Chapter 6

The Josephson Voltage Standard

6.1 Voltage Standards

History:

- **1800:** ***Alessandro Volta*** developed the so-called ***Voltaic pile***
  - forerunner of the battery (produced a steady electric current)
  - effective pair of dissimilar metals: **zinc** and **silver**.

- **in the 1880s:**
  - the ***International Electrical Congress*** (now the International Electrotechnical Commission -IEC) approved the volt as the unit for electromotive force:
  - the volt is defined as ***the potential difference (voltage) across a conductor when a current of one ampere dissipates one watt of power***

Alessandro Volta

- **1983:** the international volt is defined as ***1/1.434 of the emf of a Clark cell***

- **1908:** definition based on the Ohm and Ampère until the entire set of "reproducible units" was abandoned in 1948 ➔ ***introduction of MKSA system***

- prior to the development of the Josephson junction voltage standard, the volt was maintained in national laboratories using specially constructed batteries called ***standard cells***.
  The United States used a design called the ***Weston cell*** from 1905 to 1972.

6.1 Voltage Standards

Definition of the volt:

- a single volt is defined as the ***difference in electric potential across a wire when an electric current of one ampere dissipates one watt of power***
- it is also equal to the ***potential difference between two parallel, infinite planes spaced 1 meter apart that create an electric field of 1 Newton per Coulomb***. Additionally, it is the potential difference between two points that will impart one Joule of energy per Coulomb of charge that passes through it.
- it can be expressed in terms of SI units as follows:

$$\mathrm{V} = \mathrm{A} \cdot \Omega = \frac{\mathrm{W}}{\mathrm{A}} = \sqrt{\mathrm{W} \cdot \Omega} = \frac{\mathrm{J}}{\mathrm{A} \cdot \mathrm{s}} = \frac{\mathrm{N} \cdot \mathrm{m}}{\mathrm{A} \cdot \mathrm{s}} = \frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{C} \cdot \mathrm{s}^2} = \frac{\mathrm{N} \cdot \mathrm{m}}{\mathrm{C}} = \frac{\mathrm{T} \cdot \mathrm{m}^2}{\mathrm{s}} = \frac{\mathrm{J}}{\mathrm{C}}$$

- it can also be written using only the SI base units m, kg, s, and A as:

$$\mathrm{V} = \frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{A} \cdot \mathrm{s}^3}$$

6.1 Voltage Standards

Practical realization of the volt:

- the original definition is difficult to implement in practice
  ➔ ***use of standard cells and later Josephson voltage standard***
- between 1990 and 1997, the volt was calibrated using the Josephson effect for exact ***voltage-to-frequency conversion***, combined with cesium-133 time reference, as decided by the 18th General Conference on Weights and Measures. The following value for the Josephson constant is used:

$$\mathrm{K}_{J-90} = \frac{2e}{h} = \frac{1}{\Phi_0} = 483\ 597\ 910\ \frac{\mathrm{Hz}}{\mathrm{mV}}$$

- this is typically realized with an array of several thousand or tens of thousands of junctions, excited by microwave signals between 10 and 80 GHz (depending on the array design)
- empirically, several experiments have shown that the method is ***independent of device design, material, measurement setup, etc.,*** and no correction terms are required in a practical implementation

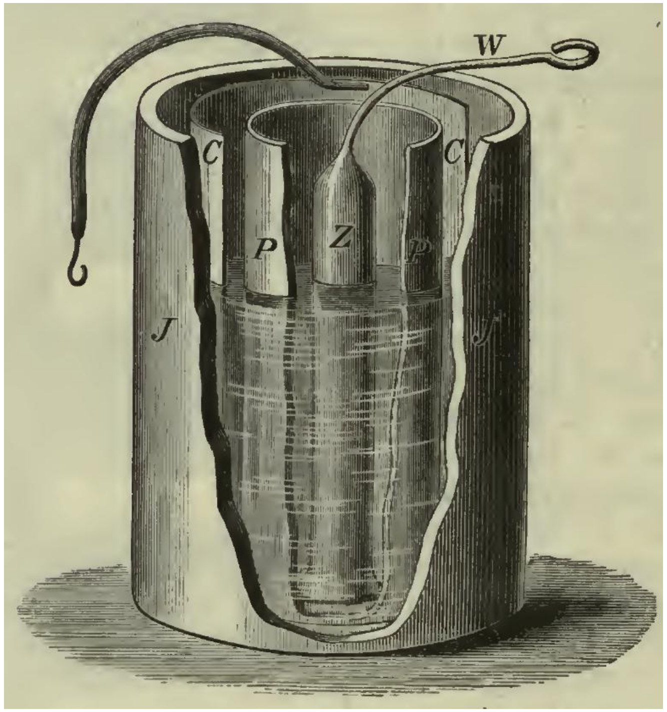
6.1 Voltage Standards

6.1.1 Standard Cells and Electrical Standards

- original ideas by ***Galvani***, first practical realization by ***Volta*** in 1794 (Zn-Ag)
- ***Zn-Cu Daniell cell*** (1834), output voltage ≈ **1.1 V**
  → stable cell, suitable for maintaining and disseminating the unit volt

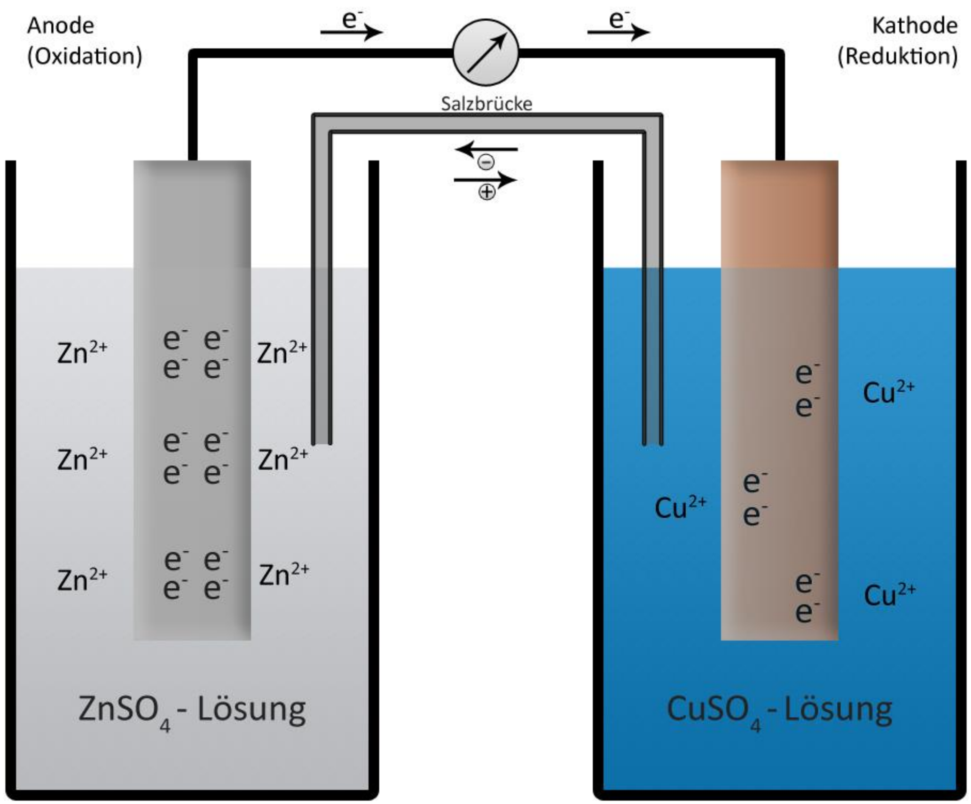
Photo: King's College London

John Frederic Daniell
(1790 – 1845)



6.1 Voltage Standards

6.1.1 Standard Cells and Electrical Standards



Zn-Cu Daniell cell (1834)

The E. M. F. of a Daniell's cell, and of all its modifications, is roughly ***1.1 V***, but it varies from about ***1.07 V*** to ***1.14 V***, depending on the densities of the solutions of copper and zinc sulphate.

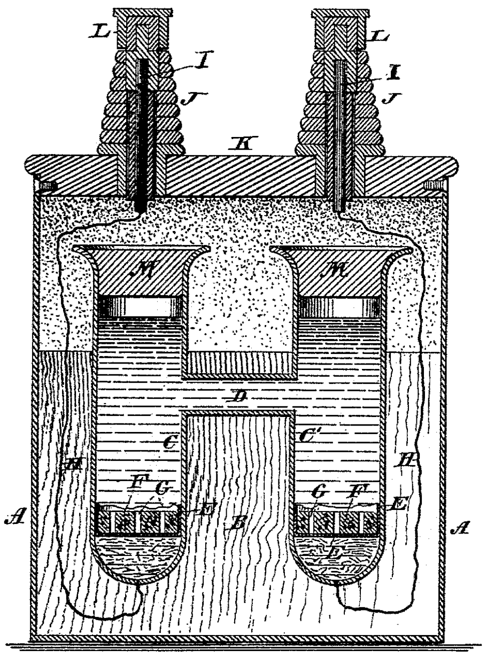
- ***Cd-Hg Weston cell***

  - output voltage: **1.0186 V**

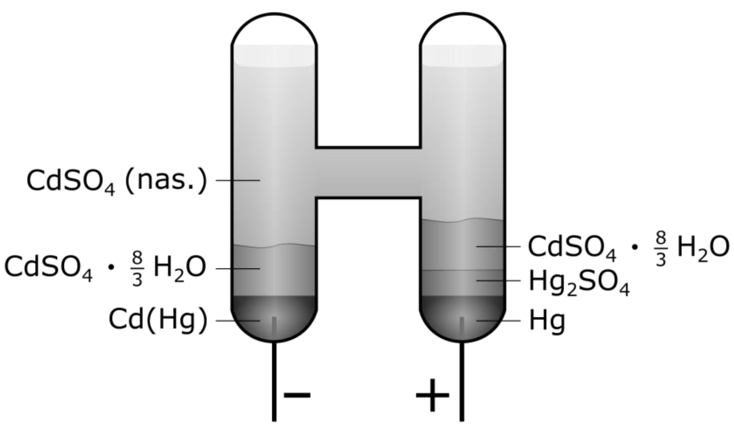
  - used as standard since 1908

  - problem:
    sensitive to external parameters
    (e.g. *T*, *I*, motion, ….)

