

# Electron Pumps and Re-Definition of the SI Unit Ampere

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## Abstract

The upcoming 2011 general conference on weights and measures (CGPM) will consider a proposal to re-define the SI unit ampere by assigning a fixed value to the electron charge  $e$ , while simultaneously releasing the permeability of free space  $\mu_0$  to become a measured parameter. This review provides the background to the proposed re-definition and describes research into electron pumps aimed at supporting it. Particular emphasis is given to recent results on semiconductor electron pumps, which are currently the most promising candidates for metrological current standards.

## 1. Realising the SI Ampere

The present definition of the SI unit ampere, which was adopted in 1960, is as follows: “*The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section and placed 1 m apart in vacuum, would produce between these conductors a force equal to  $2 \times 10^{-7}$  N/m of length.*”. Thus, to realise the ampere, or indeed the volt, in a laboratory requires access to SI units of mass, length and time, and some appropriate electro-mechanical apparatus. Until the early 1970s, the ampere balance, which directly relates the forces between two current-carrying coils, to a mass, was used. Uncertainty in the geometry of the coils, and the distribution of current flow within wires, limited the accuracy of this instrument to a few parts per million (ppm) [1].

Beginning in the 1970s, accurate digital voltmeters began to revolutionise bench-level electrical test and measurement and create a demand for more accurate realisations of SI electrical units [2]. New instruments developed to meet this demand included the absolute liquid electrometer [3] (which yields the volt) and the watt balance [4] (which yields either the volt or the ampere, when used in conjunction with another device, the calculable capacitor). These instruments are capable of uncertainties below 1 ppm, but are extremely arduous to operate successfully, requiring years, if not decades, of effort. In fact, due to the advent of new methods for *representing* electrical units, discussed below, formal *realisations* of the SI ampere, volt or ohm are undertaken rarely.

## 2. Practical quantum standards for voltage and resistance

While the definition of the SI unit ampere is based on 19<sup>th</sup> century classical physics, 20<sup>th</sup> century quantum physics has had an enormous impact on the practical dissemination of electrical units, due to two phenomena: the Josephson effect (JE) and quantum Hall effect (QHE). These effects, dating from 1962 and 1980 respectively, have allowed the development of standards of voltage [5] and resistance [6] with reproducibility better than 1 part in  $10^8$ . Josephson junctions (named after their inventor, Brian Josephson) consist of two superconducting electrodes separated by a thin insulating or normal metal layer. When irradiated with microwaves of frequency  $f_j$ , a dc voltage develops across the junction given by  $V_j = nf_j/K_j$ , where the “step number”  $n$  is an integer and the Josephson constant  $K_j = 2e/h$  where  $h$  is Planck’s constant. Using microfabrication technology, arrays of thousands of junctions can be placed on one chip [5], generating voltages up to 10 V for  $f_j$  of order 100 GHz. The quantum Hall effect takes place in layered semiconductor systems specially engineered to create a 2-dimensional sheet of conducting electrons at the interface between two layers. At low temperatures and high magnetic field, the Hall resistance  $R_H = R_K/i$ , where  $i$  is an integer (in practice either 2 or 4) and the von Klitzing constant  $R_K = h/e^2 \approx 25$  k $\Omega$ . Both the QHE and JE can only be observed at low temperature (around 4.2 K for the JE, 1 K for the QHE), but this has not been a serious impediment to their adoption as primary standards by National Measurement Institutes (NMIs), and even

some large corporations, worldwide. From 1 January 1990 onwards, the metrology community agreed to use standardised values for the constants  $K_J$  and  $R_K$ , known as  $K_{J-90}$  and  $R_{K-90}$  to enable agreement between labs basing their primary standards on the JE and QHE. These values were calculated from the best available measurements of  $K_J$  and  $R_K$  in SI units [7]. Transportable voltage and resistance standards are now routinely calibrated with reference to  $K_{J-90}$  and  $R_{K-90}$  (sometimes termed “1990 units”) with uncertainties of a few parts in  $10^8$ . However, the uncertainties in *SI* volts and ohms, which are determined by mechanical measurements, are somewhat higher: 0.4 ppm and 0.1 ppm respectively.

