling resistance of both junctions satisfy (1), the electron transfer rates are again determined by the change of the electrostatic energy of the circuit. In semiconductor devices with a small equilibrium number of electrons in the segment between the junctions, the island may form a quantum dot with an energy level separation that exceeds $k_B T$. Then the energy difference between the Fermi level of the dot and the next available state has to be considered when calculating the energy change. This case is discussed in detail by van Houten et al. [46], and a quantum dot with only a few electrons is considered by Häusler et al. [47]. Experimental results on SCT through a quantum dot are presented in the articles by Meirav et al. [13] and Kouwenhoven et al. [14]. An island in the two-dimensional electron gas with a quasi continuous energy spectrum was studied by Glattli et al. [16].

When the discreteness of the spectrum of electronic states on the island can be disregarded, the energy change due to a transition from n to $n+1$ excess electrons as a consequences of tunneling across the first junction [cf. Fig. 3] is found to be

$$\Delta E_1 = \frac{e\left[\left(C_2 + \frac{1}{2}C_G\right)V + C_G U + q - \frac{e}{2}\right]}{C_\Sigma} \tag{14}$$

where

$$C_\Sigma = C_1 + C_2 + C_G \tag{15}$$

is the capacitance of the island. In (14) the gate voltage U only appears in the combination $C_G U + q = C_G U - ne$, which leads for all measurable quantities to a periodicity in $C_G U$ with period e, since the integer part of $C_G U/e$ can always be absorbed in n. In semiconductor devices this strict periodicity is usually not met because the gate voltage U weakly influences the tunneling resistances of the junctions.

A straightforward analysis of the rate formula (12) shows that at zero temperature the state with n electrons on the island of the SET transistor is stable with respect to tunneling across the first and second junctions for voltages satisfying

$$\begin{aligned} &e(n-\tfrac{1}{2}) < C_G U + (C_2 + \tfrac{1}{2}C_G)V < e(n+\tfrac{1}{2}) \\ &e(n-\tfrac{1}{2}) < C_G U - (C_1 + \tfrac{1}{2}C_G)V < e(n+\tfrac{1}{2}), \end{aligned} \tag{16}$$

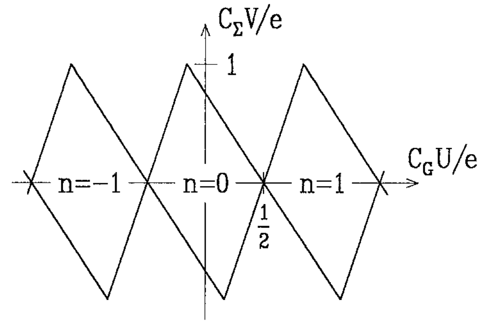

Fig. 4. The stability diagram of a SET transistor with $2C_2 = 10C_G = C_1$

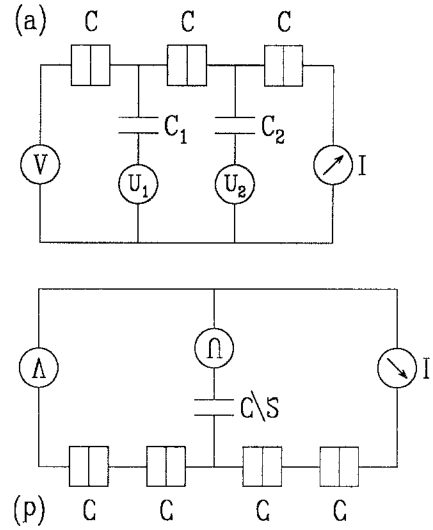

Fig. 5. The circuit diagrams of **(a)** the single electron pump and **(b)** the turnstile, which allow for a transfer of electrons one-by-one

respectively, Hence, in the UV-plane there are rhombic-shaped regions along the U-axis within which the transistor island is charged with a fixed number of excess electrons [cf. Fig. 4]. Inside these rhombi all transitions are suppressed by a Coulomb blockade and no current flows through the device.