  - note:
    since 1948: SI-system (MKSA)
    → ***cells only used for laboratory realization of volt***



Edward Weston: US Patent 494827



6.1.1 Standard Cells and Electrical Standards

electrochemical cell 1972

(photo: NIST Boulder)

6.1.2 Quantum Standards for Electrical Units

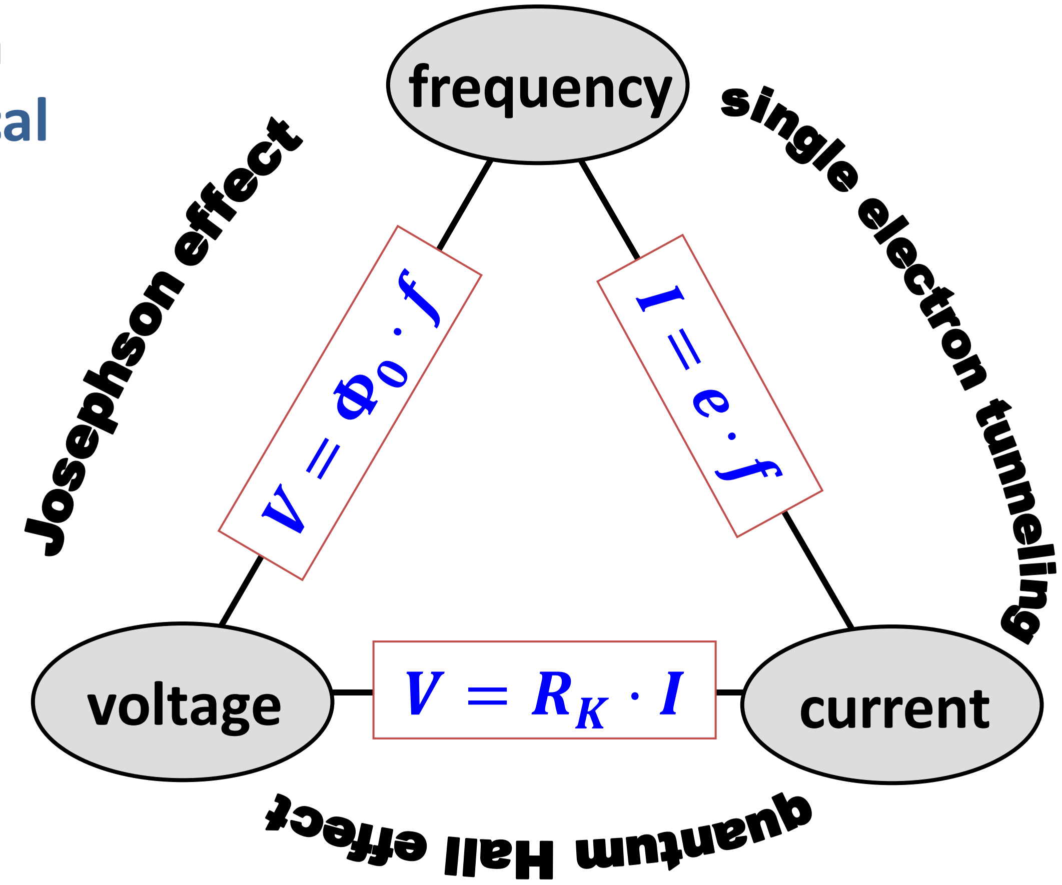
- ***problems with standard cells:***
  - damaging by improper handling
  - dependence on external parameter
  - difficult international comparison due to transport problems

- ***solution:***
  - standards based on quantum effects
    → realization of unit is linked to measurement of fundamental constants

  - fundamental constants are assumed to be independent of space and time (!!??)
    → decentralized calibration possible, stable in time

6.1.2 Quantum Standards for Electrical Units

quantum metrological triangle



- 1990:

$$\mathrm{K}_{\mathrm{J}-90} \equiv \frac{2e}{h} = \frac{1}{\Phi_0} = 483\,597\,891(12)\ \frac{\mathrm{Hz}}{\mathrm{mV}}$$

$$\mathrm{R}_{\mathrm{K}-90} \equiv \frac{h}{e^2} = 25\,812.807\,557(18)\ \Omega$$

$K_{\text{I-90}} = 1/e$ not yet availabe

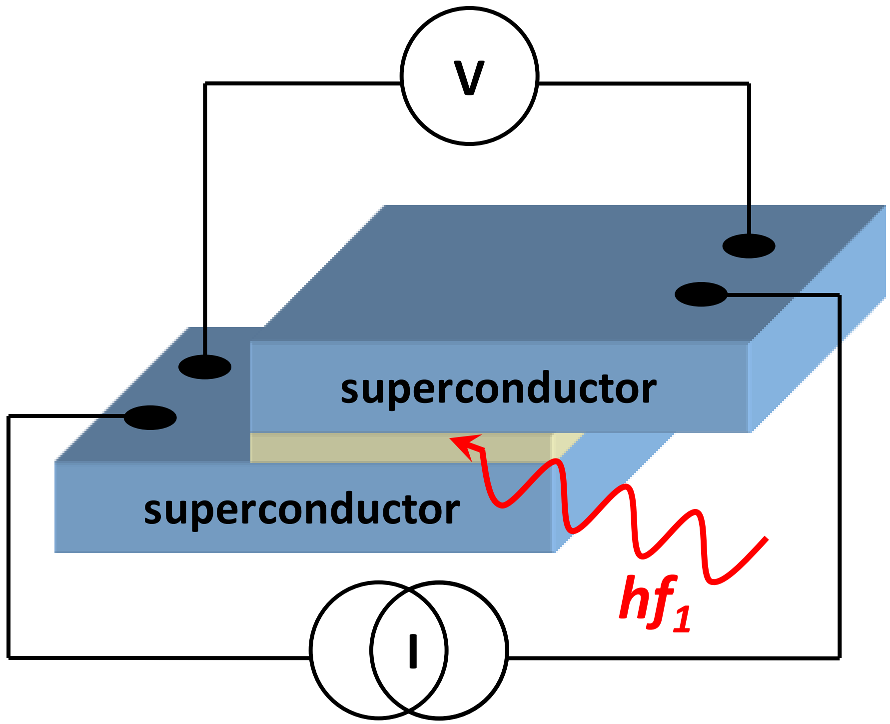
6.2 The Josephson Voltage Standard

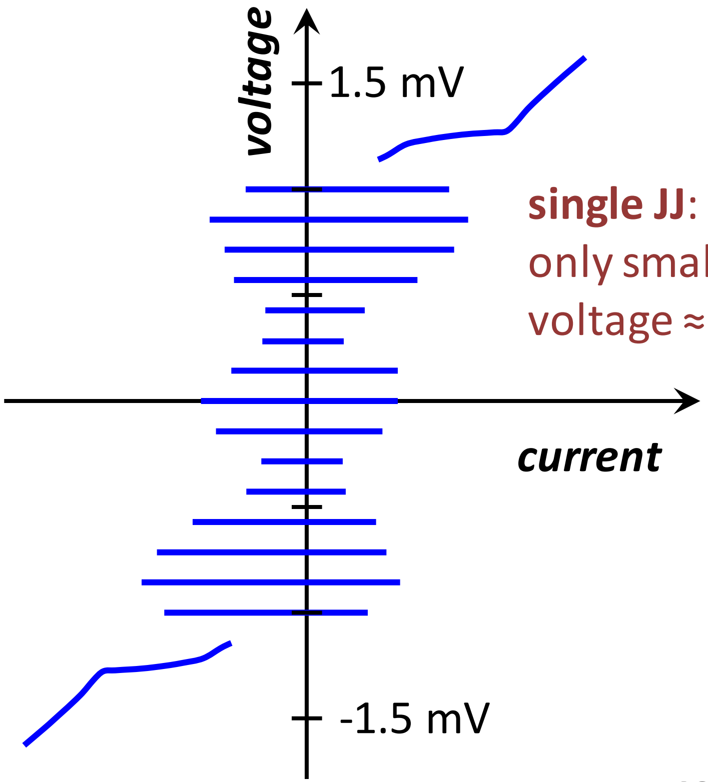
6.2.1 Underlying Physics

Shapiro steps:

$$V_n = n \frac{h}{2e} f_1 = n \Phi_0 f_1 \qquad n = 1, 2, 3, \ldots$$

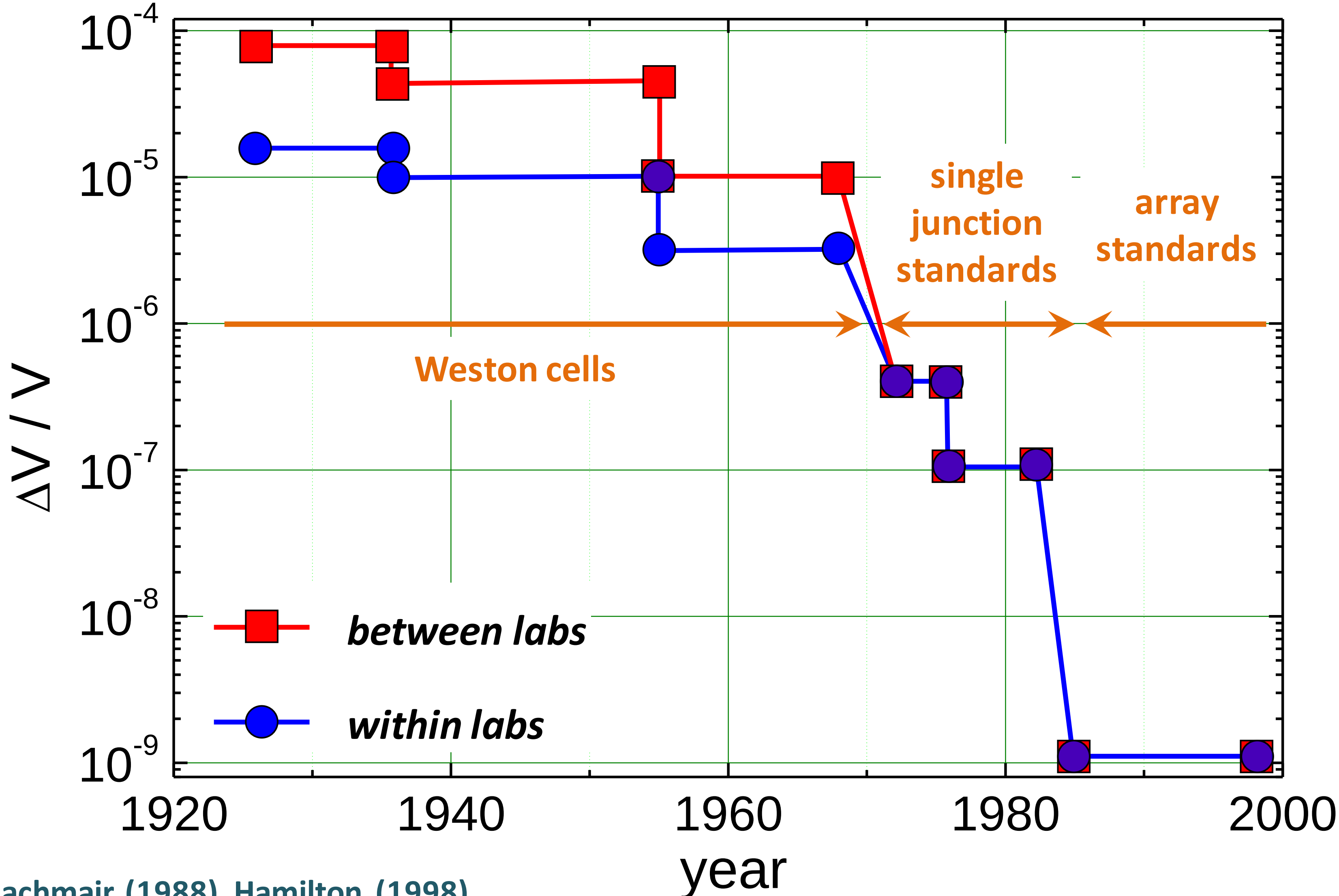
$$|\langle I_s \rangle_n| = I_c \left| \mathcal{J}_n \left(\frac{2eV_1}{hf_1} \right) \right|$$





