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Fundamental Metrology by Counting Single Flux and Single Charge Quanta with Superconducting Circuits

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Abstract

Transferring single flux quanta across a Josephson junction at an exactly determined rate has made highly precise voltage measurements possible. Making use of self-shunted Nb-based SINIS junctions, programmable fast-switching DC voltage standards with output voltages of up to 10 V were produced. This development is now extended from fundamental DC measurements to the precise determination of AC voltages with arbitrary waveforms. Integrated RSFQ circuits will help to replace expensive semiconductor devices for frequency control and signal coding. Easy-to-handle AC and inexpensive quantum voltmeters of fundamental accuracy would be of interest to industry.

In analogy to the development in the flux regime, metallic nanocircuits comprising small-area tunnel junctions and providing the coherent transport of single electrons might play an important role in quantum current metrology. By precise counting of single charges these circuits allow prototypes of quantum standards for electric current and capacitance to be realised. Replacing single electron devices by single Cooper pair circuits, the charge transfer rates and thus the quantum currents could be significantly increased. Recently, the principles of the gate-controlled transfer of individual Cooper pairs in superconducting Al devices in different electromagnetic environments were demonstrated. The characteristics of these quantum coherent circuits can be improved by replacing the small aluminum tunnel junctions by niobium junctions. Due to the higher value of the superconducting energy gap ($\Delta_{Nb} \approx 7\Delta_{Al}$), the characteristic energy and the frequency scales for Nb devices are substantially extended as compared to Al devices. Although the fabrication of small Nb junctions presents a real challenge, the Nb-based metrological devices will be faster and more accurate in operation. Moreover, the Nb-based Cooper pair electrometer could be coupled to an Nb single Cooper pair qubit which can be beneficial for both, the stability of the qubit and its readout with a large signal-to-noise ratio.

Keywords : superconducting electronics, single quantum devices, voltage standard, current standard, qubit

I. Introduction

Following the quantum mechanical principle of duality of flux and charge, single quantum electrical devices can be divided into two categories: the first one is governed by the controlled transfer of single flux quanta, $\Phi_0 = 2x10^{-15}$ Wb, and the second one by the transfer of single charge quanta, $e = 1,6x10^{-19}$ C or $2e$, respectively. The fundamental circuit elements of such devices are rather simple (Fig. 1). In the flux regime this is a superconducting ring for storing flux quanta and a Josephson junction for transferring them. As superconductivity is a macroscopic quantum effect, these components may have macroscopic dimensions and their effective output signals are large enough for practical applications such as very sensitive magnetometers (SQUIDs), large series arrays of Josephson tunnel junctions for voltage metrology, and rapid single flux quantum (RSFQ) circuits for digital operation. Basically, single flux components can be manufactured from normal metals or 2DEG semiconductors if their structures are so small that the coherence of the electronic