For example, near $U = V = 0$ the state $n = 0$ is stable. The inequalities (16) show that whenever the system leaves the stability region of $n = 0$ at a point in the UV-plane with $V \neq 0$ and a tunneling transition, say, to $n = 1$ occurs, the new state is not stable with respect to tunneling across the other junction. Hence, shortly after the first tunneling event an electron leaves the island through the other junction and the system returns to $n = 0$, where the cycle can start again. As a net effect, a current flows through the device. The second tunneling transition of this cycle does not occur at the edge of the Coulomb blockade and part of the change of electrostatic energy is left as kinetic energy of the tunneling electron. Therefore, the transistor is a dissipative element, in contrast to the SEB discussed above which is reversible when the gate voltage is changed slowly.

For voltages V of order E_c/e the current I is very sensitive to U. A small change of the polarization charge $C_G U$ by a fraction of the elementary charge e can change the current from zero to values of the order of E_c/eR_T. This is why the SET transistor can be used as a highly sensitive electrometer [45, 11]. It also could serve as a low-noise amplifier of analog signals. Accordingly, the SET transistor is the basic active element of digital and other applications proposed for SCT [48]. A detailed discussion of the SET transistor is given by Averin and Likharev [6] and further results are presented in the article by Ingold et al. [41]. Since the transistor is a dissipative element, Cooper pairs can usually be transferred only in combined processes involving quasiparticles or environmental modes or both. The complex behavior of the superconducting device is discussed in the article by Maasen van den Brink et al. [33].

At zero temperature and for voltages within the intervals (16), the state with n electrons on the transistor island is stable with respect to tunneling across either junction. However, in the presence of an applied voltage V the state can only be metastable. In fact, Averin and Odintsov [49] have pointed out that second order transitions always lead to a finite current in the presence of an applied voltage. In these co-tunneling events an electron tunnels onto the island while a second electron simultaneously leaves the island across the other junction. Since the charge on the island is only changed virtually, there is no Coulomb barrier for this process. The co-tunneling rate is proportional to $(R_K/R_T)^2$ and hence is a factor R_K/R_T smaller than the rate for first order processes. Accordingly, in more complicated multijunction circuits there are co-tunneling events involving N junctions with rates proportional to $(R_K/R_T)^N$.

Of course, co-tunneling mainly arises when the inequality (1) is only poorly satisfied. However, since the time scale of all SCT processes is proportional to R_K/R_T, very large tunneling resistances severely reduce the speed of devices. That is why a detailed understanding of co-tunneling is of essential importance to the field. Co-tunneling was studied experimentally by Geerligs et al. [50] in small arrays of oxide layer tunnel junctions and by Glattli et al. [16] in a semiconductor SET transistor. A survey of the theory is given by Averin and Nazarov [51]. Electron tunneling across single junctions for arbitrary tunneling resistances R_T is studied in the articles by Zwerger and Scharpf [52] and Scalia et al. [53]. This topic is still open to discussion, in fact, different conclusions on the nature of the crossover from Coulomb blocked to Ohmic conduction are reached in these articles.

More sophisticated multijunction circuits can be built using the SEB or the SET transistor as basic units. Figure 5 shows the circuit diagram of the "pump" and "turnstile" devices fabricated recently by the Saclay and Delft groups [8, 9, 12, 15]. The pump designed by Pothier et al. [9] can be seen as two SEB connected by a tunnel junction. The boxes allow for a control of the input and output of electrons by means of the gate voltages. When the appropriate ac voltages with frequency f are applied to the gates, precisely one electron is transferred per cycle through the device, giving a current

$$I = ef. \tag{17}$$

This relation is the basis of high precision SCT current sources. Since the pump principle employs only reversible processes, it can also be used to transfer Cooper pairs. Experimental results on the pump in the superconducting state are presented in the article by Geerligs et al. [12].

The turnstile designed by Geerligs et al. [8] can be seen as two double junctions connected by a common island. The charging and discharging of this island is controlled by a gate voltage. Again, a current obeying (17) can be generated by means of an ac voltage. In a semiconductor version of the turnstile fabricated by Kouwenhoven et al. [15], the tunneling resistances are modulated via the voltages applied to the Schottky gates. Deviations from (17) mainly arise from finite temperature effects, electron heating, co-tunneling, and moving background charges. These effects must be reduced to achieve a current standard with metrological accuracy. A detailed introduction into the art of manipulating electrons one-by-one is given by Esteve [44] and Urbina et al. [54].