single JJ:
only small
voltage ≈ few mV

6.2.2 Development of the Josephson Voltage Standard

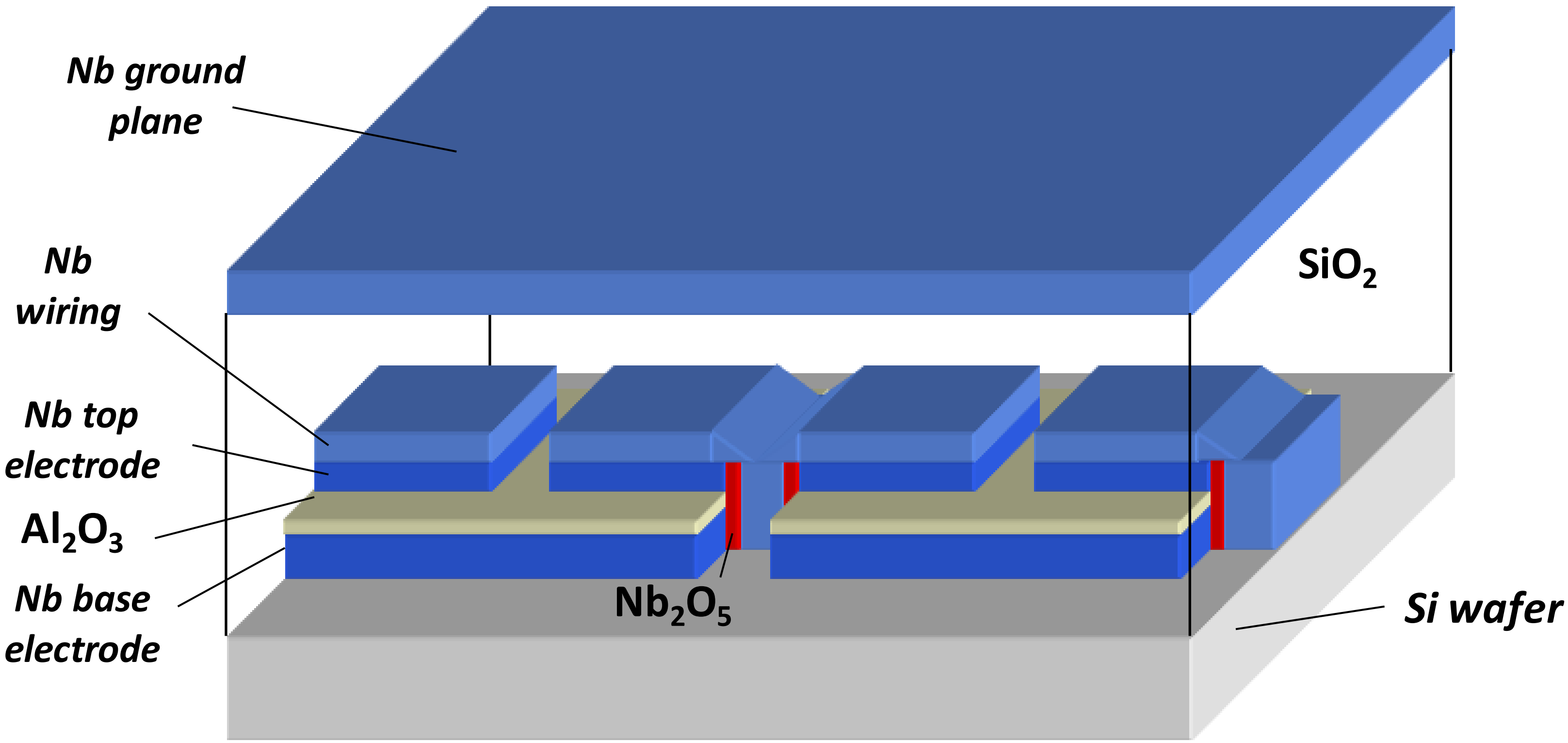


Bachmair (1988), Hamilton (1998)

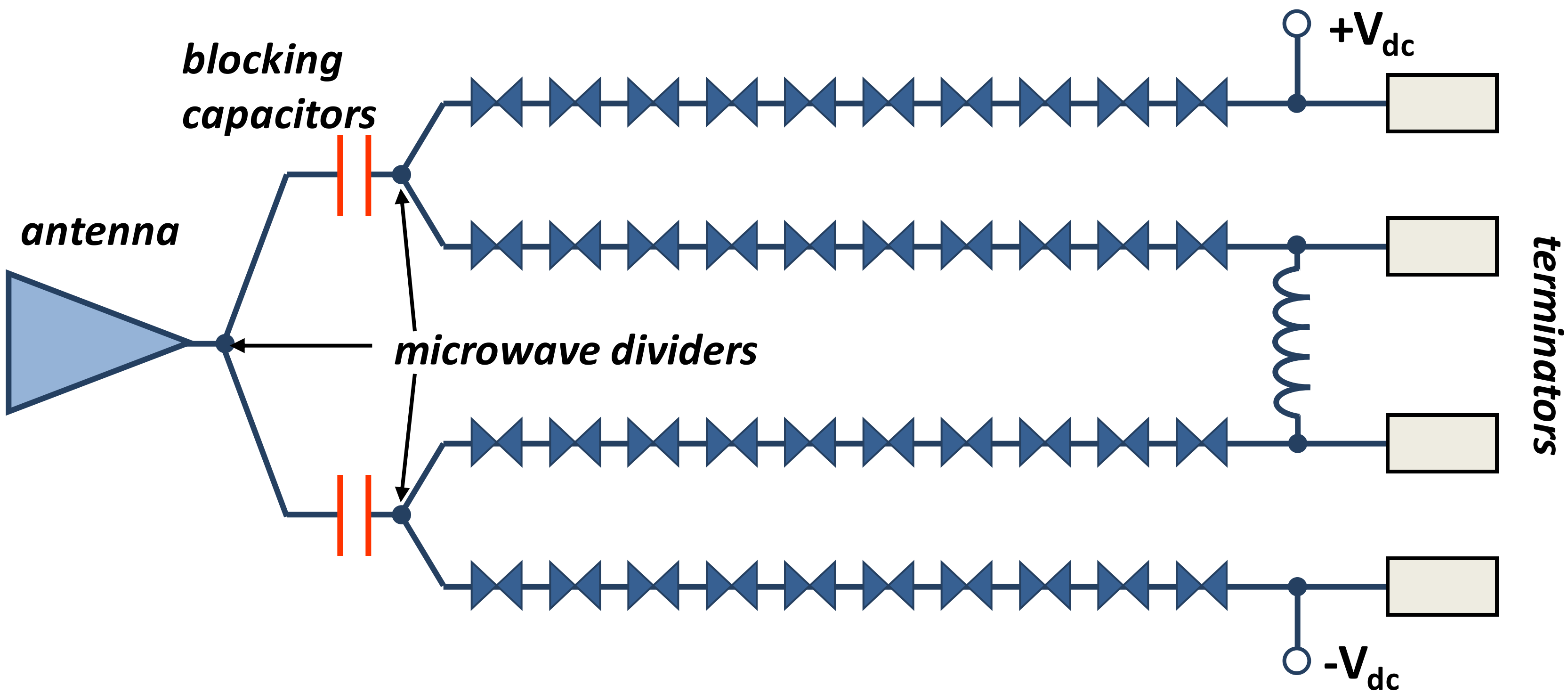
6.2.2 Development of the Josephson Voltage Standard

- ***problems in realization of voltage standard with large output voltage***
  → fabrication of large number (>1000) of junctions with almost identical parameters
  → homogeneous coupling of microwave radiation to all junctions

