A Practical Josephson Voltage Standard at One Volt

This paper [1] is considered the seminal, definitive paper describing the revolutionary one-volt Josephson-junction array standard. NIST changed forever high-accuracy voltage measurements with this development, which built on earlier work at NIST and a microwave feed design from the then West German standards laboratory, Physikalisch-Technische Bundesanstalt (PTB). The basic element of the array is the Josephson junction, in the form of a superconductor-insulator-superconductor sandwich. When irradiated with microwave energy, such a junction exhibits a dc potential uniquely determined by the frequency of the radiation, the electronic charge, and Planck's constant, with a single junction providing a few millivolts. In other words, a Josephson junction can act as a superb frequency-to-dc voltage converter. A properly designed and fabricated array of junctions can be excited to produce a series of very accurate quantized voltages, or steps.

As developed and demonstrated by the NIST team [1-8], a Josephson-junction-based voltage standard system consists of microwave source and feed, cryostat, probe, chip, and readout and control system. Microwave energy is fed into the chip mounted in the probe's chip carrier and cooled by liquid helium. The array standard microchip is fabricated by techniques analogous to those used to fabricate silicon integrated circuits, although with very different material systems.

For almost 80 years, starting in 1901, the U.S. Legal Volt was maintained by several groups of standard cells. There was a large effort in the late nineteenth century and the early twentieth century to establish a standard for electromotive force (emf) based on electrochemical reactions within chemical cells. The first legal unit of voltage for the United States was based on the Clark cell, developed by Latimer Clark in 1872, with its output assigned a value of 1.434 international volts by the 1893 International Electric Congress. Public Law 105, passed by the U.S. Congress in 1894, made this the legal standard of voltage in the U.S. During the years between 1893 and 1905, the standard cell devised by Edward Weston was found to have many advantages over the Clark cell [9]. The Weston cell consists of a cadmium amalgam anode and a mercury-mercurous sulfate cathode with a saturated cadmium sulfate solution as the electrolyte. In 1908, at the London International Conference on Electrical Units and Standards, the Weston cell was officially adopted for maintaining the volt. After 1908, only Weston cells were used for maintaining the national standard in the United States.

The Weston standard cell can be disturbed by transport or if it is subjected to a change in temperature or a small electrical current. When at times it was necessary to eliminate cells—due to changes in emf of a cell relative to the mean of the group—new cells could be added. In 1965 the National Reference Group of standard cells [10] included 11 cells made in 1906, seven cells made in 1932, and 26 cells made in 1948. Long-term stability of the volt reference was also maintained by comparisons of neutral and acid cells, preparing and characterizing new cells, and through international comparisons and absolute ampere and ohm experiments. According to Driscoll and Olsen [11], the results of the absolute current-balance measurements could be regarded "as assigning a value to the emf of the standard cell used to control the strength of the current" and as a check on the emf of the NIST standard cell bank. The use of the Weston cell as the national standard of voltage was supported by a considerable amount of research in electrochemistry and related fields at NBS.

Before the Josephson effect was discovered, it was difficult to provide incontrovertible evidence regarding the long-term stability of the U.S. Legal Volt. However, considerable evidence indicated that the unit of emf preserved with standard cells was unlikely to have changed by any significant amount, relative to the best measurements of the time, from the early 1900s to the 1960s.

In the late 1950s, research in solid-state physics stimulated the growth of the semiconductor industry. A new type of voltage standard based on a solid-state device, the Zener diode, appeared in the early 1960s. W. G. Eicke at NBS first reported the possibility of using Zener diodes as transport standards [12]. In the following years, after several manufacturers started making commercial Zener voltage standards, these references began to replace standard cells in commercial use. Although Zener voltage standards exhibit higher noise characteristics than standard cells and are affected by environmental conditions of temperature, atmospheric pressure, and relative humidity, they are now widely used in many metrology laboratories because of their robust transportability.

In 1962, Brian Josephson, a graduate student at Trinity College, Cambridge, England, predicted that electrons can tunnel in pairs (Cooper pairs) between two superconductors separated by a thin insulating barrier (a weak link or Josephson junction). An applied dc voltage V across the barrier would generate an ac current at the frequency $f = 2eV/h$, where e is the elementary charge and h is Planck's constant. Conversely, an applied ac current of frequency f would generate a dc voltage V_n at the quantized values

$$V_n = nhf/2e \ ,$$

where n is an integer and the value of $2e/h$ is approximately 483.6 MHz/μV.

