創新科技署
Innovation and Technology Commission

Standards and Calibration Laboratory, Hong Kong, China

# Seminar on New Opportunities for Testing and Certification in the Age of Technology

# Quantum Measurement Standards: New Trends in Electrical Metrology

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The Standards and Calibration Laboratory

18 March 2019

Standards and Calibration Laboratory, Hong Kong, China

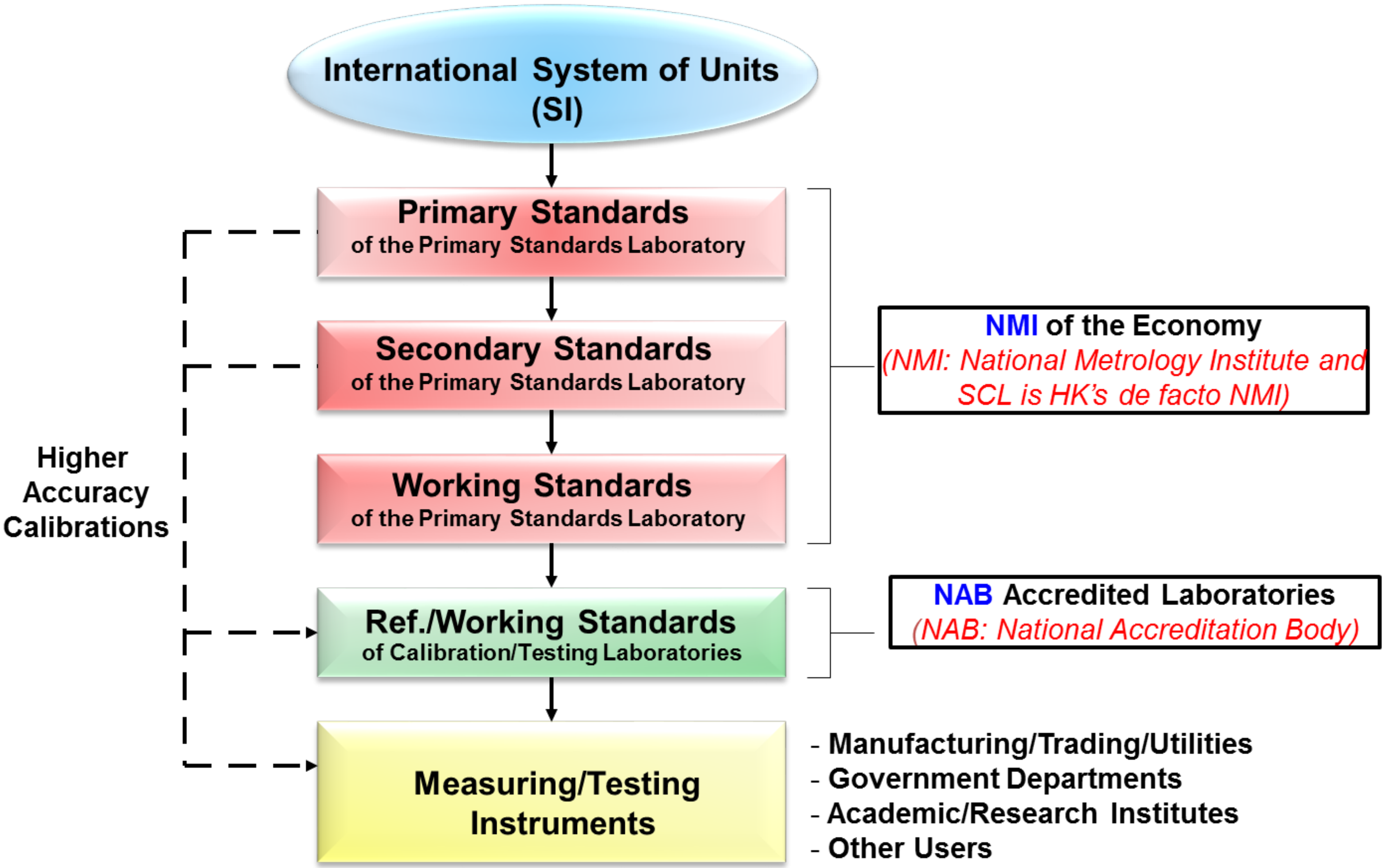
# Contents

- Introduction
- History of Electrical Metrology
- Recent Developments in Electrical Quantum Measurement Standards
- New Applications in Electrical Metrology
- Future Developments

# What is Metrology?

- Metrology is the "science and practice of measurement"
  - **Stable**: Long-term trends can be used for decision making
  - **Comparable**: Results from different laboratories can be brought together
  - **Coherent**: Results from different methods can be brought together
- The objectives of metrology are achieved through providing the framework for **traceable measurements**.

# What is traceability?



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# Introduction of SCL

- Established in 1984
- SCL is the Hong Kong's custodian of reference standards for physical measurement

**volt (volt, V)**

Josephson Array Voltage Standard

**resistance (ohm, Ω)**

Quantum Hall Resistance Standard

electric current (ampere, A)

**length (metre, m)**

Iodine Stabilized Helium-Neon Laser

**thermodynamic temperature (kelvin, K)**

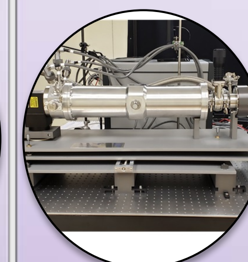
Triple Point of Water Cell

**mass (kilogram, kg)**

International Prototype of Kilogram

**time (second, s)**

Caesium Beam Electron Clock



**luminous intensity (candela, cd)**

Cryogenic Radiometer

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# History of Electrical Metrology