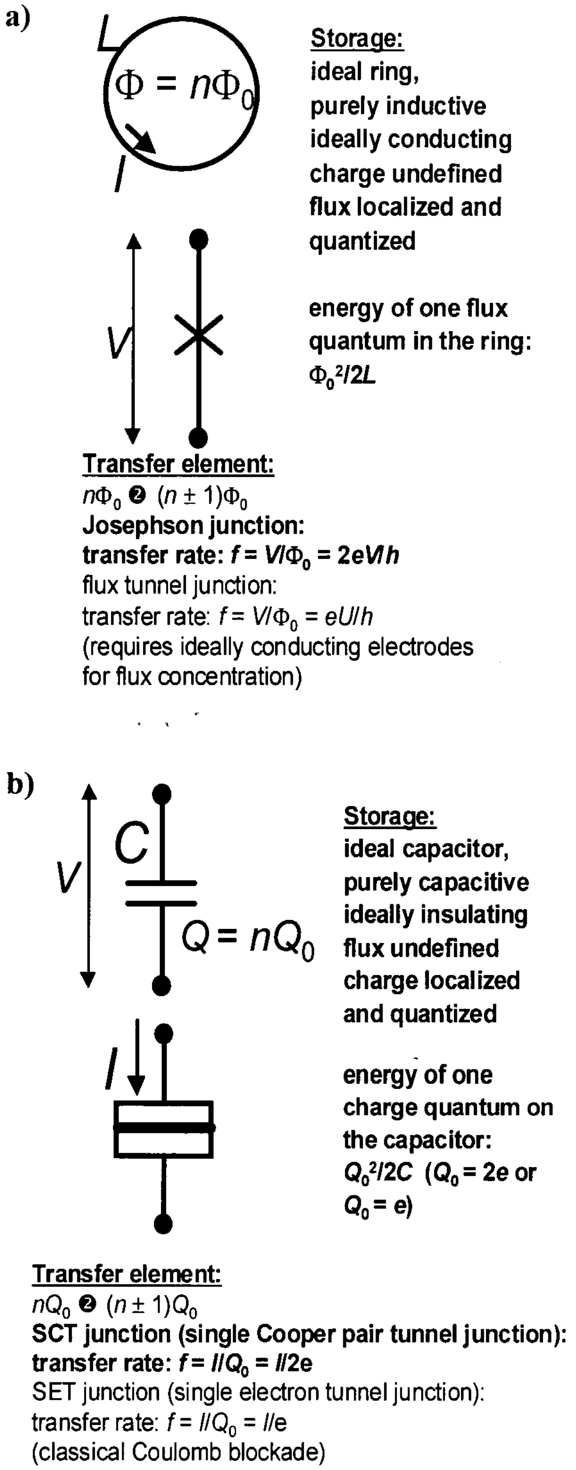

Fig. 1. Basic circuit components for single quantum devices; a) Flux regime, b) Charge regime.

wave functions is maintained over the geometrical dimensions of such a component. In the charge regime the basic circuit components – an ideal capacitor for storing single electrons or Cooper pairs and a tunnel junction for the transfer of single charges – must be of mesoscopic size because the charging energy E_c of the component has to be larger than the energies of thermal and quantum fluctuations. In the case of single Cooper pair devices, the Josephson coupling energy E_j of the junctions and the charging energy E_c of the circuit components must be of the same order of magnitude. Although for practical single charge devices, linewidths smaller than 100 nm have already been reached, operation temperatures less than 100 mK are still to be aimed at. In analogy to the flux regime, sensitive single electron tunnelling (SET) electrometers, SET pumps for quantum current metrology and SET digital devices with extremely low gate energies can be composed of the elementary circuit components.

As flux or charge quanta are precisely defined physical quantities, relevant applications of devices which make use of these properties are expected first of all in the field of fundamental metrology. For an overview, cf. [1]. Fundamental metrology serves the global harmonisation of measuring instrumentation, an important condition for international trade.

II. Single Flux Quantum Circuits

Transferring flux quanta at a well defined rate $f = V/\Phi_0$ across Josephson junctions, connected to large series arrays, is the principle of operation of extremely precise DC voltage standards. These instruments are commercially available and in use as primary voltage standards in most of the national calibration laboratories. An overview is given in [2]. Nowadays, modern technologies on the basis of niobium provide internally shunted Josephson junctions with sufficiently low parameter spread, to be connected to very large series arrays integrated into microwave coupling circuits. The series arrays are divided into binary subarrays. Rapid programmable switches allow the subarrays to be combined in such a way that the desired Josephson reference voltage appears at the circuit output [3]. Fig. 2 shows the design and maximum output voltage of a 8000 junction 1 V quantum voltmeter [4] consisting of an array of 8192 Superconductor-Insulator-Normal metal-Insulator-Superconductor (SINIS) junctions. The advantage of this junction type is its wide range of critical voltages (product of the critical current and of the normal state resistance) up to 200 μV. This allows voltage standard operation at high frequencies like 70 GHz as well as RSFQ circuit operation. Compared with Superconductor-Normal metal-Superconductor (SNS) arrays, the high operation frequency of SINIS circuits allows a considerable reduction of the number of junctions for a given maximum output voltage. Reference [3] describes a 1V SNS junction array of 32768 junctions operated at a frequency of 16 GHz. By means of a 1 V SINIS quantum voltmeter, automatic calibration of Zener references and resistance ratios was performed with high precision.