One of the issues was whether this relationship was materials independent. In 1968 Parker, Langenberg, Denenstein, and Taylor [13] compared, via a potentiometer, the Josephson voltages of junctions consisting of five different superconducting materials and various combinations of thin-film tunnel junctions or point contacts with 1.018 V Weston saturated standard cells [10] calibrated by NBS. They obtained a value of $2e/h$ with a one-standard-deviation fractional uncertainty of 3.6×10^{-6}.

It was argued on fundamental grounds that the above must be exact. The use of superconducting-quantum-interference device (SQUID) null detectors in the early 1970s allowed this to be tested to a few parts in 10^9, and thus the Josephson effect had obvious potential for use as a voltage standard [14]. By the early 1970s, NIST staff had set up a potentiometric measurement system in Gaithersburg that compared 2 mV to 10 mV dc Josephson junction voltages with 1.018 V standard cells to a few parts in 10^8 [15,16]. International comparisons in 1971-72 among national metrology institutes (NMIs), including NBS, the National Physical Laboratory (NPL) in the U.K., the National Research Council (NRC) in Canada, the National Standards Laboratory (NSL) in Australia, and the Physikalisch-Technische Bundesanstalt (PTB) in Germany, as well as the International Bureau of Weights and Measures (BIPM), found that the measured values of $2e/h$ agreed with each other to within 2×10^{-7} [17].

These results from the NMIs suggested the course of adopting a value of $2e/h$ for use in maintaining units of voltage. The United States was the first nation to do this, and the value of $2e/h$ to be used at NBS was chosen to prevent a discontinuity when NIST converted from standard cells to the Josephson effect [18]. NBS began maintaining and disseminating the U.S. volt based on the Josephson effect in July 1972, using a 10 mV measurement system with relative uncertainty of 2×10^{-8}. Soon after, the Consultative Committee on Electricity (CCE) of the CIPM recommended the value $K_{\text{J-72}} = 483\,594$ GHz/V, which was adopted by all countries except the United States, France, and the Soviet Union.

In many applications, Josephson junctions were undoubtedly better references than standard cells, which are sensitive to environmental conditions, can shift values on transport, and can drift by a few parts in 10^8 per year. The typical 5 mV to 10 mV reference output from early Josephson devices made from a few junctions required both very low-level voltage balances and scaling by a factor of 100, both of which seriously limited the accuracy of measuring 1.018 V standard cells.

Then in 1977, M.T. Levinson and colleagues showed that unbiased Josephson junctions would spontaneously develop quantized dc voltages when irradiated with microwaves, opening the path to successful Josephson junction arrays. C. A. Hamilton, R. L. Kautz, F. L. Lloyd, and others of the NBS Electromagnetic Technology Division at Boulder began developing and improving Josephson standards based on series arrays of junctions operated near zero dc voltage bias [3,19].

Stable 1 V zero-crossing arrays were operating at NBS [1] and PTB [20] by 1985, using about 1500 junctions and rf fields of 70 GHz to 90 GHz. Arrays with output voltages at the level of 1 V soon were used in NMIs throughout the world [21]. By 1989, NIST had made a 19 000 junction, 12 V array [2]. The widespread use of Josephson junction arrays in national standards laboratories, and better SI determinations of $2e/h$, led the CCE to recommend a new exact conventional value for the Josephson constant:

$$K_{\text{J-90}} = 483\,597.9 \text{ GHz/V} \, ,$$

which is fractionally larger by 8×10^{-6} than the 1972 conventional value. The new value was adopted worldwide on January 1, 1990, and thereby became the new basis for the U.S. Legal Volt. This definition of $K_{\text{J-90}}$ is the present volt representation, based on an ideal Josephson voltage standard. The conventional value was assumed by the CCE to have a relative standard uncertainty of 0.4 μV/V. By convention, this uncertainty is not included in the uncertainties of the representation of the volt, since any offset from the SI volt will be consistent among different laboratories using the Josephson effect standard.