# History of Electrical Metrology

- From 1860:
- Siemens mercury unit
  - Electricity passing through a 1-meter long column of pure mercury
- Silver voltameter
  - “International ampere”
  - Determine the mass of the cathode before and after to indicate current had passed through it

Source: NIST

# History of Electrical Metrology

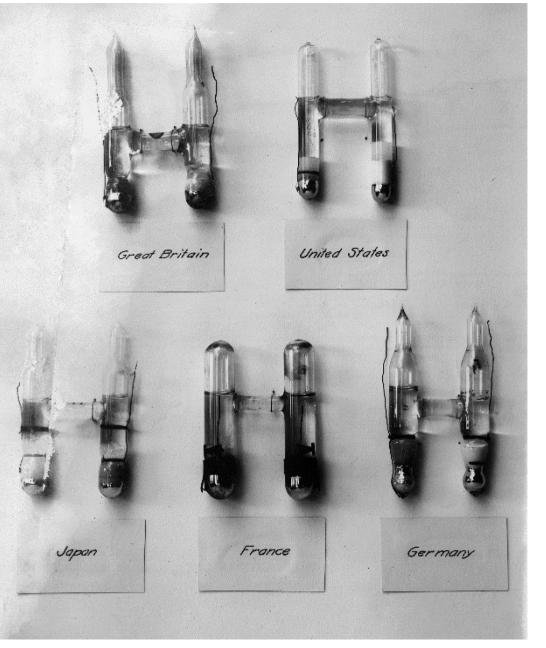
- Weston Cells
  - H-saped glass container filled with chemical for stable voltage

- Ampere balance
  - Current pass through a coil will produce a physical motion to move the indicator

Source: NIST

# History of Electrical Metrology

- In 1920s:
  - International comparison of Weston cells
- In 1933:
  - CGPM determined to move from “international ampere” to “absolute system” based on length, weight and time.
- In 1948:
  - Officially adopted by CIPM




Source: NIST

# Current SI Definition (1948)

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 meter apart in vacuum, would produce betwe
a force equal t
per meter of le

Ampere's Force Law:

$$\Delta F = \frac{\mu_0 I_1 I_2}{2\pi r}\Delta l$$

$$\Downarrow \quad 2\times 10^{-7} = \frac{\mu_0 \times 1 \times 1}{2\pi \times 1}\times 1$$

$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H/m}$$

# History of Electrical Metrology

- In 1960:
  - The “ampere” joined the family of SI base unit.

- In 1970-80:
  - Evolution of quantum technologies

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# Current Practical Realization


### *Josephson effect*

$$V = \frac{nf}{K_{J-90}} \approx nf\frac{h}{2e}$$

### *Quantum Hall effect*

$$R_H = \frac{R_{K-90}}{i} \approx \frac{h}{ie^2}$$

# Josephson Effect

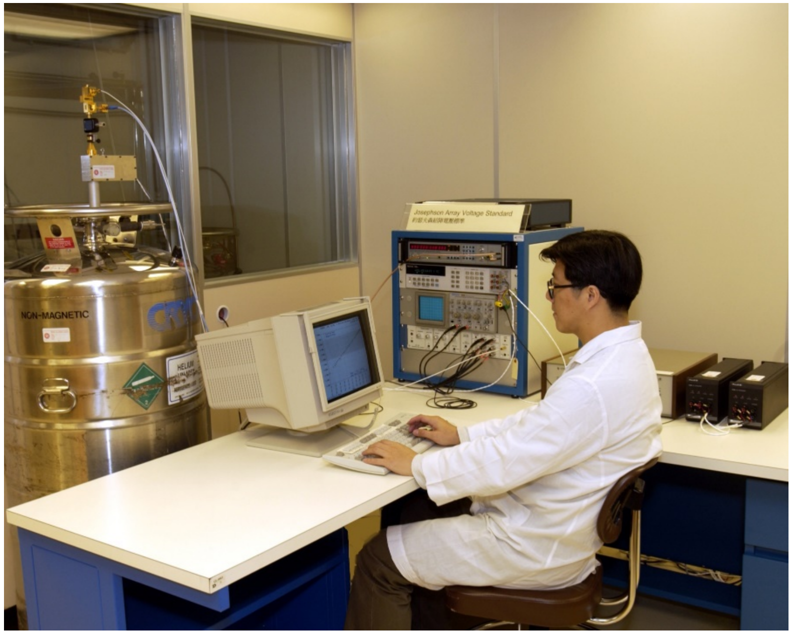
- Nobel Prize in Physics in 1973
- Prof. Brian Josephson

- Josephson Array Junction
  - Superconductor
  - Tunneling effect

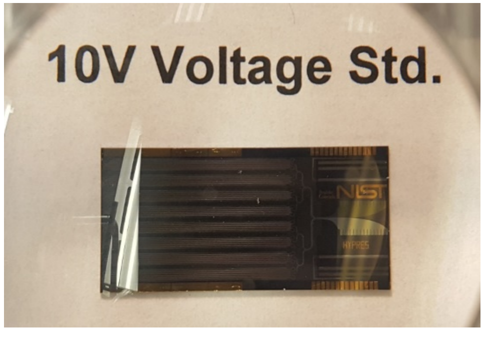
- At 4.2 K (liquid helium)
  - Cooper pair of electron can tunnel through the insulation barrier giving rise to a DC current
  - No voltage drop across the tunnel barrier