Another class of multijunction circuits studied so far are one-dimensional arrays. Here the work by the Göteborg group recently surveyed by Delsing [55] is most remarkable. Furthermore, two-dimensional arrays show a fascinating interplay between charging effects and collective phenomena. This topic is reviewed in an article by Mooij and Schön [56]. A detailed discussion of these systems would be beyond the scope of this brief introduction to SCT.

4. Conclusion

Single charge tunneling has only recently developed into a field investigated in many laboratories world-wide, partly due to the progress in nanoscale fabrication techniques. Yet this area of research is about to leave its infancy. The main problems still to be overcome have been identified, and it might be appropriate to conclude by speculating about possible applications.

As mentioned above, the SET transistor serves as a highly sensitive electrometer. The sensitivity of existing prototypes already exceeds those of other electrometers by orders of magnitude, and the performance can certainly be improved further. The maximal sensitivity attainable is presently not known, but it should be at least $10^{-5}\, e/\sqrt{\mathrm{Hz}}$. Despite this very high precision, the SET electrometer is for the measurement of electrical charges not quite as revolutionary as the SQUID was for the measurement of magnetic flux. Since there is no analogue of the superconducting flux transformer, the very small input capacitance of the SET electrometer might limit its usefulness.

The pump and turnstile devices demonstrate that SCT can be employed to construct frequency-controlled current sources. The relative uncertainty of the current produced by existing devices is about 10^{-2}, but the error sources are being analysed and improved designs are under investigation. Whether metrological accuracy of 10^{-8} is really achievable is not known, although the prospects are rather promising. Since the ampère is presently

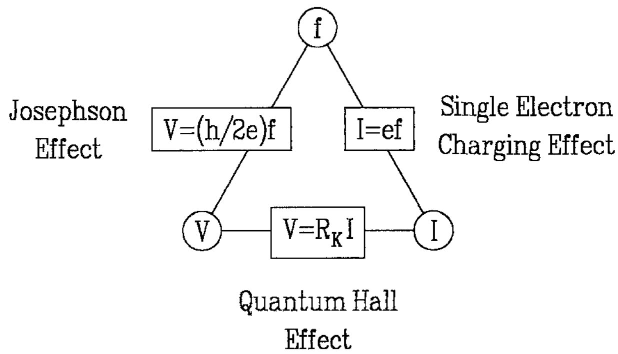

Fig. 6. The quantum metrological triangle formed by the Josephson effect, the quantum Hall effect, and the single electron charging effect

derived from the kilogram, a closure of the quantum metrological triangle (see Fig. 6) could ultimately revolutionize the metrological system, and perhaps do away with the last relic of the Bureau International des Poids et Mesures in Sèvres.

Much of the fascination of SCT derives from the fact that in the future a single bit in an information flow might possibly be represented by a single electron. Although concrete designs are being proposed, the moderate gain of the SET transistor for only a small range of input amplitudes remains a problem, and extensive research would be needed to achieve this goal. However, along the way other striking advances are likely to be made, perhaps even the controlled transfer of fractional charges in semiconductor transistors in the quantum Hall effect regime.

I should like to thank the participants of the NATO Advanced Study Institute on SCT in Les Houches for many inspiring discussions, in particular G.-L. Ingold and the members of the Quantronics Group in Saclay. This work was completed during an extended stay at the Centre d'Etudes de Saclay whose kind hospitality is gratefully acknowledged. Financial support was provided through grants from NATO, the European Community, and the Deutsche Forschungsgemeinschaft. Last but not least, special thanks are due to Springer Verlag for the considerable effort made by its staff to ensure that the original research papers collected in this Special Issue appear in accord with the traditionally fast publication scheme of Zeitschrift für Physik B – Condensed Matter.