- ***solution: series JJ array embedded into microwave stripline***

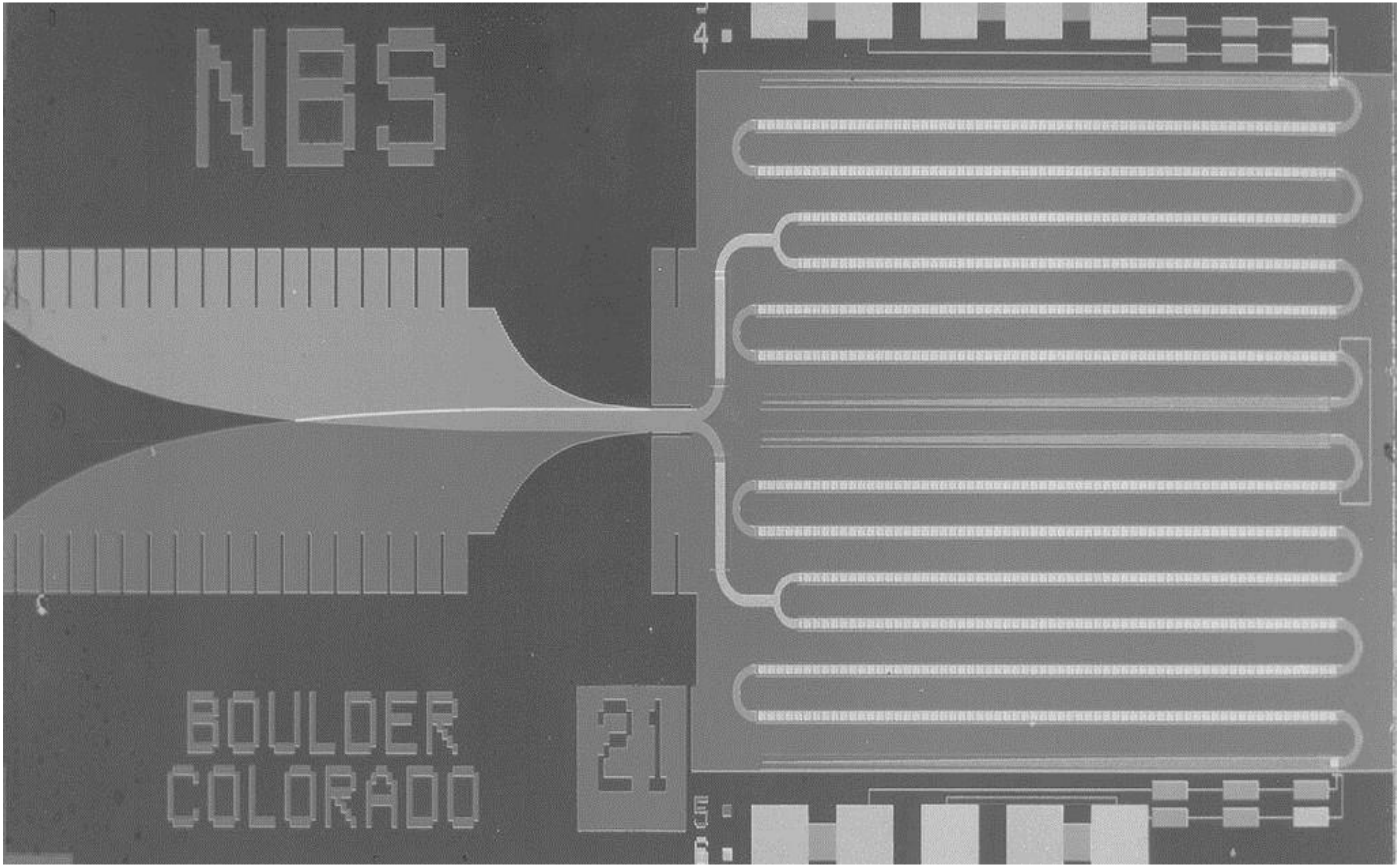


6.2.2 Development of the Josephson Voltage Standard



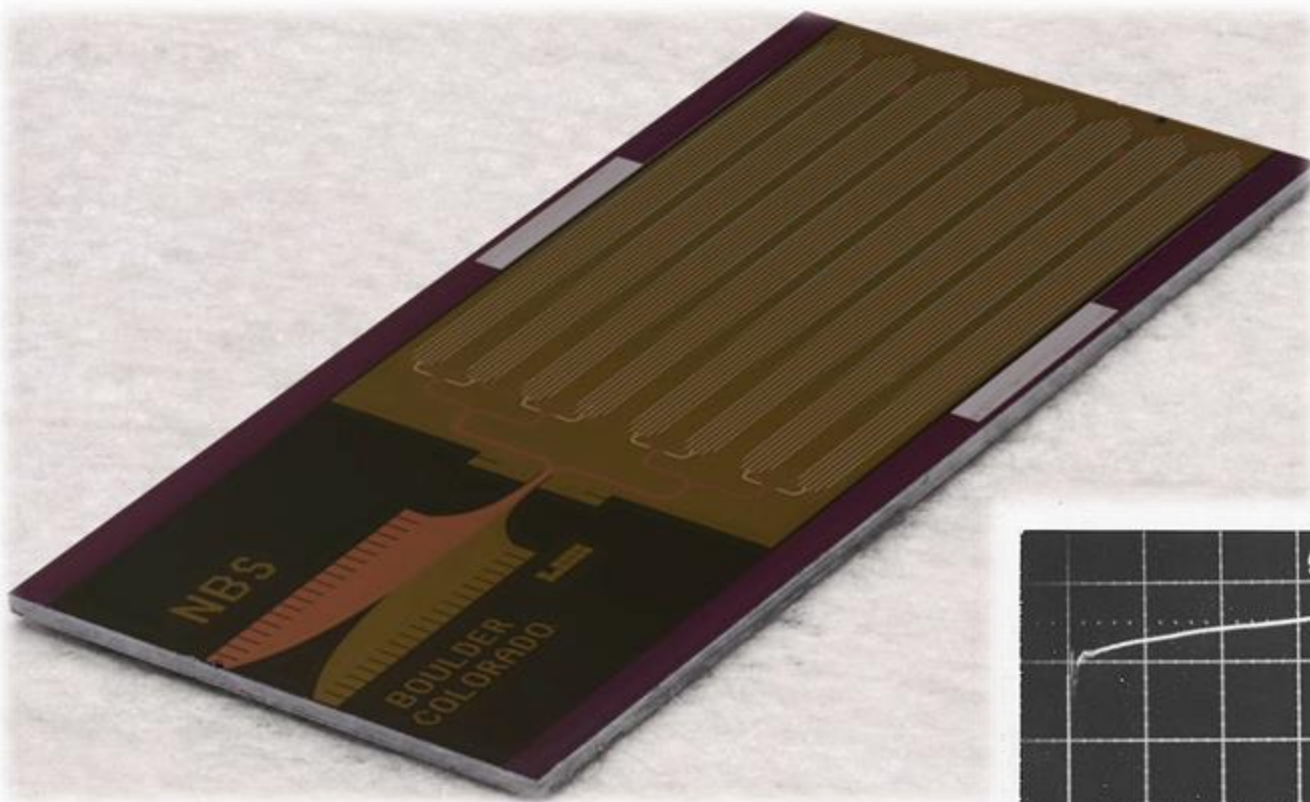
- parallel circuit for microwave signal
  - → total array length << decay length of wavelength of microwave signal
  - → homogeneous coupling of microwave radiation to all junctions
- series circuit for dc voltage
  - → large dc voltage output

6.2.2 Development of the Josephson Voltage Standard

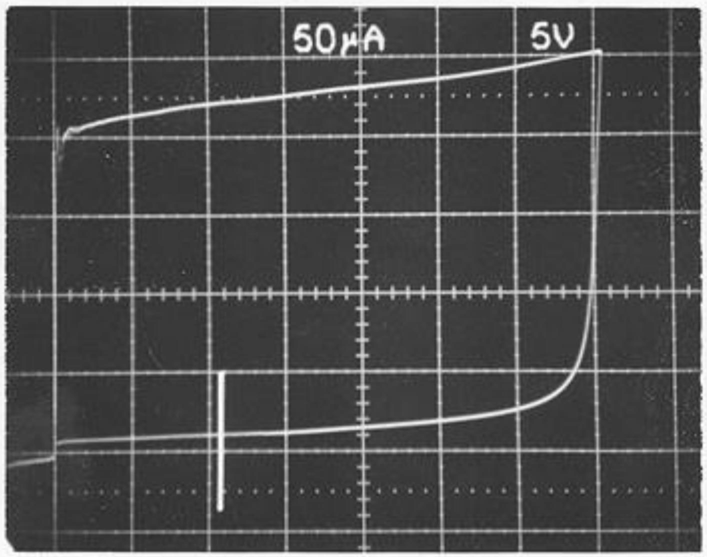


one-volt NIST Josephson Junction array standard having 3020 junctions

6.2.2 Development of the Josephson Voltage Standard

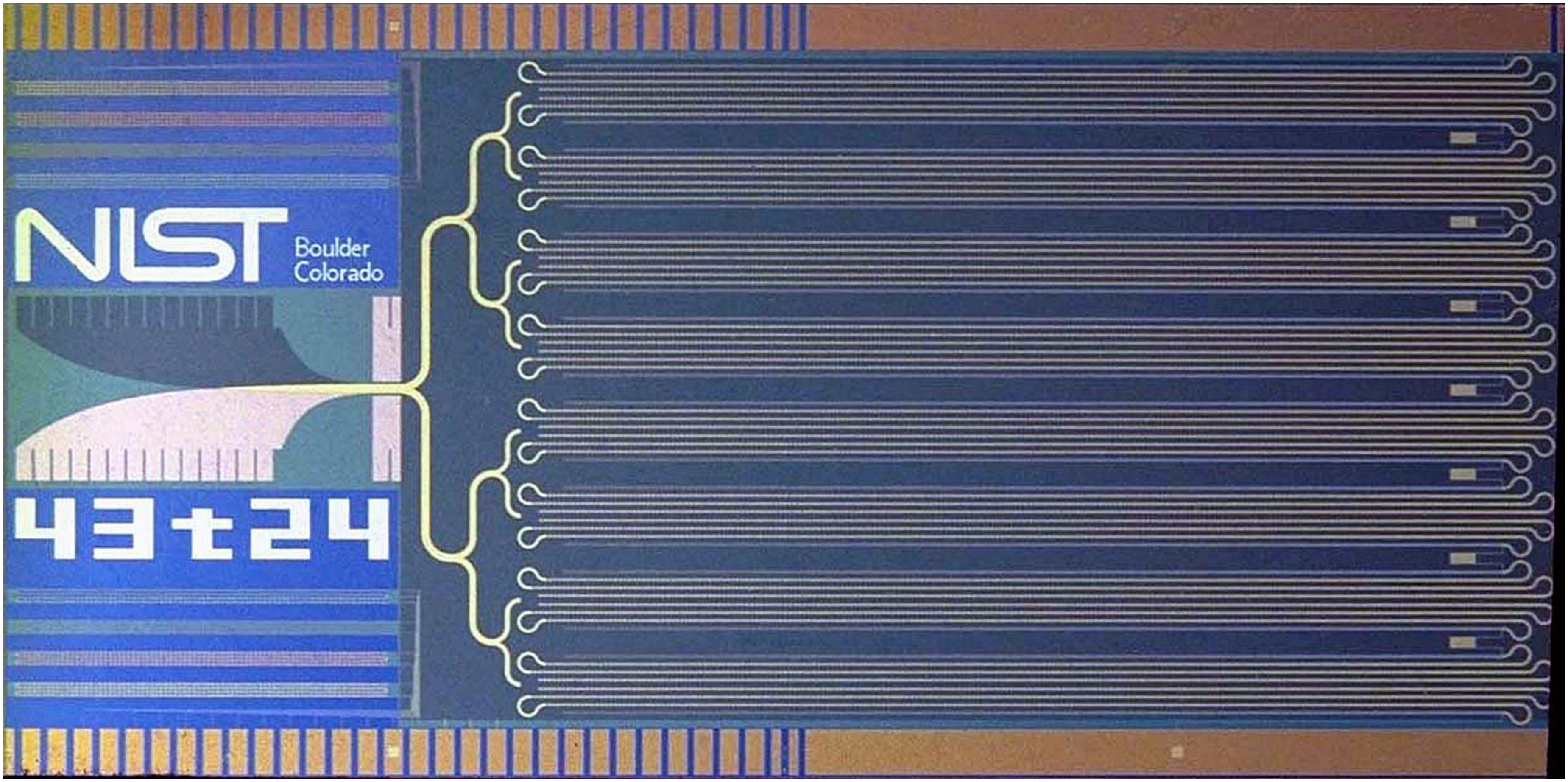


world's first 10-volt chip (NIST, 1989),
with 14 184 junctions (Nb/AlO_x/PbInAu)



C.A. Hamilton , F. L. Lloyd, K. Chieh, & W.C. Goeke, IEEE Trans. Inst. Meas. Vol. 38, April 1989, pp. 314-316)

6.2.2 Development of the Josephson Voltage Standard



10 V Josephson Junction array standard (NIST, 1992) having 20 208 Nb/AlO$_x$/Nb junctions (chip size: 10 x 20 mm²)

PREMA Josephson Junction Array (JJA) Voltage Standard Chip JVS 7010 (10V)

chip size	25 x 11 mm^2
# of JJs	13,920 JJs
Operating range	-11V to +11V
technology	refractory all niobium full wafer process
operating temperature	4.2 K
operating frequency	70 - 75 GHz
lead and bond wire resistance	< 3 Ohm
order No.	JVS 7010

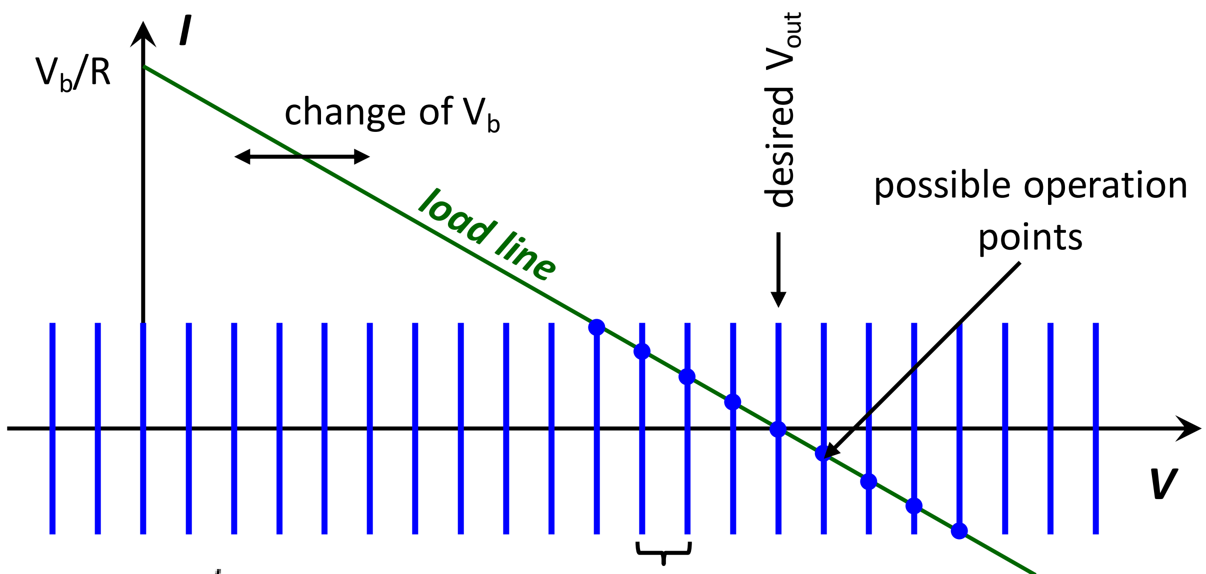
6.2.2 Development of the Josephson Voltage Standard

- 10 Volt Josephson voltage standard circuit mounted on a chip carrier
- 19 700 SIS Josephson junctions (JJs), operating frequency: 75 GHz

complete microprocessor controlled 10 V Josephson voltage standard (JVS) system made by Supracon.