# Josephson Voltage

$$V = nf\frac{h}{2e} = \frac{nf}{K_j}$$



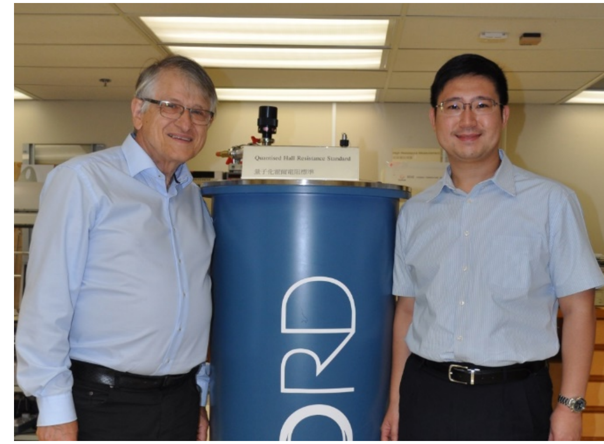

- $h \approx 6.626\text{x}10^{-34}$ Js
- $e \approx 1.602\text{x}10^{-19}$ C
- where $K_J$ : Josephson constant = $2e/h$ $\approx$ 483597 GHz/V
- $K_{J\text{-}90}$ = 483597.9 GHz/V



# Quantum Hall Effect

- Nobel Prize in Physics in 1985
- Prof. Klaus von Klitzing

- Two-dimensional (2D) electrons in strong magnetic field at low temperature shows quantized Hall resistance with the universal fundamental constant.



Prof. Dr. Klaus von Klitzing visited SCL on 29 July 2016

# Quantum Hall Resistance

$$R_H = \frac{h}{ie^2}$$

- $h \approx 6.626\text{x}10^{-34}$ Js
- $e \approx 1.602\text{x}10^{-19}$ C
- For $i$=1,
  $R_k \approx 25812\ \Omega$
- CIPM conventional defined value $R_{k\text{-}90} = 25812.807\ \Omega$
- $R_H = R_{k\text{-}90}/i$

# Revised definition of electric current

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The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge $e$ to be 1.602 176 634 $\times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.

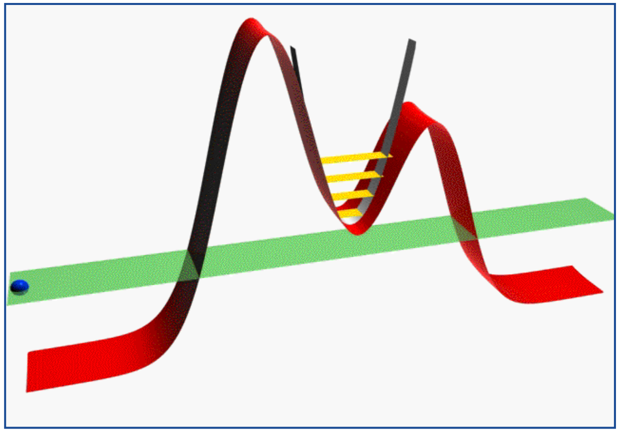
To be implemented on 20 May 2019

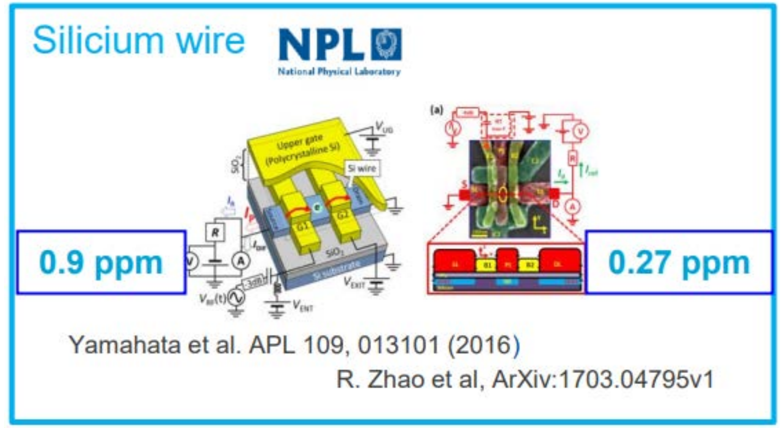
# Revised definition of electric current

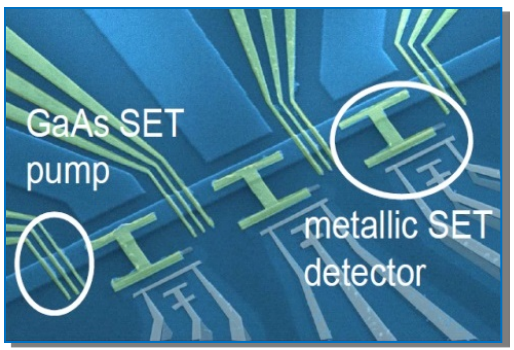
A = C/s

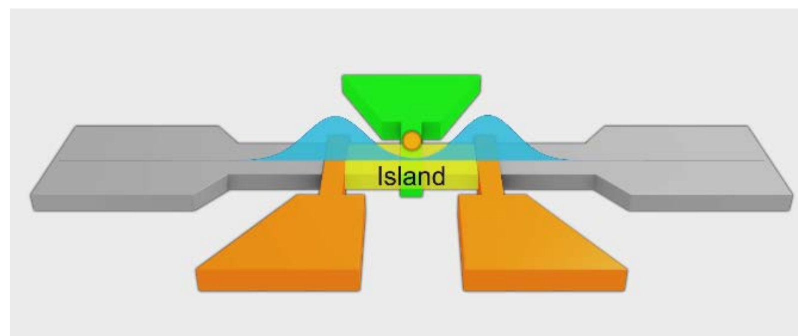
Count the flow of electrons in a second

# Revised definition of electric current






## Single Electron Transport (SET)

(Sources: NIST, PTB, NPL)