In 2011, the 24th CGPM will consider a proposal to re-define the SI ampere, by fixing the value of the electron charge, a move which would formally break the link between the electrical and mechanical units. The CGPM will also consider a related proposal, to re-define the kilogram in terms of a fixed value of Planck’s constant  $h$ . To understand the proposed Ampere re-definition, we will now consider in detail a third type of quantum electrical device, the electron pump.

### 3. The electron pump

Electric charge is naturally quantised, with the electron conventionally having one negative charge. However, due to their quantum-mechanical nature electrons in metals and bulk semiconductors lose their individual identity and behave more like a continuous fluid than a flow of discrete particles. It is only when the electrons are forced to jump over an insulating barrier, as happens at a transistor gate or vacuum tube electrode, that they appear to behave as single particles (shot noise, a manifestation of the discreteness of charge, was first observed in vacuum tubes by Schottky in 1918). Throughout the second half of the 20<sup>th</sup> century, increasingly sophisticated techniques were developed for making small electrical devices, and by the mid-1980’s, it became possible to trap and manipulate single electrons in a metal-oxide solid state device [8]. The basic element is a small conducting island (the metal, usually Al), less than 1  $\mu\text{m}$  in size, isolated from the macroscopic source and drain leads by thin insulating barriers (the oxide,  $\text{Al}_2\text{O}_3$ ) just a few atoms thick. Because they obey the laws of quantum mechanics, electrons can tunnel on and off the island, through the insulating barriers, giving rise to current through the device, but these tunnel events are discrete, and unlike in bulk metals the number of electrons on the island is always well defined. By adjusting the voltage on a nearby gate electrode, it is possible to change the number of electrons on the island and modulate the current through the device. Such a “single electron transistor” was first demonstrated in 1987 [9]. Adding the additional complexity of a second island allows the controlled transfer of single electrons through the device. Manipulating the two gate voltages in the correct sequence transfers one electron from the source to the drain, and repetition of this control sequence at a frequency  $f$  produces a current given by  $I_p = ef$ . The first 2-island electron pump was demonstrated, for currents up to a few pA, in 1992 [10].

The electron pump offers a completely new way of defining a unit of current independently of mechanical units, based only on the discreteness of charge, and the ability to accurately measure frequency. This possibility was recognised a few years before the first experimental demonstration of a pump [11]. If the ampere were to be re-defined by assigning a fixed value to the electron charge, operation of the pump would directly realise the unit, constituting what is termed a “*mise en pratique*”, or practical laboratory realisation. Operating the metal-oxide electron pumps requires temperatures of 0.05 K, much lower than the JE or QHE, but such temperatures are realisable using a dilution refrigerator, and starting in the early 1990s a major research effort was mounted at the National Institute of standards and technology (NIST) in the USA, with the aim of developing the electron pump into a workable current standard. It was discovered that to minimise errors, more complex devices than the original 2-island pump were needed. In 1996, NIST scientists demonstrated a pump with 6 islands (and 6 corresponding control signals). By shuttling one electron repeatedly back and forth through the pump, they were able to demonstrate that the pump could transfer electrons with an error rate of only 15 errors per billion pumped electrons [12], a record that still stands to this day, albeit at a low pumping frequency of 5 MHz. Interestingly, when all known error processes were taken into account, the theoretically predicted error rate was many orders of magnitude lower, approximately 1 part in  $10^{20}$ . The source of the errors remains an intriguing unsolved problem and may be due to the relaxation of non-equilibrium charge defects [13].

The metal-oxide pump described above has one key drawback with respect to metrological application: if the control voltages are manipulated too quickly, the electrons can no longer keep up, and the current drops below  $ef$ . The thin insulating barriers, which as noted above are crucial for isolating single electrons, can be represented electrically by a parallel  $RC$  circuit, with  $R$  and  $C$  of order 100 k $\Omega$  and 1 fF respectively. The resulting time constant

of 0.1 ns implies a cut-off of 10 GHz, but to ensure metrological accuracy it is necessary to wait many times  $RC$  in between control pulses, and the maximum pump frequency  $f_{\text{MAX}}$  is restricted to around 10 MHz. This equates to a maximum current of 1.6 pA which is roughly two orders of magnitude too small to constitute a practical current standard. Instead, in 1999 NIST scientists demonstrated a prototype *capacitance* standard by using the pump to charge a capacitor with a known number  $m$  of electrons [14]. A precise measurement of the voltage across the capacitor defined the capacitance according to  $C = me/V$ . The experiment was a technical *tour de force*, but the complexity of cooling, tuning and operating the pump meant that this method could not compete with established methods for realising the farad, and it was not adopted as a primary standard.