- problem of series array with underdamped JJs:

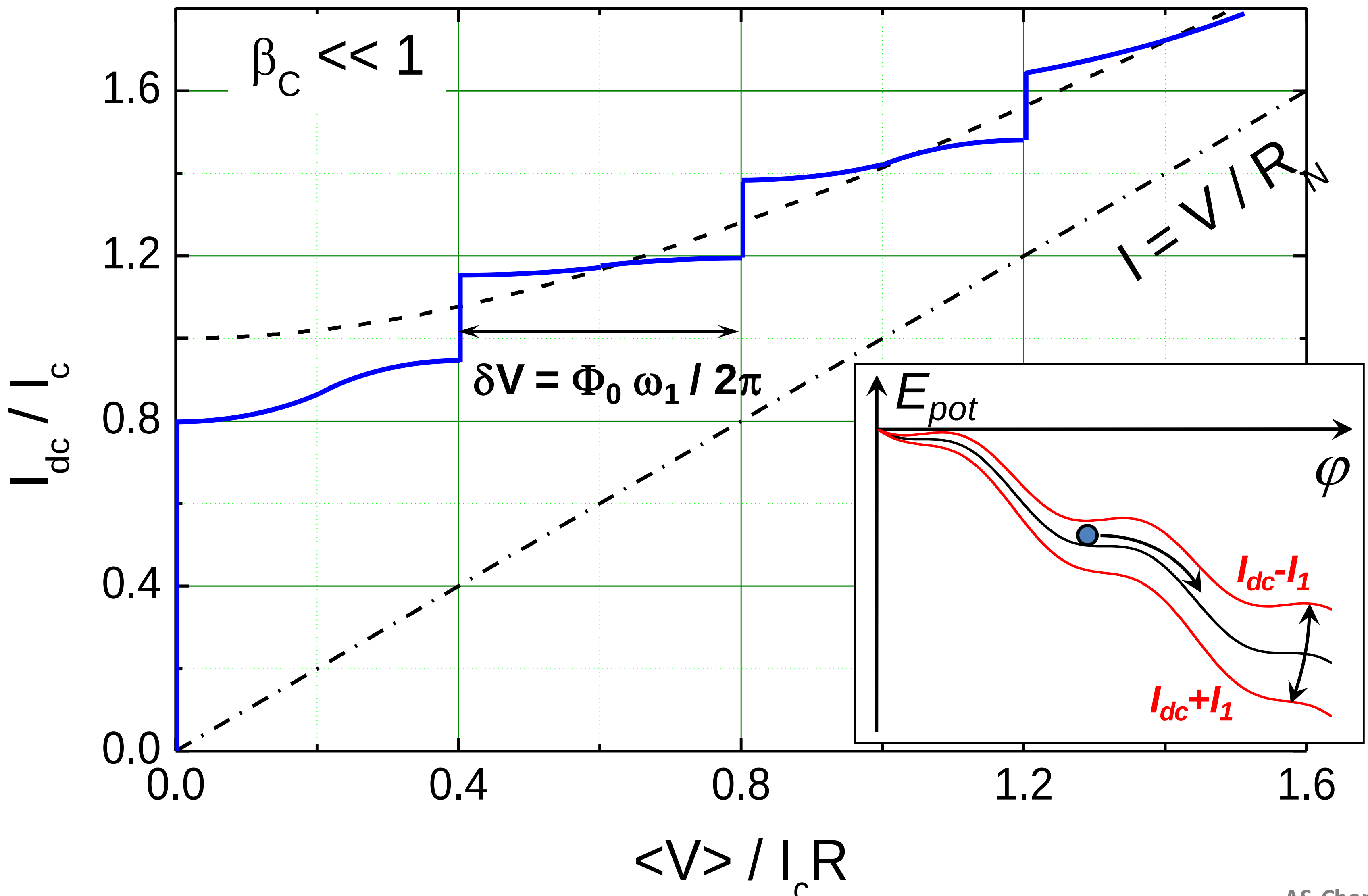
  - current steps strongly overlap → rapid switching between steps is difficult
    ➔ ***use overdamped junctions***

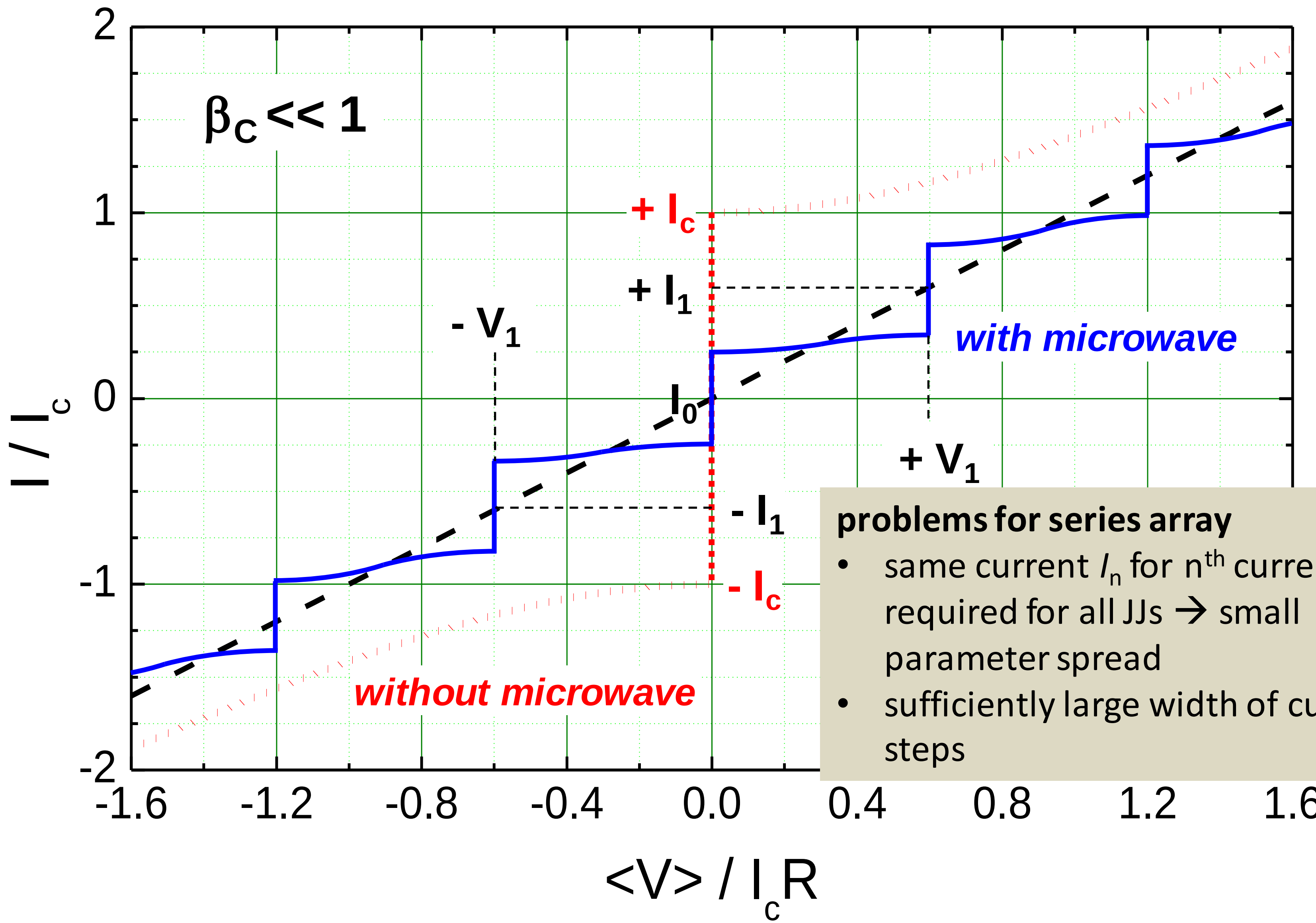


$$\Delta V = \frac{h}{2e} f_1 = \Phi_0 f_1 \simeq 145\,\mu\mathrm{V} \;@\; 70\,\mathrm{GHz}$$