# Continuity of Electrical Standards

*Defining constants:*

$e = 1.602\,176\,634 \cdot 10^{-19}$ C

$h = 6.626\,070\,15 \cdot 10^{-34}$ J s

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

$R_{K\text{-}90} = 25\,812.807\ \Omega$

$$K_J = \frac{2e}{h}$$

$$R_K = \frac{h}{e^2}$$

*Revised SI:*

$K_J = 483\,597.848\,416\,984$ GHz/V

$R_K = 25\,812.807\,459\,3045\ \Omega$

$K_J/K_{J\text{-}90} - 1 = -1.1 \cdot 10^{-7}$

$R_K/R_{K\text{-}90} - 1 = 1.8 \cdot 10^{-8}$

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# Implementation

| Criteria | CCEM 17-09 recommended actions |
| --- | --- |
| $2.5\ d \le U$ | no action is necessary until the next recalibration (or measurement). |
| $U < 2.5\ d$ | numerical correct or recalibrate before the standard's next use for traceability. |

| Instruments | U ($\times 10^{-6}$) | d ($\times 10^{-6}$) | U < 2.5 d |
| --- | --- | --- | --- |
| Zener voltage standards | 0.06 | +0.11 | Yes |
| Calibrators (DC voltage) | 0.7 | | No |
| DMM (DC voltage) | 1.5 | | No |
| | | | |
| Standard resistors | 0.3 | +0.018 | No |
| Calibrators (Resistance) | 1.0 | | No |
| DMM (Resistance) | 1.0 | | No |
| | | | |
| Calibrators (DC current) | 2.6 | +0.087 | No |
| DMM (DC current) | 1.0 | | No |

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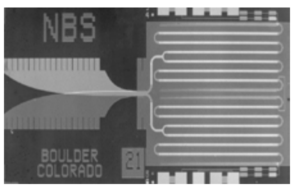
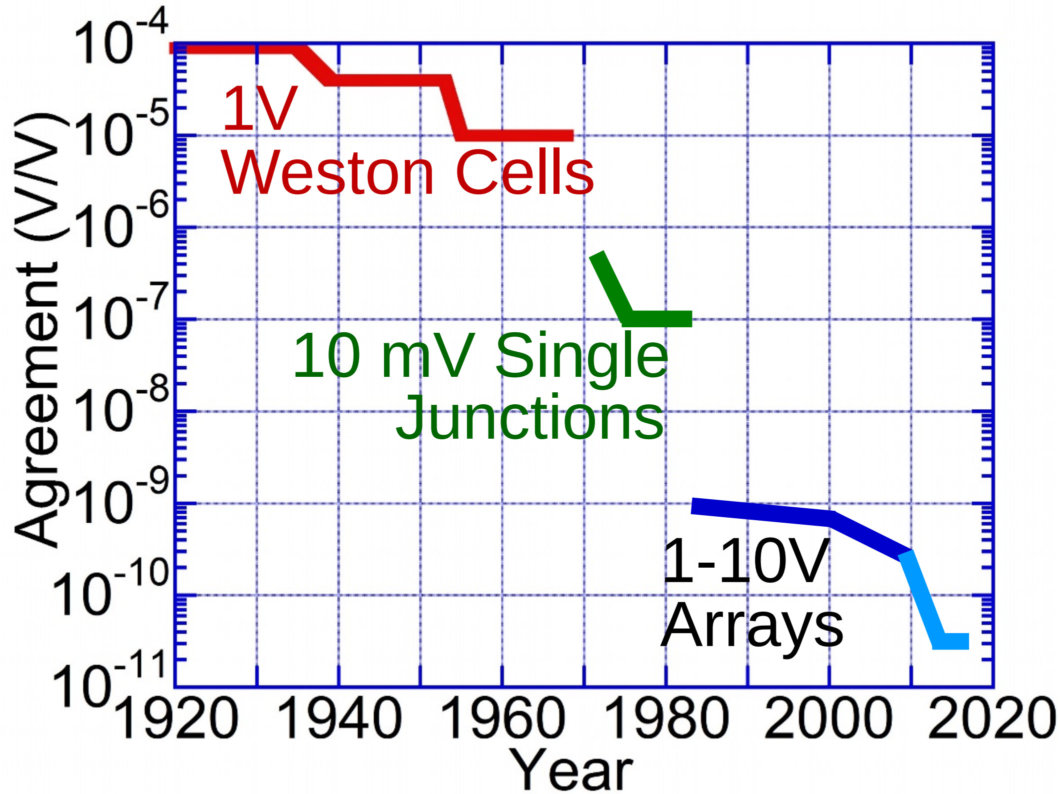
# DC Voltage Metrology



