Measurement, Backaction, and Future Standard in Ultra-small Force Metrology
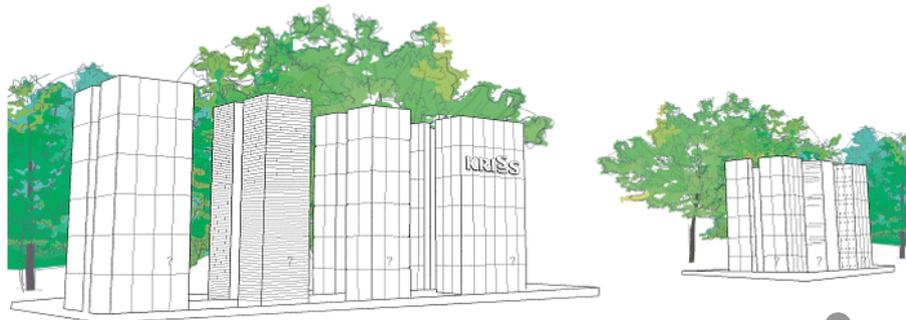
2010.11.24

Korea Research Institute of Standards and Science

Center for Emerging Measurement Standards

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KRISS 한국표준과학연구원

Contents

KRISS

Better Standards, Better Life!

Introduction – Wide, wide range of small force

Small force measurement and application

1 mN

Mass balances

Instrumented indentation

1 µN

AFM

1 nN

Optical tweezers

1 pN

Magnetic resonance force microscopy

1 fN

1 aN

Bell Lab
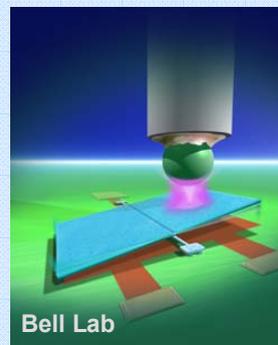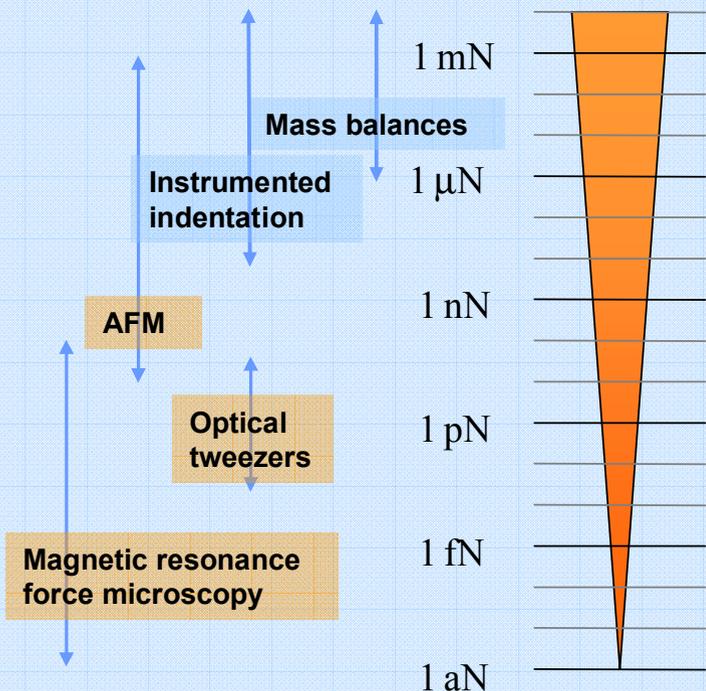
Casimir & Non-Newtonian Force
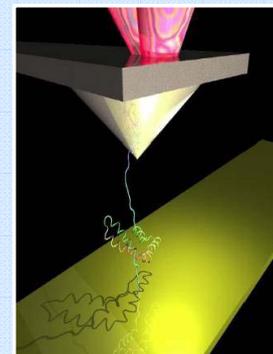
Single molecule pulling

& Solving scientific puzzles with a unprecedented sensitivity

Inspired by J. Pratt's viewgraph
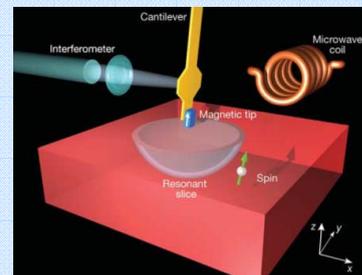
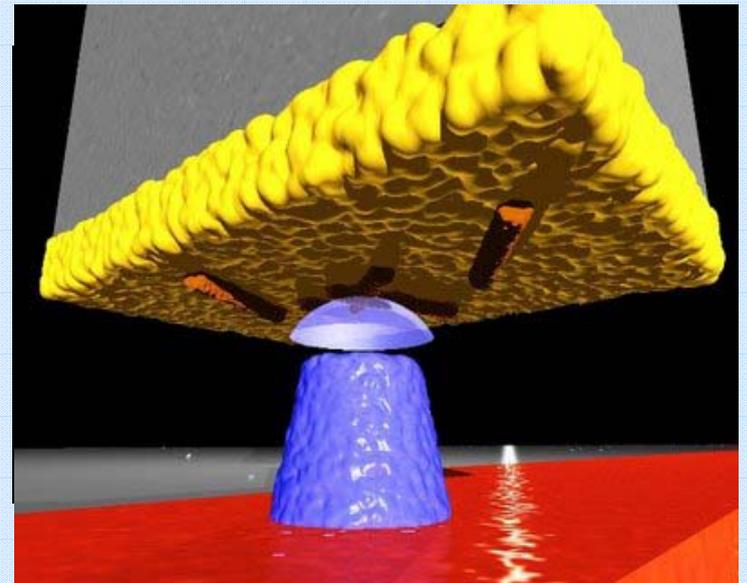**Single electron spin resonance & Nano-MRI**