With SINIS arrays it is technologically possible to increase the output voltage to 10 V. In that case about 70000 junctions must be connected in series(Fig. 3). Constant voltage steps at 10 V were successfully used for the calibration of Zener references. [5].

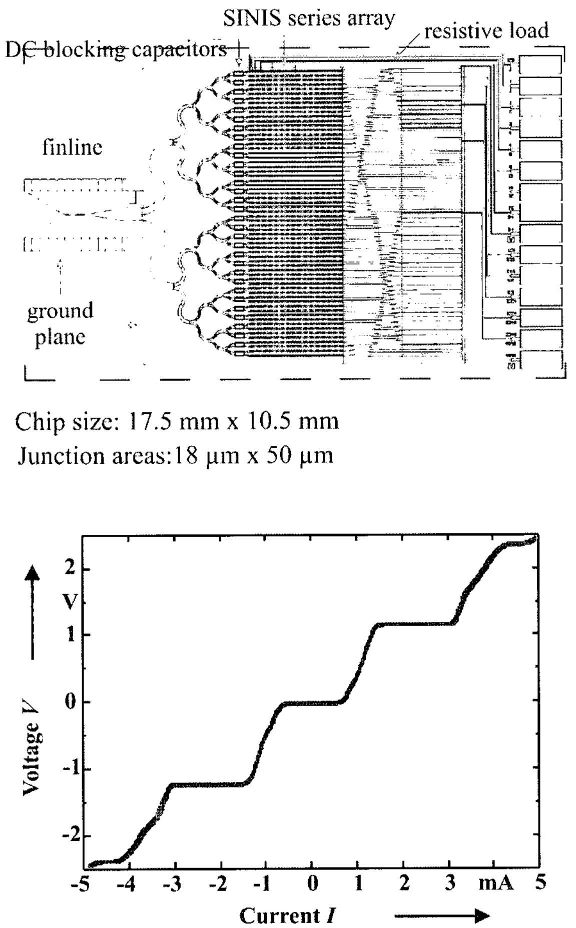

Fig. 2. 1V Quantum Voltmeter with binary subsections and the DC characteristic with the maximum Josephson reference voltage.

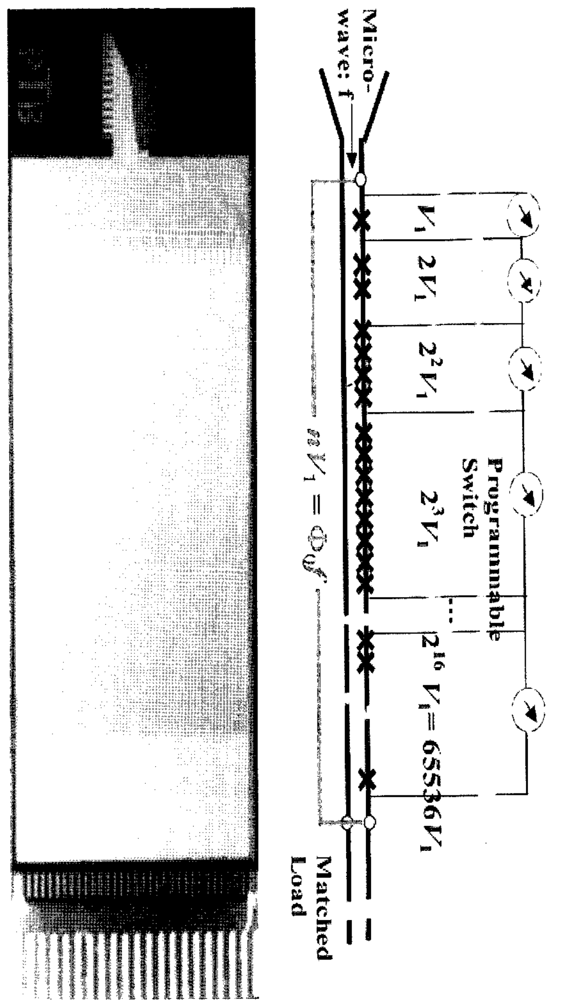

Fig. 3. 10V Quantum Voltmeter chip and schematic diagram of the 10V array with binary subsections.