References

1. Gorter, C.J.: Physica **17**, 777 (1951)
2. Neugebauer, C.A., Webb, M.B.: J. Appl. Phys. **33**, 74 (1962)
3. Giaever, I., Zeller, H.R.: Phys. Rev. Lett. **20**, 1504 (1968)
4. Lambe, J., Jaklevic, R.C.: Phys. Rev. Lett. **22**, 1371 (1969)
5. Kulik, I.O., Shekhter, R.I.: Zh. Eksp. Teor. Fiz. **68**, 623 (1975) [Sov. Phys. – JETP **41**, 308 (1975)]
6. For recent reviews see: Likharev, K.K.: IBM J. Res. Dev. **32**, 144 (1988); Averin, D.V., Likharev, K.K.: In: Altshuler, B.L., Lee, P.A., Webb, R.A. (eds.) *Quantum effects in small disordered systems*. Amsterdam: Elsevier 1991
7. Schön, G., Zaikin, A.D.: Phys. Rep. **198**, 237 (1990)
8. Geerligs, L.J., Anderegg, V.F., Holweg, P.A.M., Mooij, J.E., Pothier, H., Esteve, D., Urbina, C., Devoret, M.H.: Phys. Rev. Lett. **64**, 2691 (1990)
9. Pothier, H., Lafarge, P., Orfila, P.F., Urbina, C., Esteve, D., Devoret, M.H.: Physica B**169**, 573 (1991)