Introduction – U-small force measurement

Ultra-small force for extreme magnetic detection

Increased resolution by a factor of 100 million than a conventional MRI !!!
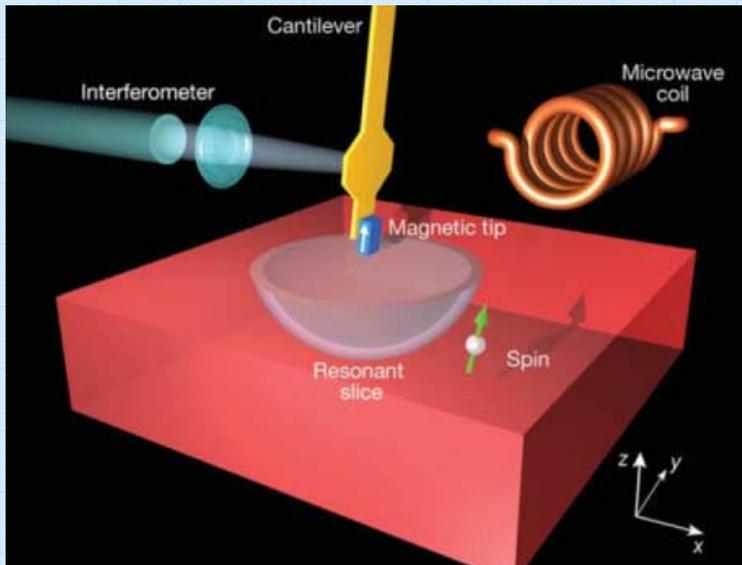
Single electron spin detection (IBM, 2005)

Nano-MRI of a single virus (IBM, 2009)

Introduction – U-small force measurement

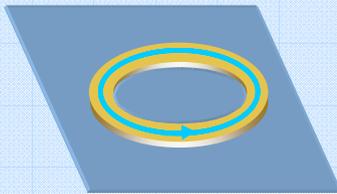## Ultra-small force for extreme magnetic detection

Persistent Currents in Metal Rings – 20-years unsolved problem

$$\psi_n(x+L) = \exp\left[2i\pi\frac{\phi}{\phi_0}\right]\psi_n(x)$$

Bloch wave vector k_n

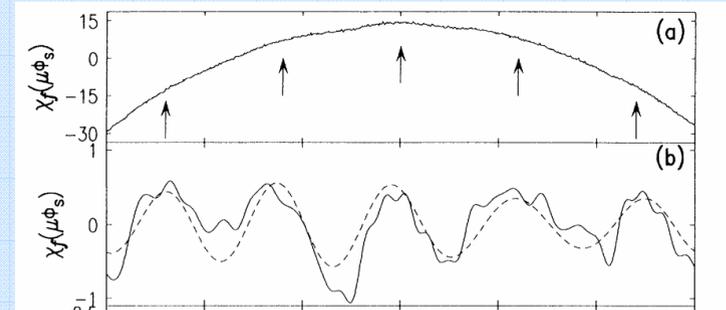$$k_n = (2\pi/L)(n + \phi/\phi_0)$$

$$\phi_0 = h/e$$

Gold ring

Energy spectrum and related quantities ~ periodicity of h/e !

$j = -\partial F/\partial\phi$ in thermal equilibrium

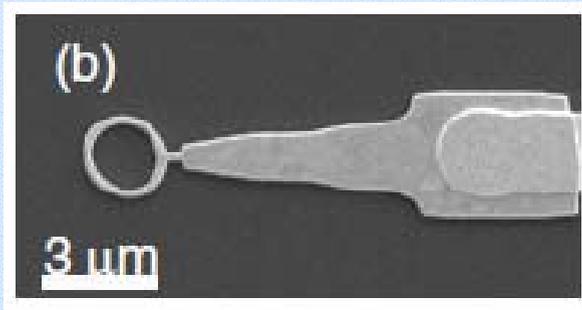PC of I ~ 1 nA at T < 1 K

SQUID data (IBM, 1991)

Introduction – U-small force measurement

Ultra-small force for extreme magnetic detection

Persistent Currents in Metal Rings – 20–years unsolved problem

Scanning SQUID

Micromechanical detector

Solved !