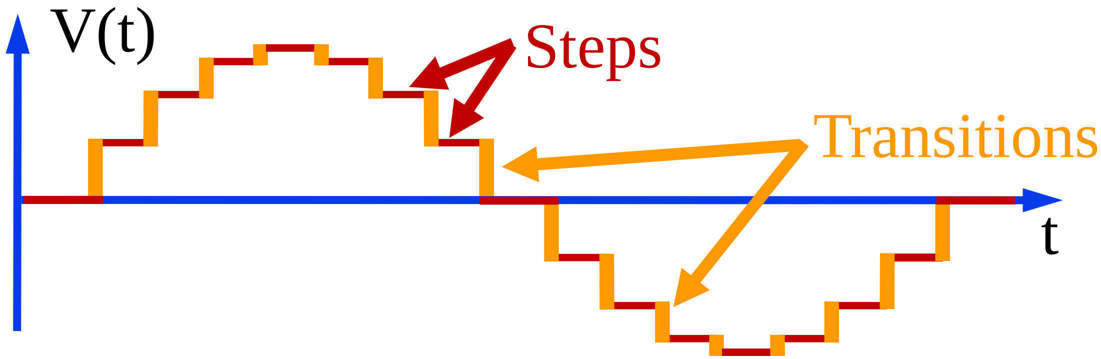

| Voltage | Mean Difference | U |
|---|---|---|
| 10 V | 0.22 nV | 2.2 nV |
| 1.018 V | -0.51 nV | 1.8 nV |

(Source: NIST)

# AC Voltage Synthesis

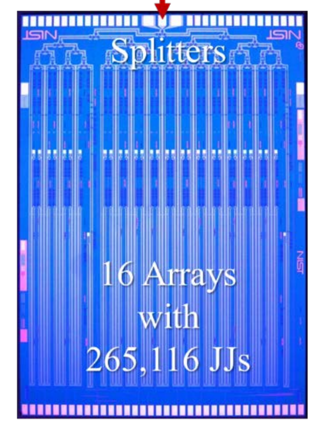
## Programmable Josephson Voltage Standard (PJVS)

- step-wise approximated sine waves




(12 x 17) mm² PJVS Chip

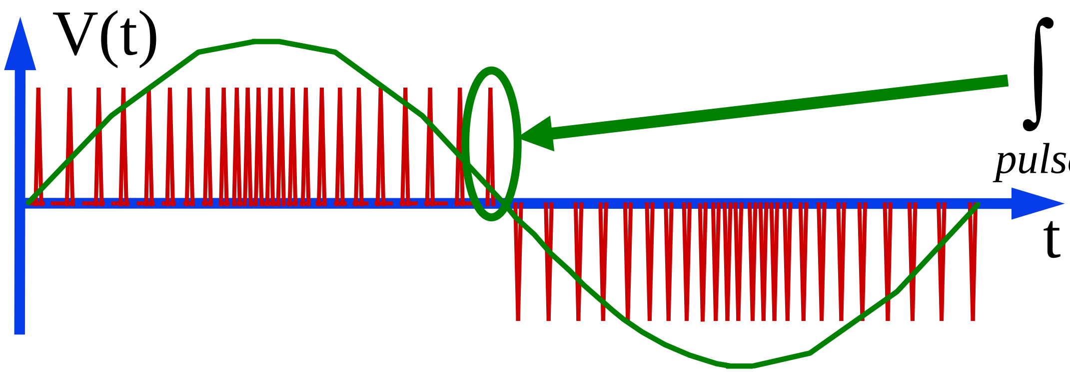
Microwave Input




DC Input/Output Pads

## Josephson Arbitrary Waveform Synthesizer (JAWS)

- direct digital synthesis with current pulse sequences




$$\int_{pulse} V(t) = \frac{h}{2e}$$

(Source: NIST)

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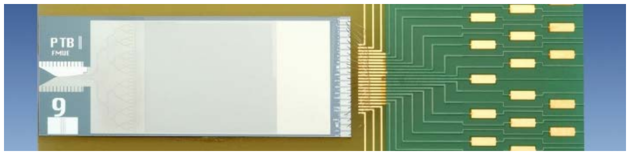
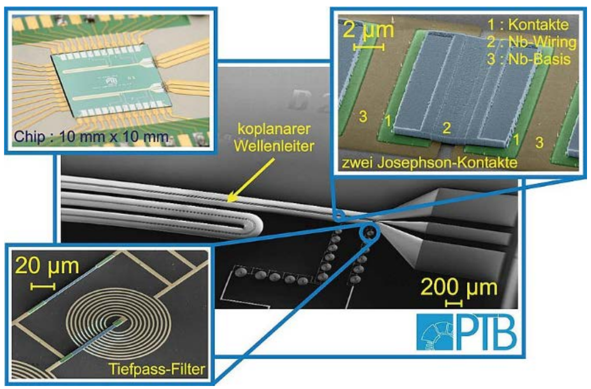
# AC Voltage Metrology