#### 4. The semiconductor tunable-barrier electron pump and other approaches

The metal-oxide technology described briefly above is not the only way of creating small conducting islands. Several semiconductor systems exist in which the application of a voltage to a gate electrode depletes the conduction electrons in a channel adjacent to the gate. The most famous example of this effect in action is in the ubiquitous silicon MOSFET. In the 1980's, researchers began to use metallic gates patterned above a gallium-arsenide heterostructure to create artificial atoms, also known as quantum dots: regions of semiconductor roughly 100 nm wide containing a very small number of electrons [15]. The depleted regions below the gates can fulfil the role of the insulating barriers in the metal-oxide devices, with the crucial difference that the barrier transparency (the resistance in the  $RC$ -model) can be varied. The ability to dynamically vary  $R$  raises the possibility of circumventing the  $RC$  limit and raising  $f_{\text{MAX}}$ . During the pump cycle, electrons are transferred across the barrier when  $R$  is small, and the number of electrons on the island is fixed when  $R$  is large. Early experiments showed that the tunable-barrier (TB) pump, as it became known, could indeed be operated at frequencies as high as 1 GHz [16]. Subsequently, detailed investigations of the TB pump have been undertaken at the National Physical Laboratory (NPL) in the UK, and the Physikalisch-Technische Bundesanstalt (PTB) in Germany, and in 2010 the pump was shown to have an error rate less than 15 parts per million at a pump frequency of 340 MHz ( $I_p = 54$  pA) [17]. Experiments currently underway at NPL are aimed at verifying the pump accuracy below the 1 ppm level for currents up to 100 pA. Establishing  $f_{\text{MAX}}$  is considerably more complex than for the metal-oxide pumps. For  $f$  of the order 1 GHz and above, electrons are lost from the TB pump via a process termed "quantum spillage" [18], which cannot be modelled using an equivalent electrical circuit such as the  $RC$  circuit representing a tunnel barrier, and can only be understood in terms of the response of quantum-mechanical particles to a rapid change in their environment. Very recently it was discovered that the quantum spillage process can be suppressed by applying strong magnetic fields  $> 10$  T [19], and the ongoing strong research effort into the TB pump at NPL and PTB is motivated by the strong possibility that the TP pump could generate accurate quantised currents as large as 1 nA.

Three other types of electron pump are under investigation and worthy of mention. The "hybrid turnstile" developed at Aalto university in Finland, is related to the simple single-electron transistor, but with the key difference that the island is superconducting while the leads are metallic (or vice versa) [20]. It has not yet demonstrated the same pumping accuracy as the TB pump, but it is easier to fabricate multiple turnstiles with the same operating parameters, such that they can be driven by common control signals. Taking advantage of this property, 10 hybrid turnstiles have been fabricated on one chip and operated in parallel [21]. An extreme type of parallel operation has recently been achieved by a group at ETH Zurich. They used an array of millions of self-assembled quantum dots, each just a few nm in size, optically driven by a laser pulsed with a repetition rate up to 100 kHz. Each laser pulse ejects one electron from each dot, and the very large number of dots means that currents of up to 100 nA can be generated [22]. The difficulty is knowing exactly the number of active dots in the device, and it is not clear that metrological accuracy can be achieved. Nonetheless it remains an exciting and novel approach, worthy of further investigation. Finally, an exotic possibility is the quantum phase-slip (QPS) device, proposed theoretically in 2006 [23]. This is the quantum mechanical "dual" to the Josephson effect, and could be realised experimentally using ultra-narrow superconducting wires. Ongoing research at NPL and PTB is aimed at demonstrating the feasibility of this approach.

### Conclusions

The development of current standards based on controlled single electron transfer is a major ongoing research topic in fundamental metrology, with the aim of supporting a future re-definition of the base unit ampere. The semiconductor tunable-barrier pump represents the current state-of-the-art in metrological pump research, able

to output currents of order 100 pA with an accuracy of 10 ppm. Experimental demonstration of sub-ppm accuracy is expected in the near future. Currently available data on pump accuracy is unlikely to justify an ampere re-definition in 2011, but there is a strong possibility of a re-definition being agreed at the next CGPM meeting in 2015.

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