Quantum voltmeters or voltage standards of this type need a precise HF-frequency control because the exact determination of the rate of transferred flux quanta is decisive for the precision of the instrument. At present, the frequency control is realised by conventional frequency counters which are very expensive for the relevant frequencies between 10 and 100 GHz. It would therefore be useful to develop on-chip superconducting digital electronics for frequency control. Fig. 4 shows a schematic diagram of such a circuit.

A first four bit pulse rate divider is realised in the same SINIS technology as used for the preparation of series arrays for the quantum voltmeter. Moreover, it could be shown that RSFQ circuits of the complexity needed for frequency control have bit error rates (BER) smaller than 10^{-15} which are sufficient for the precision instruments described (Fig. 5) [6].

Unfortunately, programmable voltage standards with binary subarrays cannot be used for high frequency AC voltage measurement or the synthesis of the high frequncy AC voltages with sufficient precision because while switching over the transients between the defined Josephson reference voltages (constant voltage steps in Fig. 2) the output voltage of the device is not well defined. Joint experiments of PTB and NPL with a 1 V SINIS quantum voltmeter indicate that generation of an AC waveform up to 1kHz with 1μV/V should just be possible with the present system. Therefore a bipolar version has been suggested with an adequately coded DC-current bias being switched synchronously with the sinusoidal drive of a series array of internally shunted Josephson junctions [7]. Following the polarity of the DC current bias, the Josephson circuit generates precisely defined pulses ($\pm\int V dt = \Phi_0$) with positive and negative polarity.

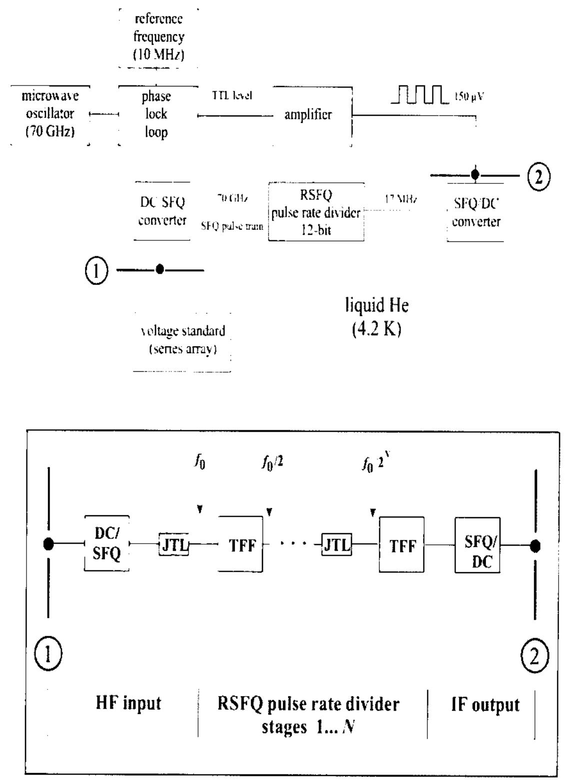

Fig. 4. Block diagram of a Josephson voltage standard with integrated RSFQ frequency control. The lower part of the figure describes the RSFQ module of the standard: TFF (T-flip-flop), JTL (Josephson transmission line).