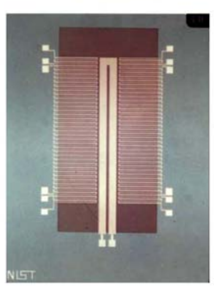




Thermal Converter


|←1 cm→|

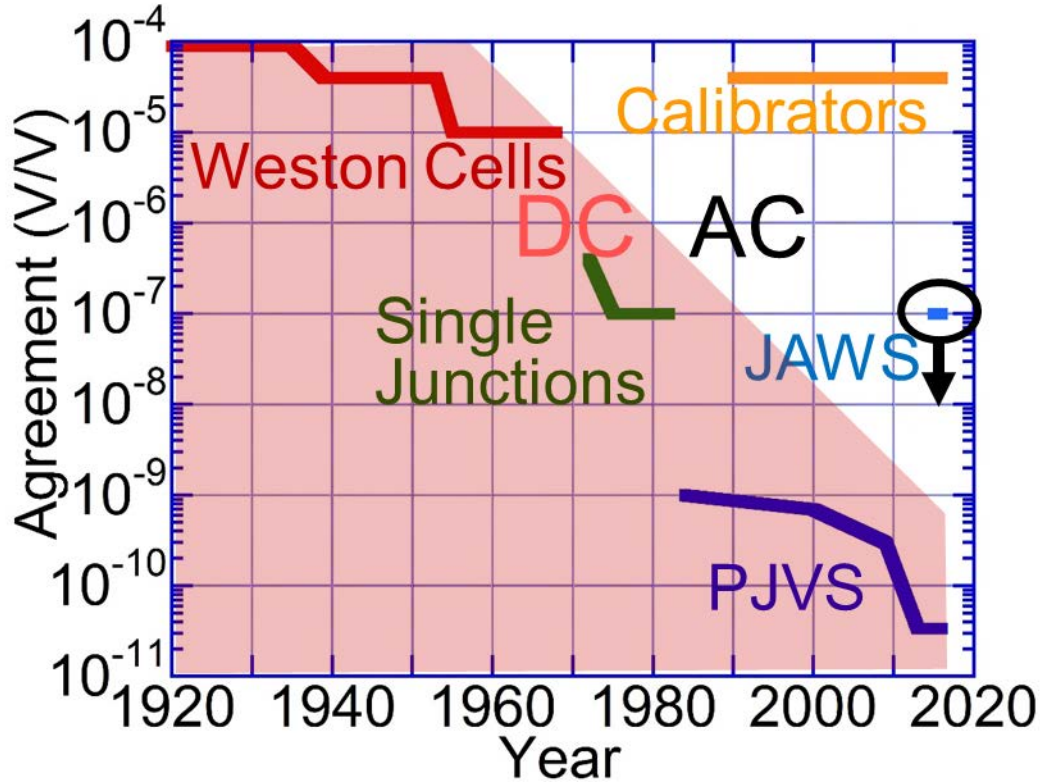
Few ppm

Multijunction Thermal Converter




|←2 mm→|

Sub ppm




(Sources: NIST, PTB)

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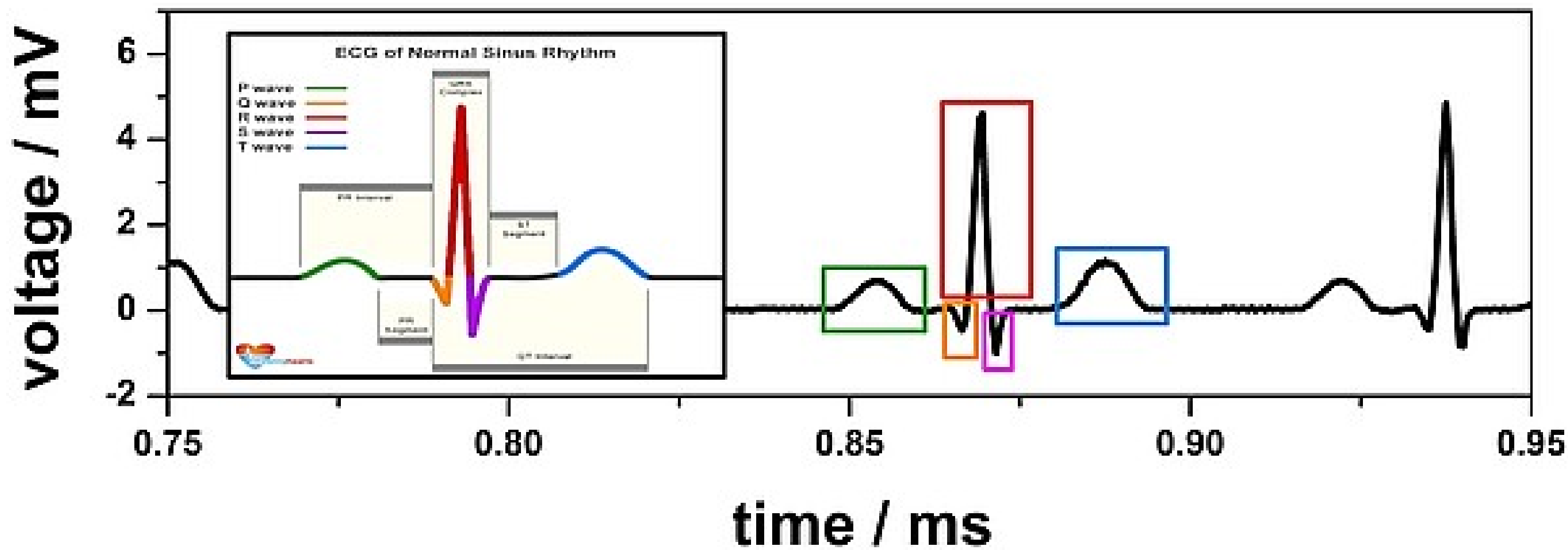
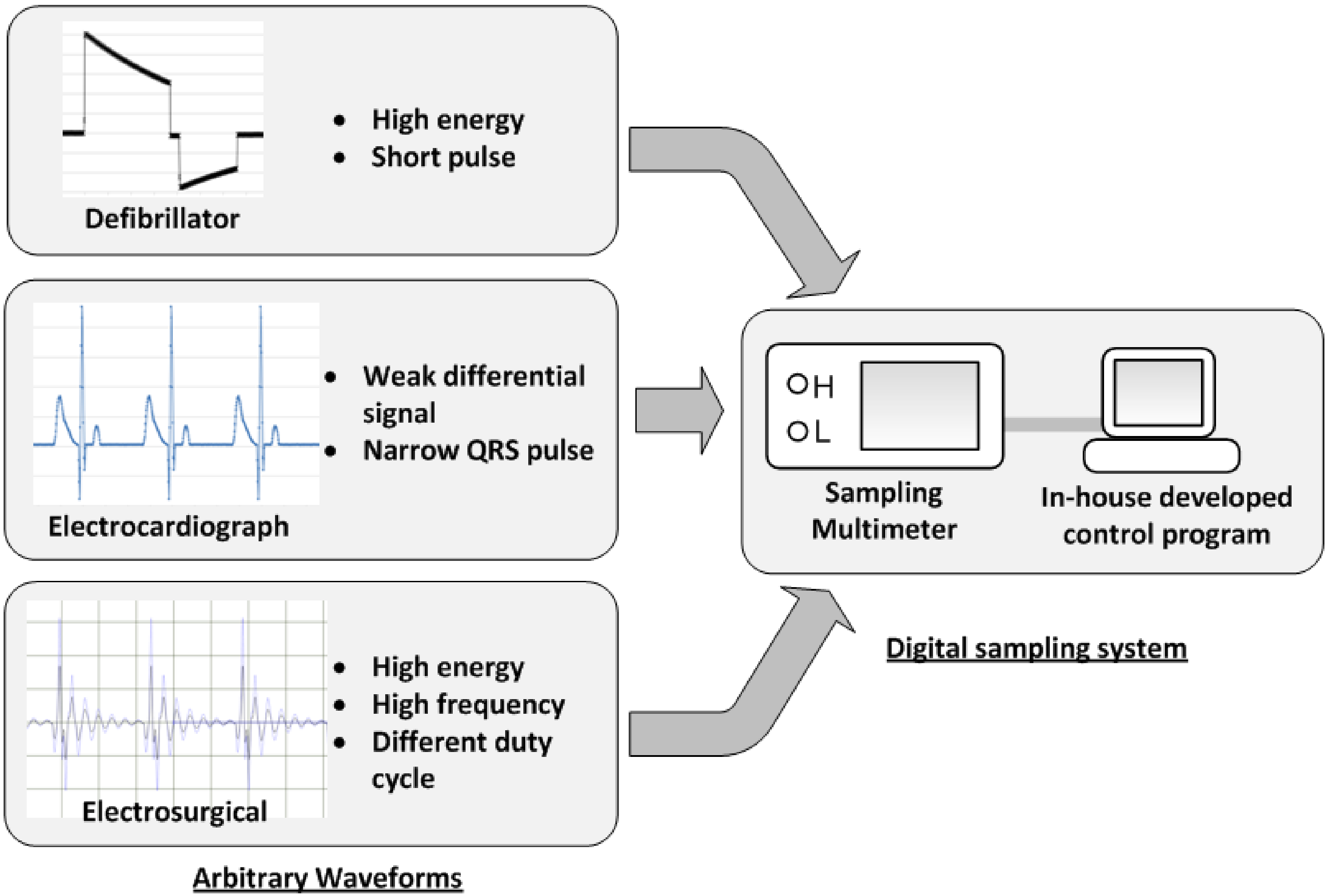
# Medical Application