6.3 Programmable Josephson Voltage Standard

- IVC of overdamped Josephson junction with microwave irradiation

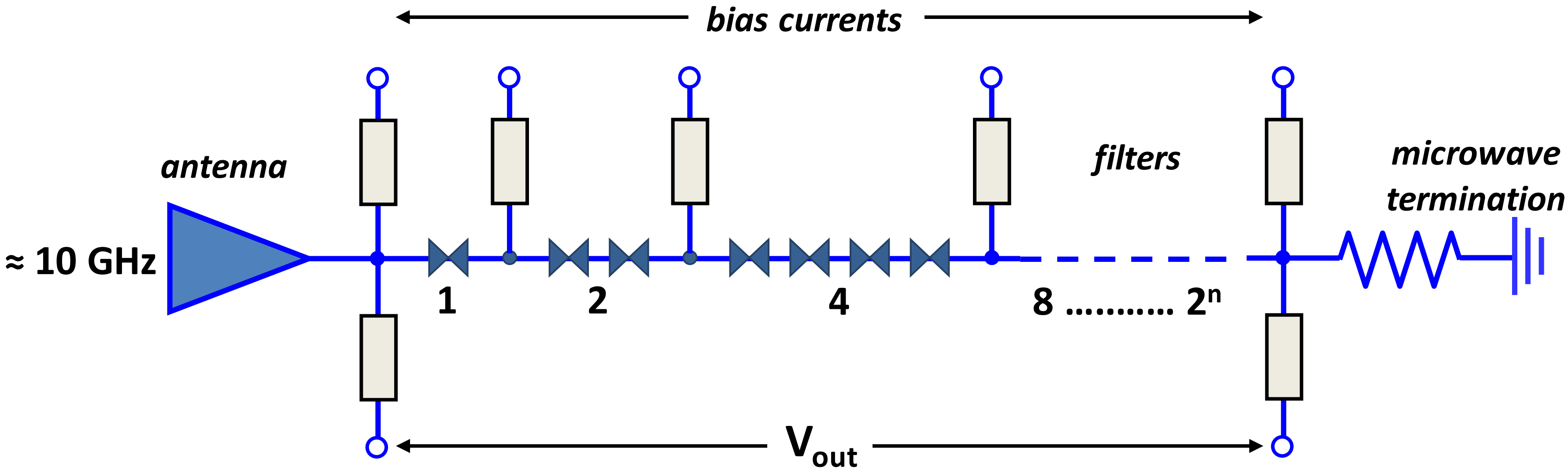




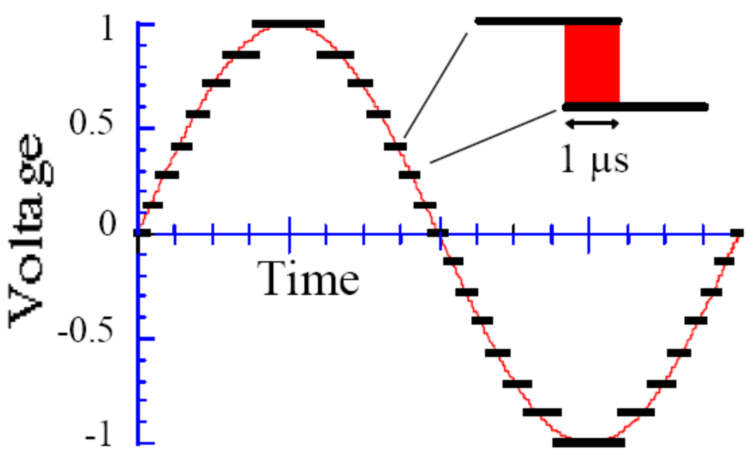
problems for series array

- same current I_n for n^{th} current step required for all JJs → small parameter spread
- sufficiently large width of current steps

6.3 Programmable Josephson Voltage Standard

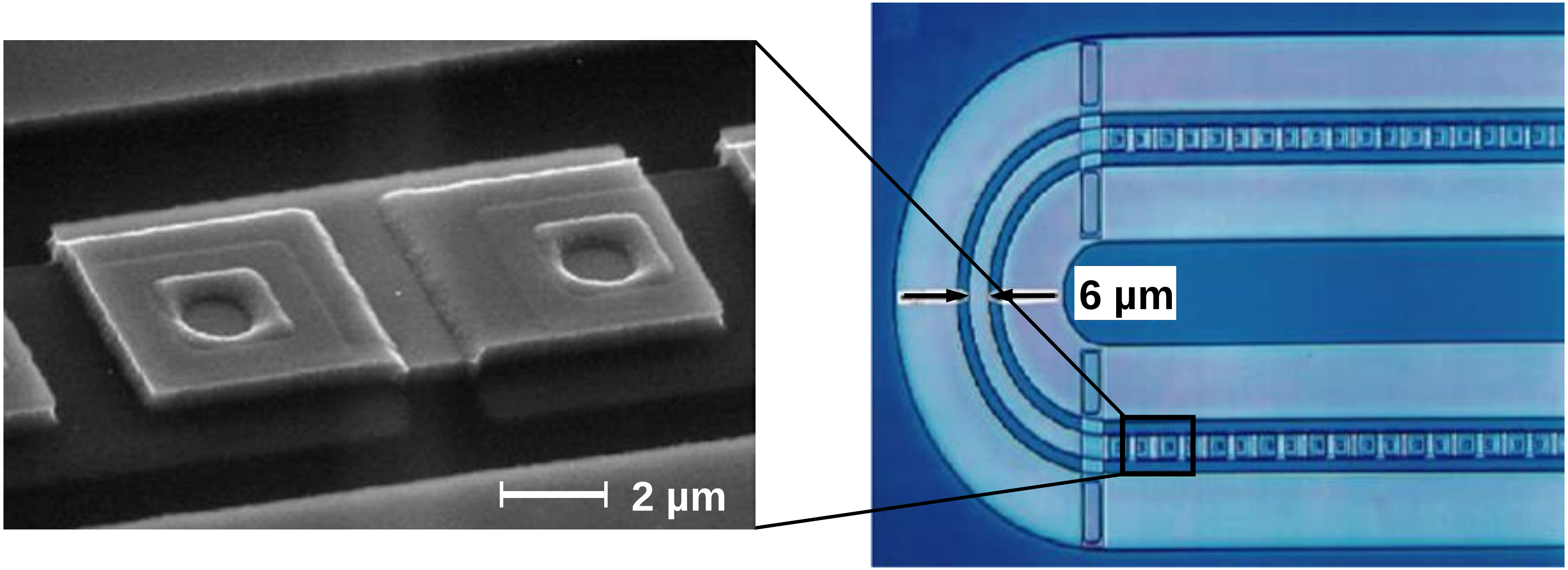


- binary sequence array
  - large number of Josephson junctions required (e.g. $2^{16} = 65\,536$)
  - frequency determines minimum voltage step: $\Delta V \simeq 2\ \mu\mathrm{V/GHz}$
- accuracy limited by speed of semiconductor current drivers ($\simeq 1\ \mu s$)
  - ac waveforms with accurate $V(t)$ only at mHz



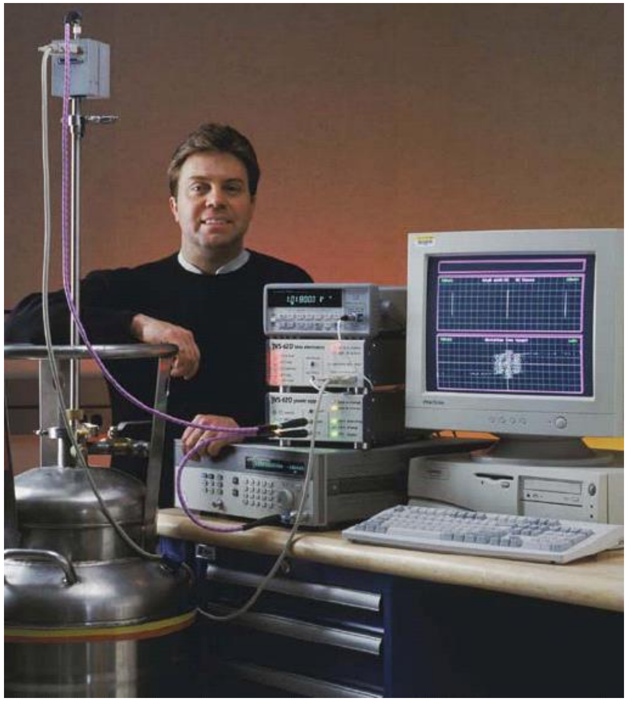
6.3 Programmable Josephson Voltage Standard

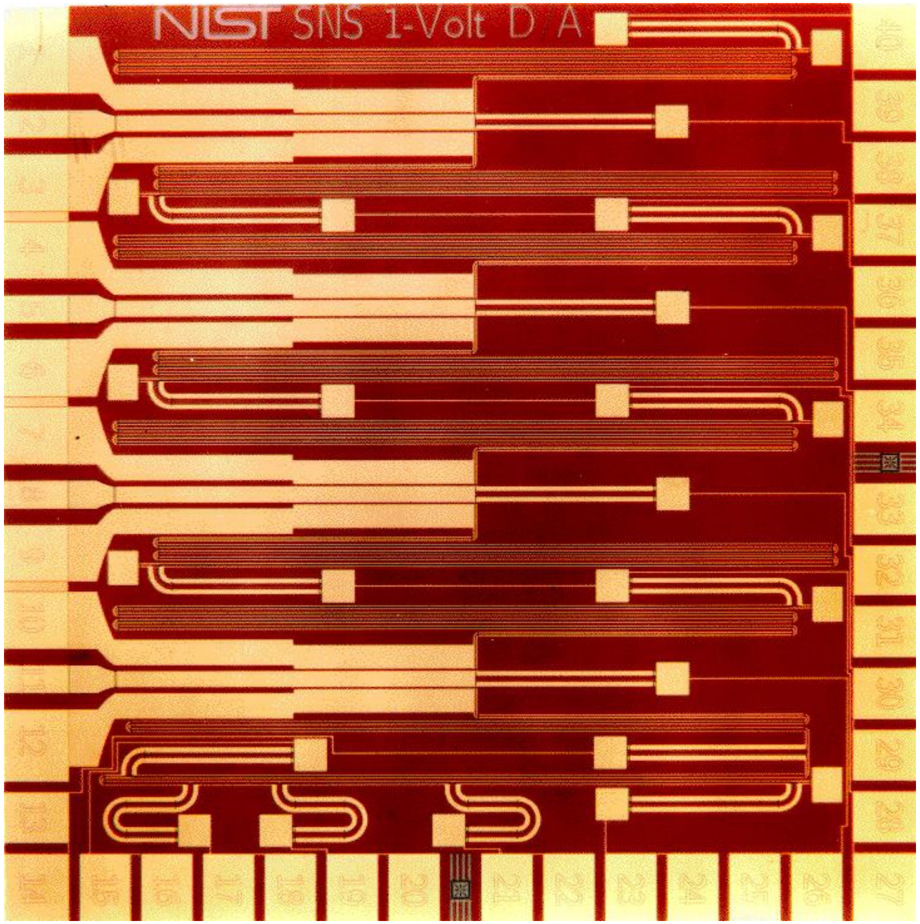
- superconductor/normal metal/superconductor (SNS) Josephson junctions required
  - Nb/PdAu/Nb
  - area $\simeq 2 \times 2\ \mu m^2$
  - low resistance: $3\ m\Omega$
  - high uniformity over large number of junctions