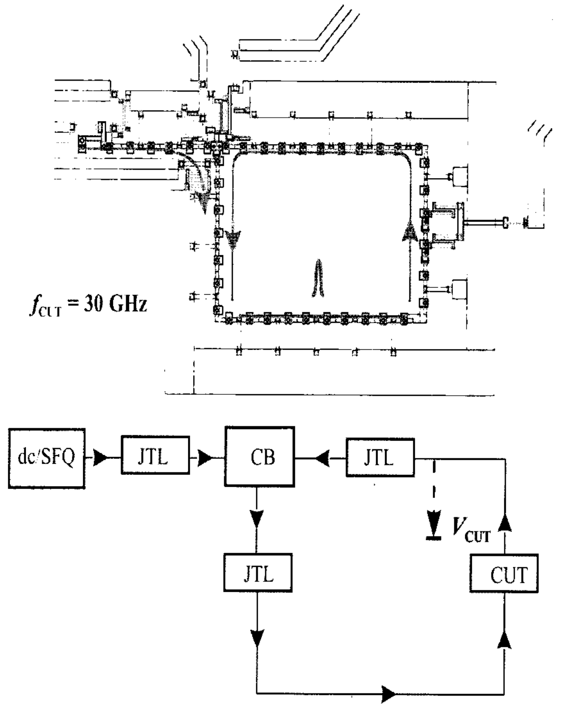

Fig. 5. RSFQ testing device for bit error rates (BER). JTL (Josephson transmission line), CB (confluence buffer), dc/SFQ (DC-SFQ converter), CUT (circuit under test, in this case a Josephson transmission line).

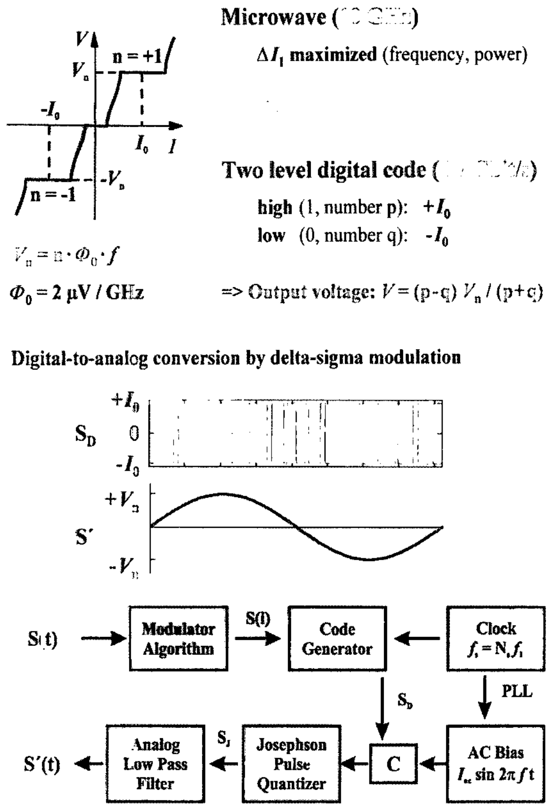

Fig. 6. Operation principle of a bipolar Josephson arbitrary waveform synthesiser.

Averaging the sequences of pulses with negative or positive polarity and filtering of the averaged signal allows AC voltages to be generated with fundamental precision, cf. Fig. 6. At NIST AC voltages with an amplitude of 42 mV at 50 kHz and 120 mV at 4.8 kHz were achieved [8].

A conventional HF-code generator for the DC current bias is very expensive. The construction of a versatile and inexpensive DC and AC quantum voltmeter requires developing an integrated RSFQ version of such a device, which would allow the fabrication of both parts, the array and the coded DC bias, on one chip. A block diagram of such an integrated version of a quantum voltmeter which can also be used as digital-to-analog converter is shown in Fig. 7. The most important part of the device is a circular shift register which allows the two-level digital code of the input signal to be slowly stored and rapidly propagated. A 4 bit SINIS

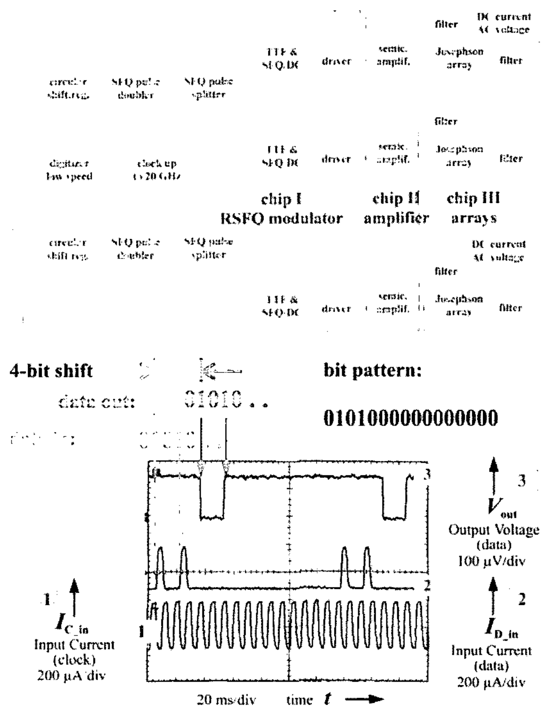

Fig. 7. Block diagram of an AC quantum voltmeter with RSFQ code generator.

version of a circular shift register has successfully been tested (Fig. 7).