- Synthesis of Normal sinus ECG waveform by JAWS




(Source: PTB)

# Medical Application



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# Electrical Testing

- RCD tester
- Insulation resistance
- Clamp meter
- Withstanding voltage
- Electrical safety analyzer

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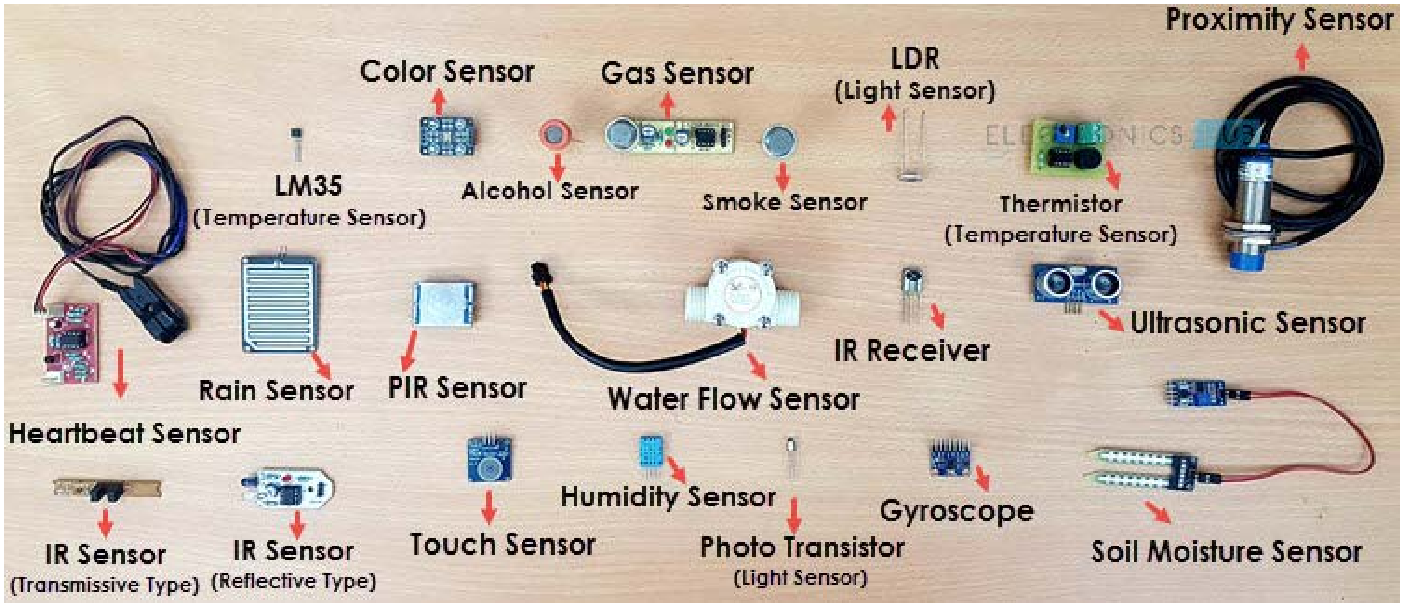
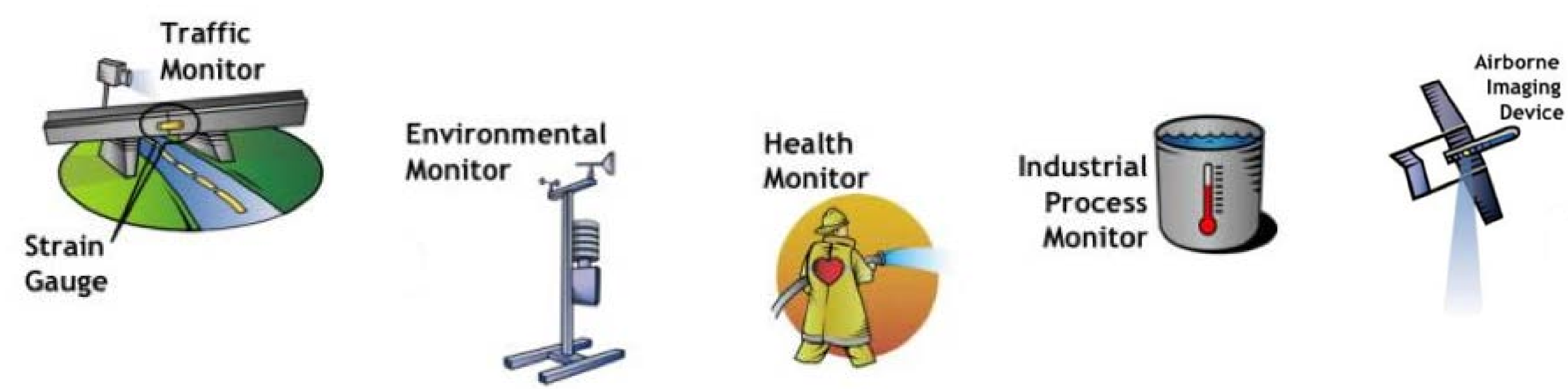
# Advanced Sensors