The term "intrinsic standard" is sometimes used to describe a type of standard, such as a Josephson Voltage Standard (JVS), quantum Hall resistance standard, triple point cell, deadweight pressure gauge, etc., based on physical laws rather than on the stability of physical

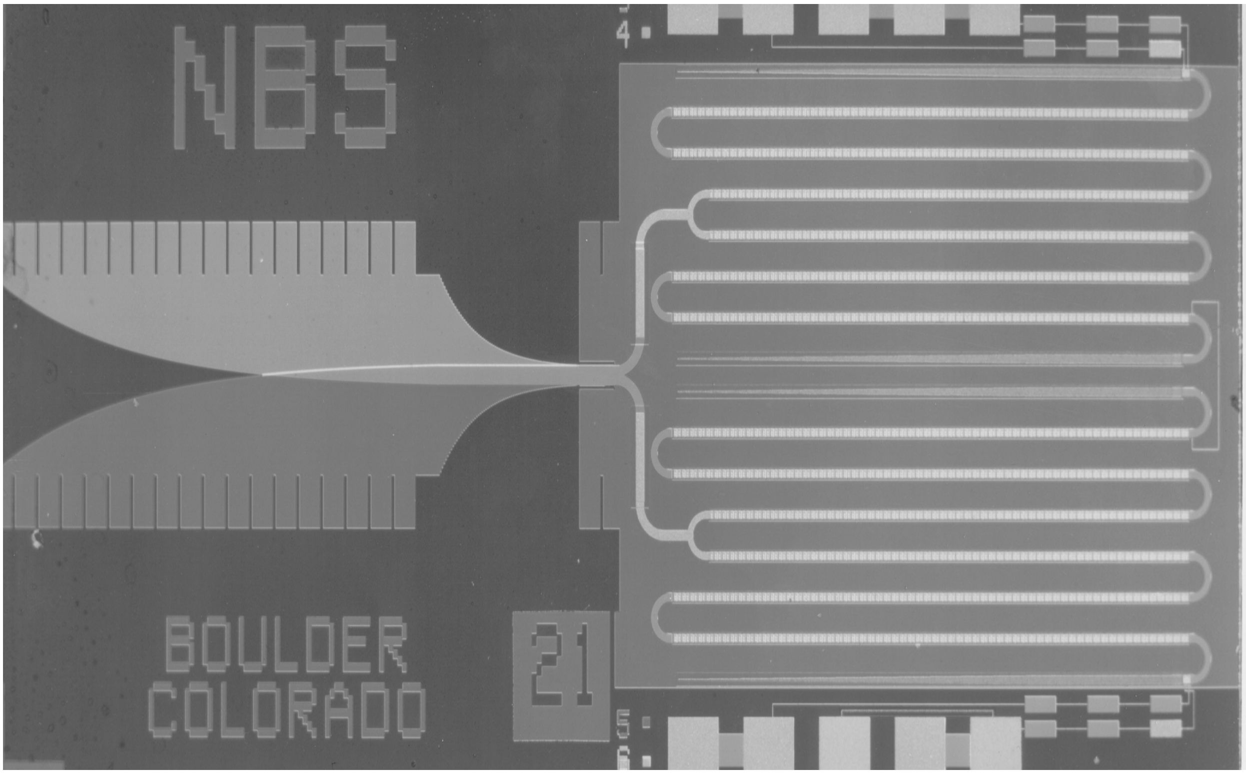

Fig. 1. One-volt NIST Josephson Junction array standard having 3020 junctions. The chip was designed and built by staff of the Electromagnetic Technology Division in Boulder in the cryoelectronic fabrication laboratory. It operates at liquid-helium temperatures; microwave energy is fed to four chains of junctions through the finguide structure at the left. The thin tapered structures at the end of each chain are terminations to prevent reflection of energy back up the chain.

artifacts that depend on bulk materials properties. There are approximately twenty industrial and military calibration laboratories throughout the United States that operate a JVS as a basis for traceable calibration measurements. The JVS consists of many cryogenic and microwave components, and each of these, as well as the environment and the user technique, can contribute uncertainty to the voltage measurement. Accordingly, it is necessary to make intercomparisons among independent JVS laboratories, to ensure the correctness of the measurements in these laboratories, just as it is at the international level. In 1991 NIST conducted the first JVS laboratory comparison experiment using transportable 10 V Zener standards, in which five other U.S. industrial and military laboratories participated [22]. Such comparisons are now carried out regularly under the auspices of the National Conference of Standards Laboratories, an industry trade association, with support from NIST as necessary.

Prepared by Y. Tang, N. B. Belecki, and J. F. Mayo-Wells based on excerpts from the paper The Ampere and Electrical Units *[23], authored by members of the Electricity Division.*

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