This development not only could improve international metrology but would open up a field of application for RSFQ circuits of medium complexity for which their speed and low power consumption is needed and the necessarily low operation temperatures in the range of 4 K are not disadvantageous. The application of the NbN-junction technology for the devices described (and by this the introduction of the operation temperature of 10 K) would support wider application of the instruments described [9, 10]

III. Single Charge Quantum Devices

In contrast to the single flux quantum regime, the application of superconductivity does not lead to macroscopic devices for single electron or single Cooper pair (2e) manipulation. As a result, the development of the mesoscopic metrological circuits for electrometry and quantum current determination is still a matter of basic research. It has been shown that the noise figure of SET electrometers with screened islands can be reduced to $8x10^{-6}$ e/$Hz^{1/2}$. This sensitivity cannot be reached by any conventional electrometer.

In analogy to the flux quantum devices, for precision metrology, the precise counting of single charges for quantum current determination is the most interesting topic. The core element of a quantum current generator is a single charge pump which allows to precisely determine a current by measuring the transfer rate of the electrons: I/e = f. With a single electron pump version, which prevents unwanted co-tunnelling effects to a great extent by mesoscopic resistances at the source and drain of the pump (Fig. 8), a current in the range of a few picoamps could be determined with an uncertainty of 10^{-4} at room temperature [11]. The circuit was manufactured in Al-Al_2O_3 technology.

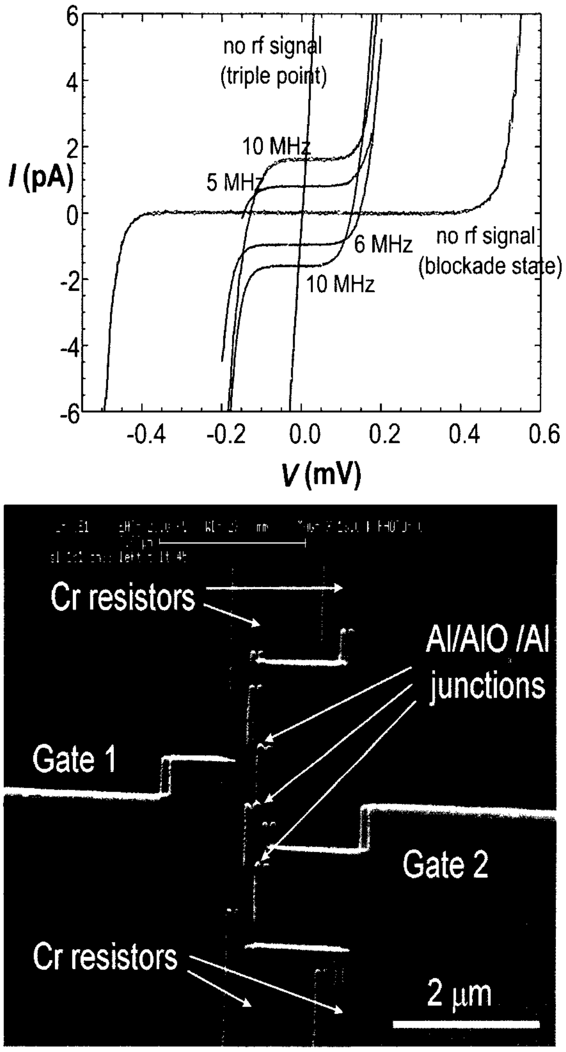

Fig. 8. I-V characteristic and micro-graph of a 3 junction Al-Cr R-pump. $C_j \approx 250$ aF (junction capacitance), $R_j \approx 120$ kΩ (junction resistance), $R_{Cr} \approx 60$ kΩ (on chip resistance), $T_{bath} < 20$ mK.