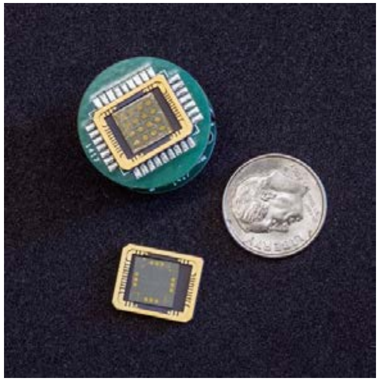


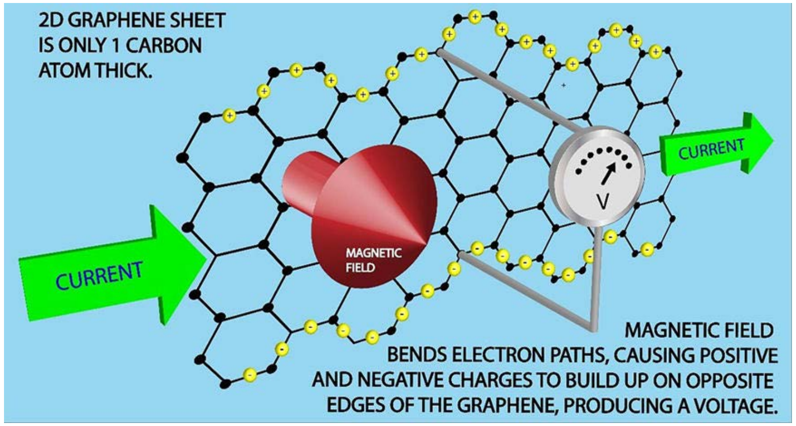



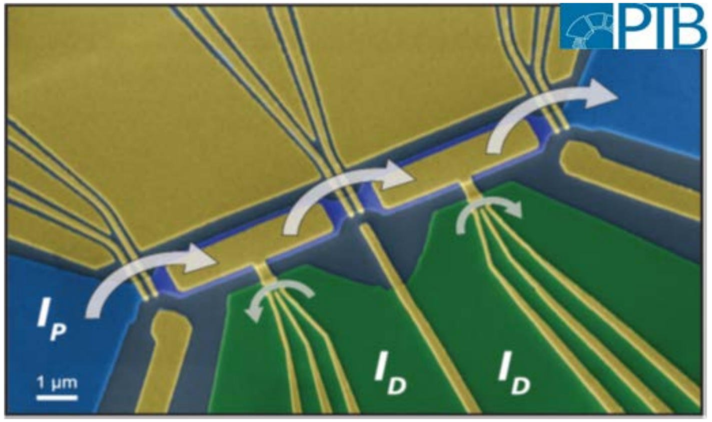

(Sources: Electronicshub.org, logisticsarena.eu)

# Future development

- Lower magnetic field for QHR
- Higher operating temperature for quantum standards
- Quantum calibrators (DC/AC)
- SET
- Ultra Low Current Amplifier (ULCA)


Graphene based QHR




(Sources: NIST, PTB)

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# Conclusions


- The development of quantum measurement standards have evolved rapidly in recent years.
- These measurement standards ensured the accuracy of electrical calibration for new opportunities in the technology age.

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# Thank you!