10. Haviland, D.B., Kuzmin, L.S., Delsing, P., Likharev, K.K., Claeson, T.: Z. Phys. B – Condensed Matter **85**, 339 (1991)
11. Lafarge, P., Pothier, H., Williams, E.R., Esteve, D., Urbina, C., Devoret, M.H.: Z. Phys. B – Condensed Matter **85**, 327 (1991)
12. Geerligs, L.J., Verbrugh, S.M., Hadley, P., Mooij, J.E., Pothier, H., Lafarge, P., Urbina, C., Esteve, D., Devoret, M.H.: Z. Phys. B – Condensed Matter **85**, 349 (1991)
13. Meirav, U., McEuen, P.L., Kastner, M.A., Foxman, E.B., Kumar, A., Wind, S.J.: Z. Phys. B – Condensed Matter **85**, 357 (1991)
14. Kouwenhoven, L.P., van der Vaart, N.C., Johnson, A.T., Kool, W., Williamson, J.G., Staaring, A.A.M., Foxon, C.T.: Z. Phys. B – Condensed Matter **85**, 367 (1991)
15. Kouwenhoven, L.P., Johnson, A.T., van der Vaart, N.C., van der Enden, A., Harmans, C.J.P.M., Foxon, C.T.: Z. Phys. B – Condensed Matter **85**, 381 (1991)
16. Glattli, D.C., Pasquier, C., Meirav, U., Williams, F.I.B., Jin, Y., Etienne, B.: Z. Phys. B – Condensed Matter **85**, 375 (1991)
17. Ramdane, A., Faini, G., Launois, H.: Z. Phys. B – Condensed Matter **85**, 389 (1991)
18. Ruggiero, S.T., Barner, J.B.: Z. Phys. B – Condensed Matter **85**, 333 (1991)
19. Scott-Thomas, J.H.F., Field, S.B., Kastner, M.A., Smith, H.I., Antonadis, D.A.: Phys. Rev. Lett. **62**, 583 (1989)
20. See e.g.: van Bentum, P.J.M., van Kempen, H., van de Leemput, L.E.C., Teunissen, P.A.A.: Phys. Rev. Lett. **60**, 369 (1988)
21. Grabert, H., Devoret, M.H. (eds.): Proceedings of the NATO ASI on *Single Charge Tunneling*, Les Houches, March 1991, New York: Plenum Press 1992
22. Widom, A., Megaloudis, G., Clark, T.D., Prance, H., Prance, R.J.: J. Phys. A **15**, 3877 (1982)
23. Likharev, K.K., Zorin, A.B.: J. Low Temp. Phys. **59**, 347 (1985)
24. Ben-Jacob, E., Gefen, Y.: Phys. Lett. **108**A, 289 (1985)
25. Averin, D.V., Likharev, K.K.: J. Low Temp. Phys. **62**, 345 (1986)
26. Nazarov, Yu.V.: Pis'ma Zh. Eksp. Teor. Fiz. **49**, 105 (1989) [Sov. Phys. – JETP Lett. **49**, 126 (1989)]
27. Devoret, M.H., Esteve, D., Grabert, H., Ingold, G.-L., Pothier, H., Urbina, C.: Phys. Rev. Lett. **64**, 1824 (1990)
28. Girvin, S.M., Glazman, L.I., Jonson, M., Penn, D.R., Stiles, M.D.: Phys. Rev. Lett. **64**, 3183 (1990)
29. For a specific example see e.g.: Martinis, J.M., Kautz, R.L.: Phys. Rev. Lett. **63**, 1507 (1989)
30. Grabert, H., Ingold, G.-L., Devoret, M.H., Esteve, D., Pothier, H., Urbina, C.: Z. Phys. B – Condensed Matter **84**, 143 (1991)
31. Averin, D.V., Nazarov, Yu.V., Odintsov, A.A.: Physica B**165/166**, 945 (1990)
32. Falci, G., Bubanja, V., Schön, G.: Europhys. Lett. **16**, 109 (1991) Z. Phys. B – Condensed Matter **85**, 451 (1991)
33. Maasen van den Brink, A., Odintsov, A.A., Bobbert, P.A., Schön, G.: Z. Phys. B – Condensed Matter **85**, 459 (1991)
34. Cleland, A.N., Schmidt, J.M., Clarke, J.: Phys. Rev. Lett. **64**, 1565 (1990)
35. Flensberg, K., Girvin, S.M., Jonson, M., Penn, D.R., Stiles, M.D.: Z. Phys. B – Condensed Matter **85**, 395 (1991)
36. Ingold, G.-L., Nazarov, Yu.V.: In Ref. 21
37. Geerligs, L.J., Anderegg, V.F., van der Jeugd, C.A., Romijn, J., Mooij, J.E.: Europhys. Lett. **10**, 79 (1989)
38. Amman, M., Ben-Jacob, E., Cohen, J.: Z. Phys. B – Condensed Matter **85**, 405 (1991)
39. Ueda, M., Guinea, F.: Z. Phys. B – Condensed Matter **85**, 413 (1991)
40. Grabert, H., Ingold, G.-L., Devoret, M.H., Esteve, D., Pothier, H., Urbina, C.: In: Cerdeira, H.A., Guinea López, F., Weiss, U. (eds.) Proceedings of the Adriatico Research Conference on *Quantum Fluctuations in Mesoscopic and Macroscopic Systems*, Triest, July 1990. p. 199. Singapore: World Scientific 1991
41. Ingold, G.-L., Wyrowski, P., Grabert, H.: Z. Phys. B – Condensed Matter 85, 443 (1991)
42. Likharev, K.K., Bakhvalov, N.S., Kazacha, G.S., Serdyukova, S.I.: IEEE Trans. Mag. **25**, 1436 (1989)
43. Geigenmüller, U., Schön, G.: Europhys. Lett. **10**, 765 (1989)
44. Esteve, D.: In Ref. 21
45. Fulton, T.A., Dolan, G.J.: Phys. Rev. Lett. **59**, 109 (1987)
46. van Houten, H., Beenakker, C.W.J., Staring, A.A.M.: In Ref. 21
47. Häusler, W., Kramer, B., Masek, J.: Z. Phys. B – Condensed Matter **85**, 435 (1991)
48. Averin, D.V., Likharev, K.K.: In Ref. 21
49. Averin, D.V., Odintsov, A.A.: Phys. Lett. A**140**, 251 (1989)
50. Geerligs, L.J., Averin, D.V., Mooij, J.E.: Phys. Rev. Lett. **65**, 3037 (1990)
51. Averin, D.V., Nazarov, Yu.V.: In Ref. 21
52. Zwerger, W., Scharpf, M.: Z. Phys. B – Condensed Matter **85**, 421 (1991)
53. Scalia, V., Falci, G., Fazio, R., Giaquinta, G.: Z. Phys. B – Condensed Matter **85**, 427 (1991)
54. Urbina, C., Lafarge, P., Pothier, H., Esteve, D., Devoret, M.H.: In: Koch, H. (ed.) Proceedings of SQUID '91, Berlin, June 1991, Heidelberg: Springer (to be published)
55. Delsing, P.: In Ref. 21
56. Mooij, J.E., Schön, G.: In Ref. 21