It was earlier shown that the counting of electrons as measured on chip at low temperatures is precise with an uncertainty of 10^{-8} [12]. This allows a capacitance standard to be constructed in which a cold precision capacitor is charged electron by electron. As a result, the charge on the capacitor is precisely known and if, moreover, the voltage of the charged capacitor is determined by a Josephson quantum voltmeter, the capacitance will be known on a quantum basis.

Unfortunately, for the room temperature realisation of a quantum current, the uncertainty of 10^{-4} is too high by four orders of magnitude. To measure a current of 1 pA with an uncertainty of 10^{-8} means a current resolution of two electrons in about 10 s. It would therefore be very useful to increase the value of the quantum current from the pA- to the nA-range. The easiest way to reach this would be to raise the transfer rate of the electrons from the MHz- to the GHz-range. For the single electron devices presently used this is not possible as the transfer errors would be strongly enhanced with increasing transfer frequency. Only superconducting Cooper pair pumps allow transfer frequencies in the GHz range without the error rate being increased. The key element for superconducting single charge circuits is the shunted Bloch transistor, a small superconducting island with two small Josephson junctions as drain and source. The charge on the island is controlled by a capacitively coupled gate. The circuit and its principle of operation are shown in Fig. 9. The elementary Bloch transistor has been shown to operate together with an SET electrometer circuit [13]. As Cooper pairs tunnel elastically (without dissipation), a simple Bloch transistor shows constant current steps if it is gated by a high

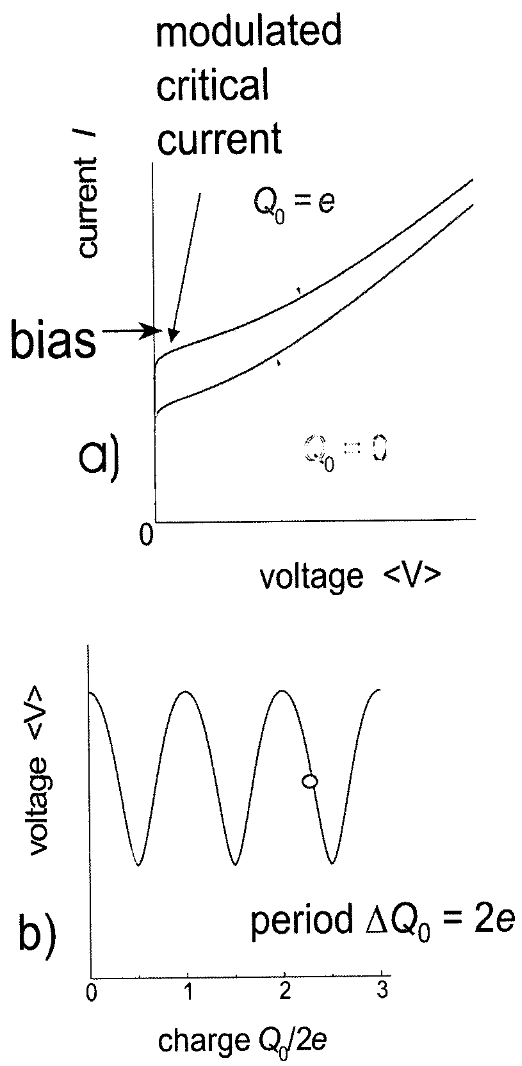

Fig. 9. Operation principle of a Bloch transistor. a) I-V characteristics at different gate voltages, Q_0 (effective charge on the gate). b) Modulation of the I-V with the effective charge on the gate (gate voltage) at the bias current.

frequency signal. High-resistance on-chip resistors (R≈ h/4e2 ≈ 6.5 kΩ) are crucial for the realisation of a unidirectional transport of Cooper pairs (Fig. 10). The circuit is made in $Al\text{-}Al_2O_3$ technology.