6.3 Programmable Josephson Voltage Standard

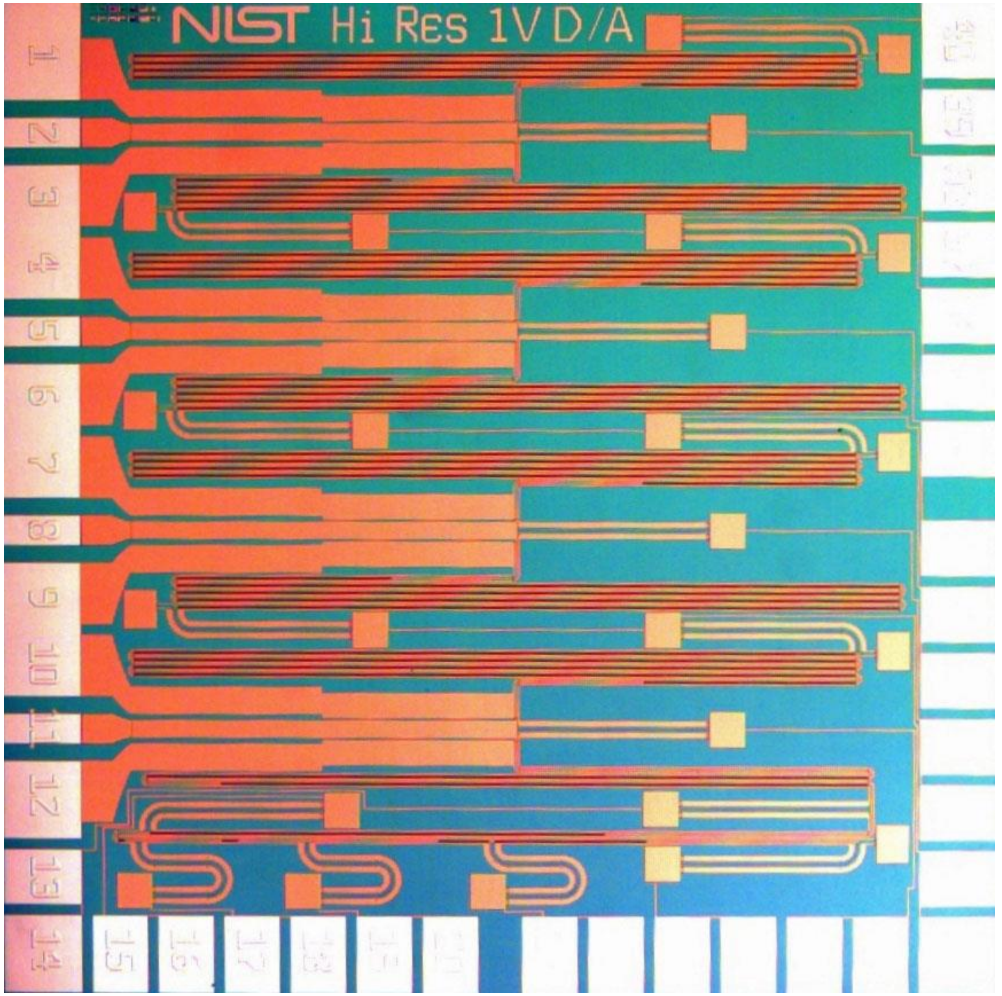
- first programmable 1-volt standard (NIST, 1997)
  - 32 768 junctions on a 1 cm^2 chip
  - new normal-metal junction barrier technology (Nb/PdAu/Nb)
  - junction size: $2 \times 2\ \mu m^2$
  - programmable from +1.1 V to -1.1 V
  - 1 μs settling time





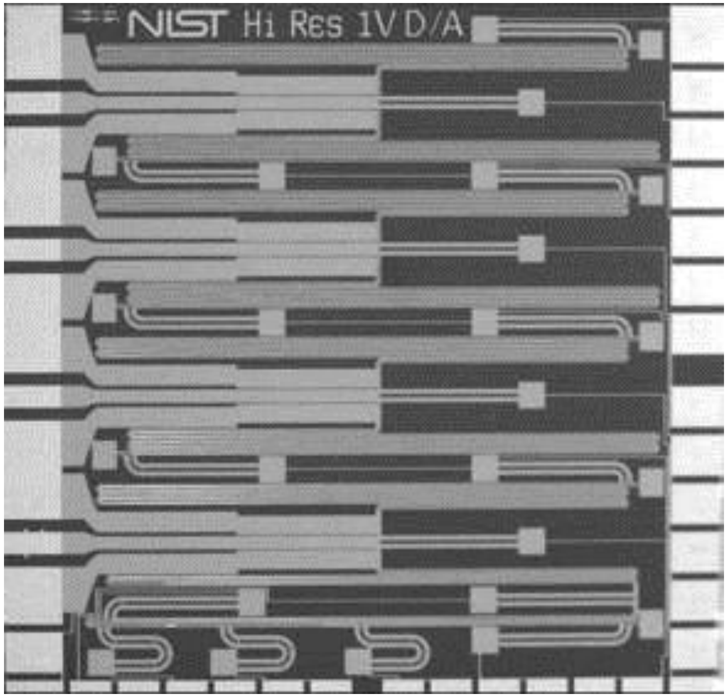
S. P. Benz et al, "Stable 1-volt Programmable Voltage Standard," Appl. Phys. Lett. 71, 1866 (1997)
S. P. Benz, "SNS junctions for programmable voltage standards," Appl. Phys. Lett. 67, 2714-2716 (1995)

- integrated an advanced programmable standard chip (NIST, 2005)
  - the maximum voltage: 2.6 V
  - double-stacked Josephson junctions ($Nb/MoSi_2/Nb$)
  - junction area: $4 \times 8\ \mu m^2$
  - 67 410 junctions on 1 cm² chip

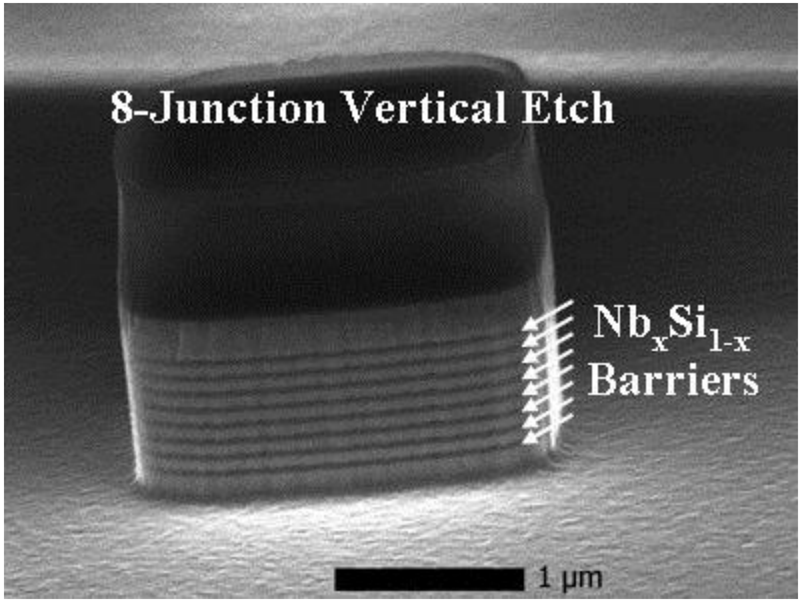


Y. Chong et al., IEEE Trans. Inst. Meas., vol. 54, pp. 616-619, April 2005)

6.3 Programmable Josephson Voltage Standard



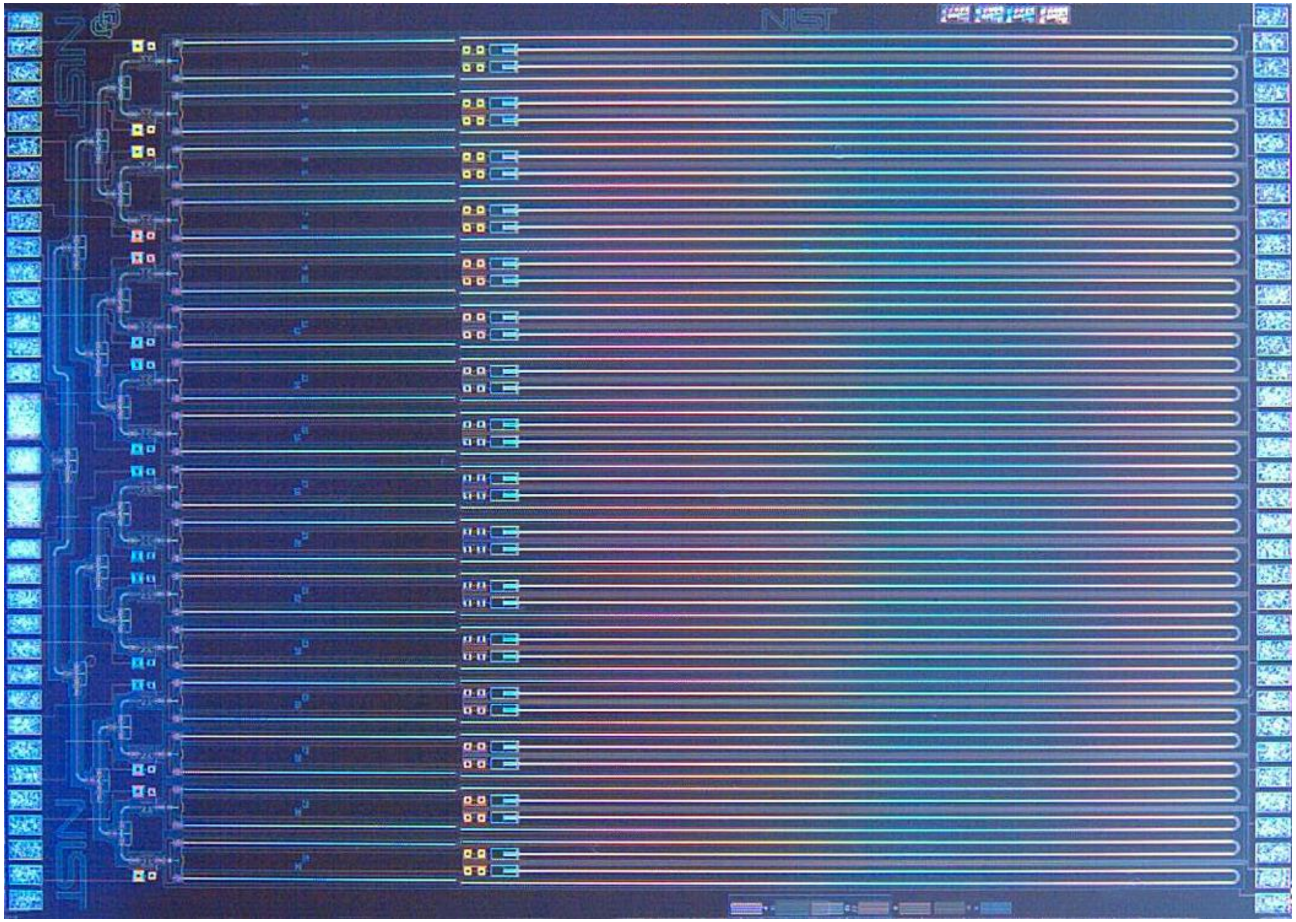
a 1 centimeter × 1 centimeter superconducting integrated circuit with over 132,000 triple-stacked SNS Josephson junctions for the 5.0 volt high-resolution programmable voltage standard operating at 18.5 GHz.