For precision metrology Cooper pair pumps with high and precise transfer rates must be developed. It is an interesting question as to whether in analogy to the series arrays for the generation of large quantum voltages in the flux regime, it will be

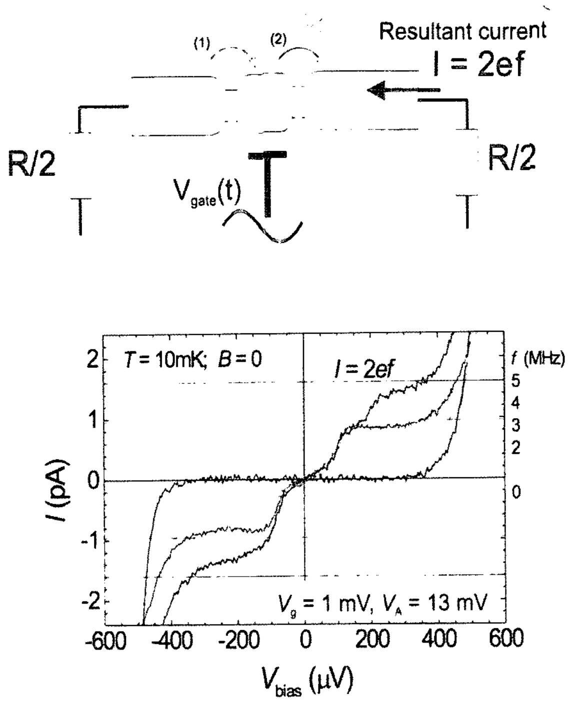

Fig. 10. Schematic diagram and experimental demonstration of sequential resonance tunneling of single Cooper pairs in an $Al\text{-}Al_2O_3$ Bloch transistor.

possible to design and fabricate large parallel arrays of single charge pumps to further increase the quantum current. As such a design has to be realised on a mesoscopic scale, coupling could be realised via the electronic wave function instead of using conventional electromagnetic coupling as in the flux regime. Up to now the problem of the background charges (in analogy to frozen flux quanta) in the insulating circuit parts prevent the possibility of using larger parallel array.

IV. Superconducting Qubit Devices

For the flux regime [14, 15] as well as for the charge regime [16] mesoscopic superconducting circuits with two quantum states representing the information bits "0" and "1" were successfully operated, so far the only available solid state qubit device which can be adapted to an integrated circuit technology. For an overview and more references, cf. [17]. The main problem is to measure a quantum

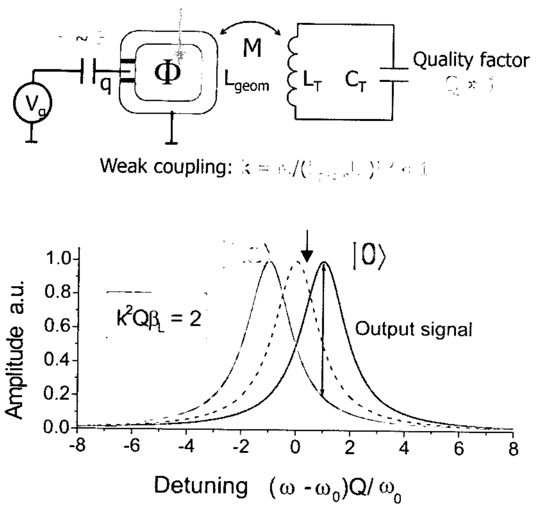

Fig. 11. Operation principle of a qubit with a superconducting readout system (upper part of the figure). Depending on the quantum state of the island (|0> or |2e>) the effective inductance of the superconducting loop $L = L_{geom} + L_{transistor}$ takes either negative or positive values. The variation of L can be measured by the determination of the resonance peaks of the system (loop and tank) (lower part of the figure). ω_0 (resonance frequency of the system), Q (quality factor of the resonance circuit), $k = (M/ (L_{geom}\, L_T)^{1/2}$.

state without destroying the inherent information. So far successful operation of more complex quantum computing circuits depends on the enhancement of the relatively short decoherence times of the present devices. To overcome this problem, a superconducting Bloch transistor as qubit device, integrated into a superconducting ring inductively coupled to a low noise superconducting rf readout system, might be a promising means [18]. The superconducting charge qubit device and the readout principle are shown in Fig.11.

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