Scanning electron microscope image of an 8-junction stack with niobium-silicide barriers and niobium electrodes. The image shows that the nano-stacked junctions can be vertically etched which is critical for achieving uniformity of the electrical characteristics. (Image by Burm Baek, NIST)

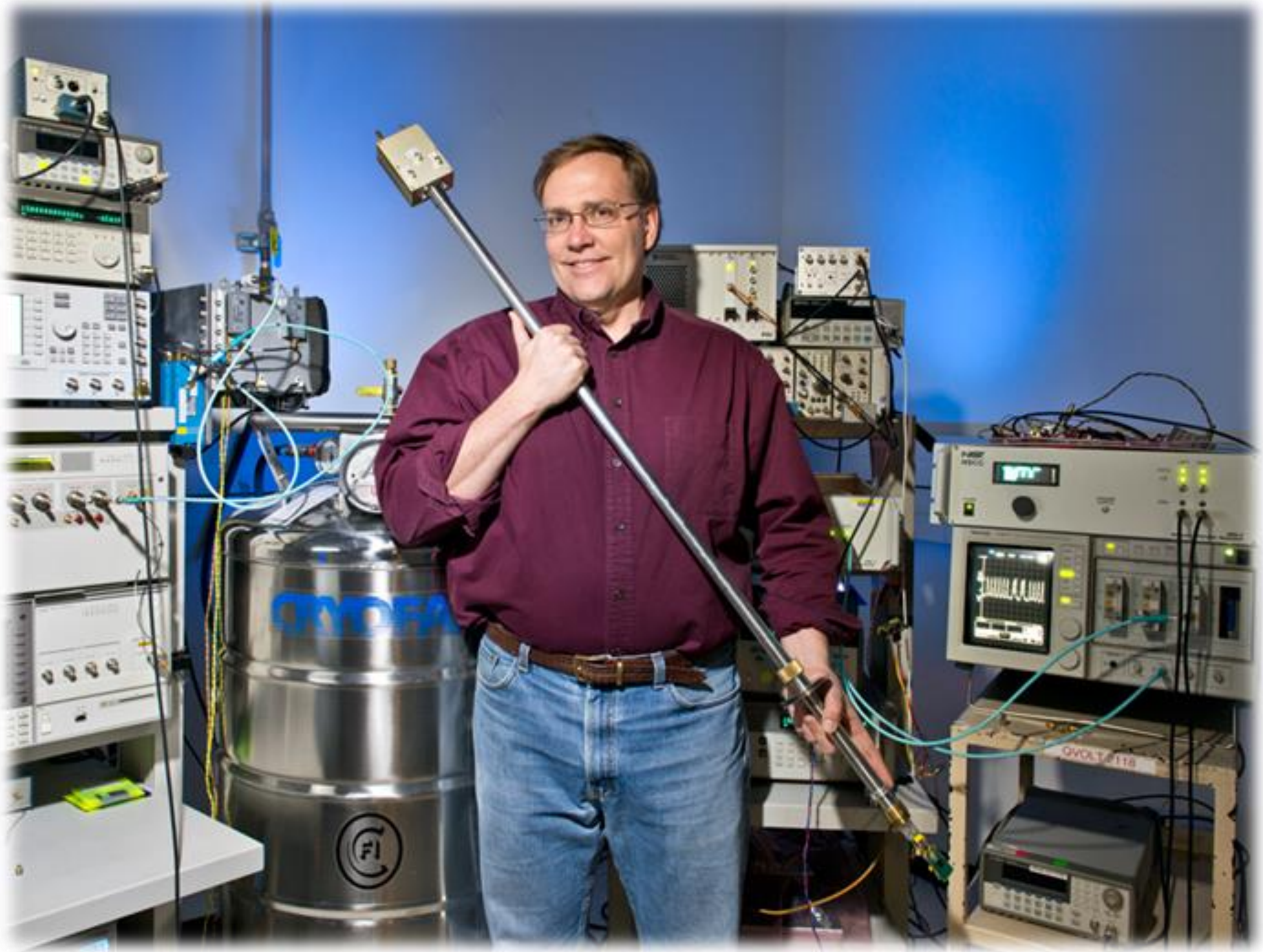
6.3 Programmable Josephson Voltage Standard

- 10-volt programmable standard chip (NIST, 2011)
  - the maximum voltage: 2.6 V
  - triple-stacked Josephson junctions ($Nb/Nb_xSi_{1-x}/Nb$)
  - about 300 000 junctions on 12 x 17 mm² chip



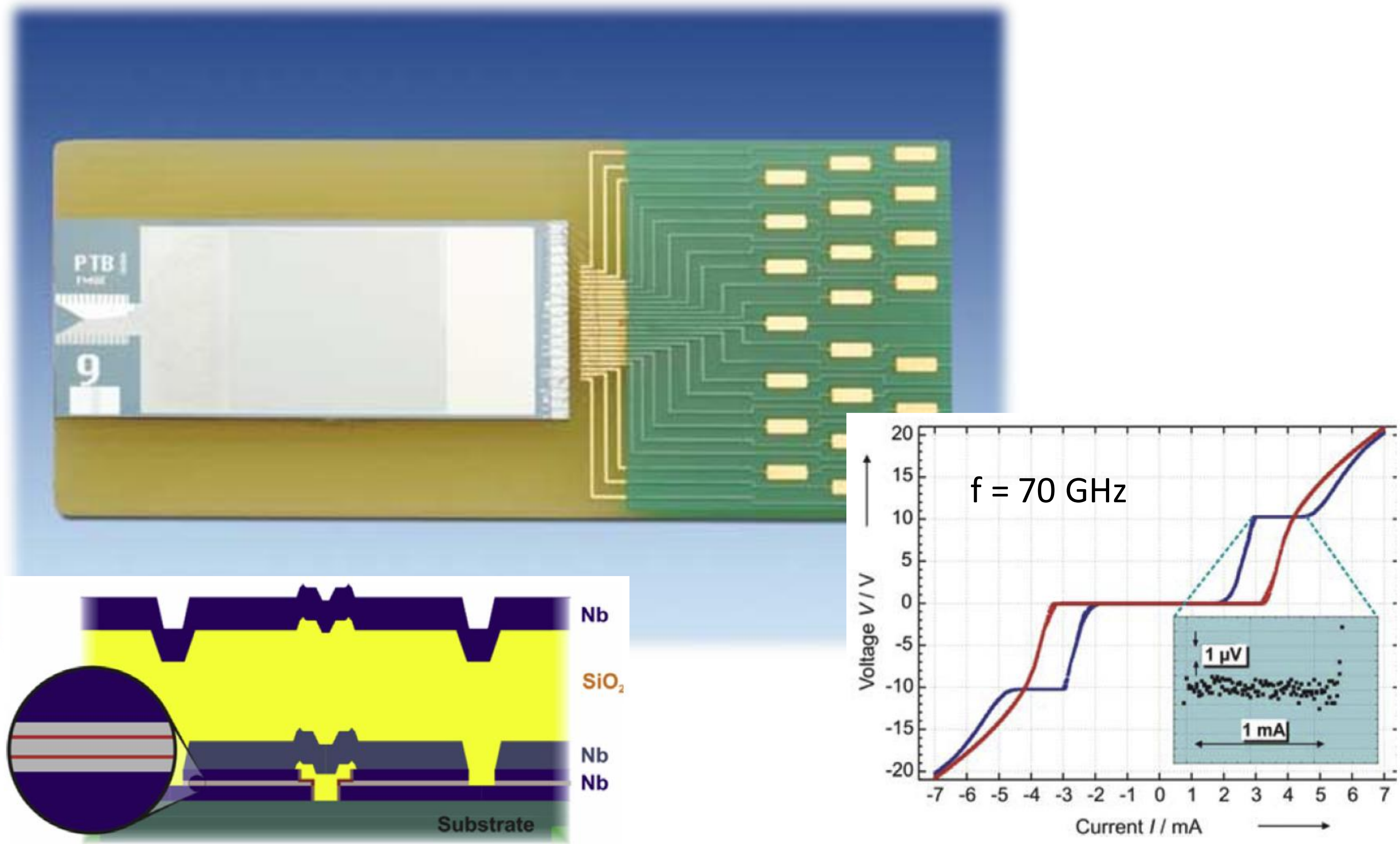
P.D. Dresselhaus et al, "10 Volt Programmable Josephson voltage standard circuits using NbSi-barrier junctions," IEEE Trans. Appl. Supercond. (2011)

6.3 Programmable Josephson Voltage Standard

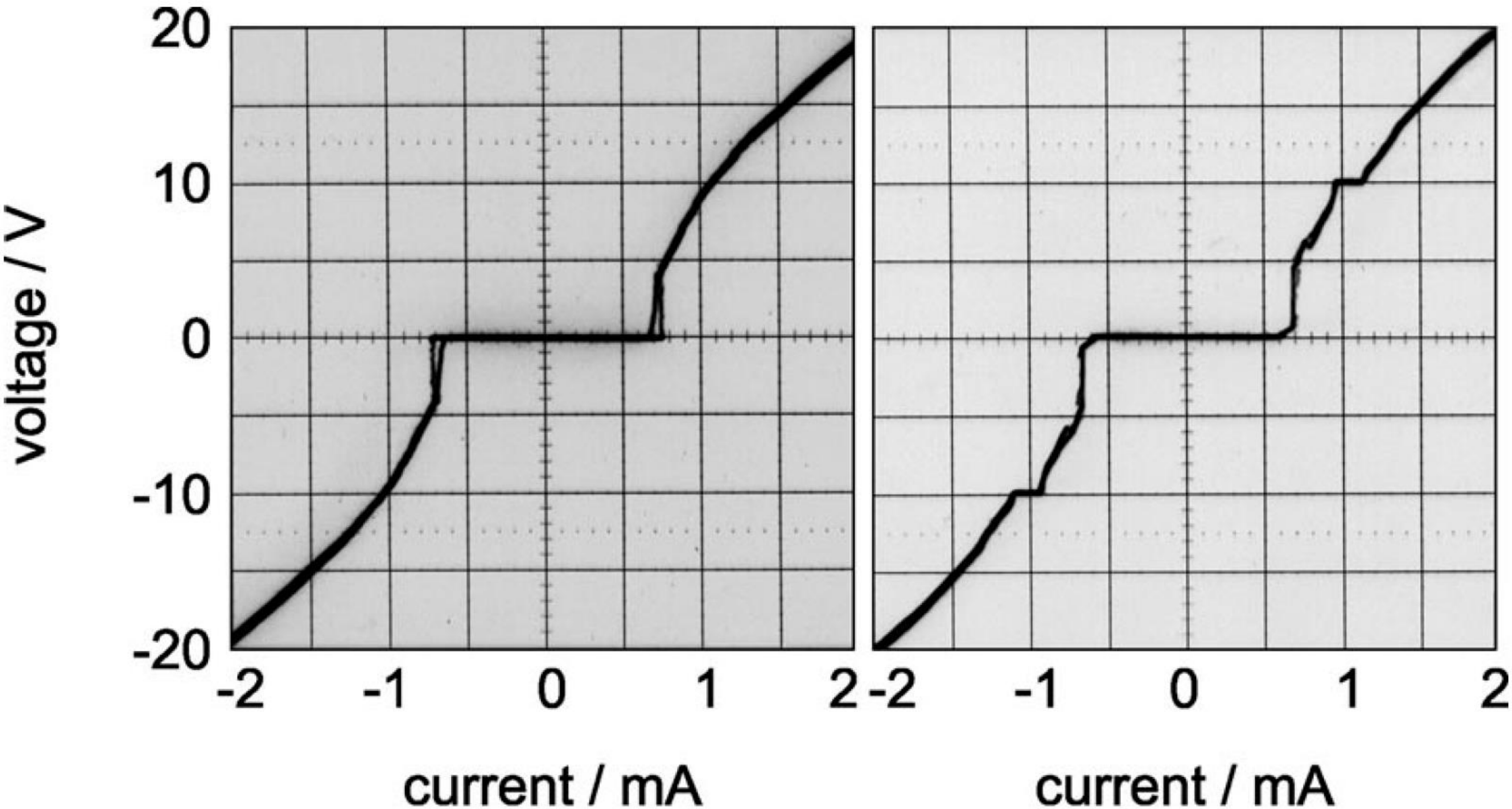


Sam Benz of NIST demonstrates the relatively small amount of equipment required for the newly automated voltage standard. The chip containing Josephson junctions is at the lower end of the rod.

6.3 Programmable Josephson Voltage Standard



programmable 10-V array (PTB, 2006) with 69 632 Josephson contacts in SINIS technology



Current–voltage characteristic of a 69120 SINIS Josephson junction series array
(a) without and (b) with 70 GHz microwave irradiation, at T = 4.2 K.
The microwave power applied to the antenna is about 0.5 mW (source: PTB Braunschweig)