Sensitivity
~ 2.9 aN/Hz$^{1/2}$ at T = 300 mK
~ 20 pA/Hz$^{1/2}$

Sensitivity ~ 5 nA/Hz$^{1/2}$

Yale, 2009

Introduction – Back-action
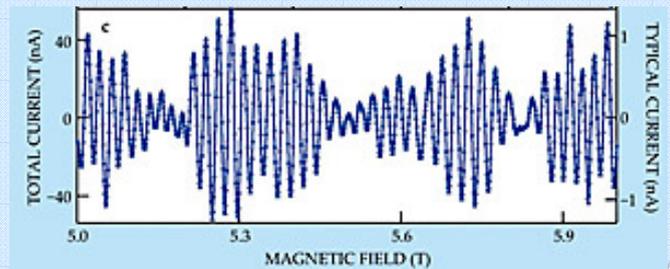
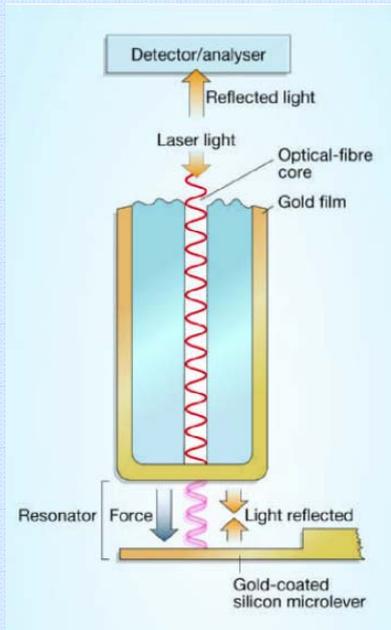## Quantum back-action

$$\Delta x \, \Delta p \geq \frac{\hbar}{2}$$

light

electron

Δx
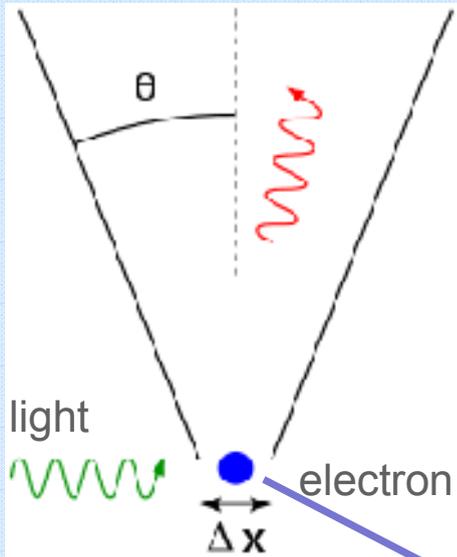
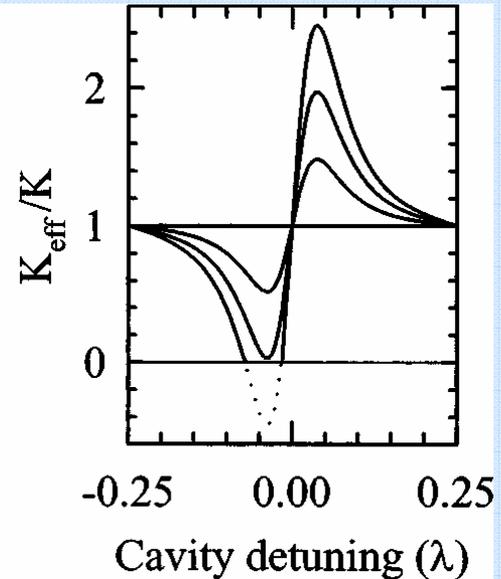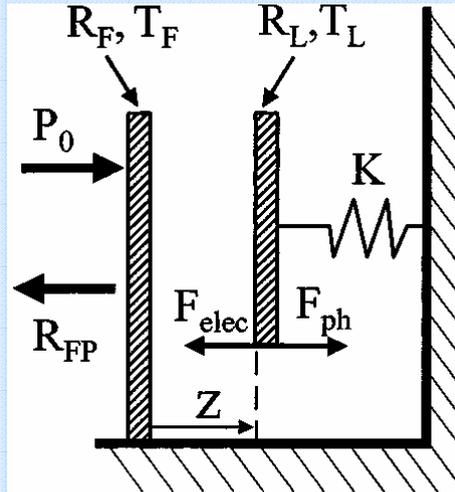**Quantum mechanics demands that the act of measurement must affect the measured object.**

Fundamental limit of measurement !

Back-action in opto-mechanical systems

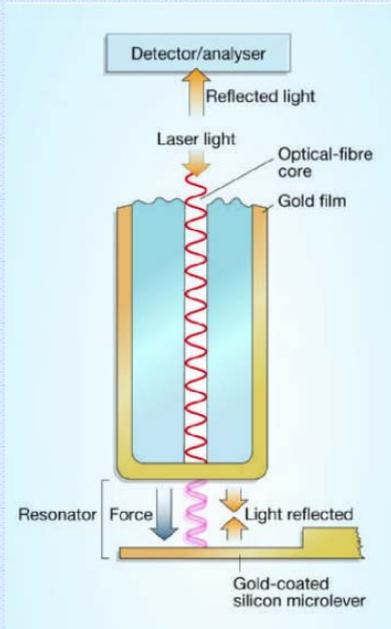**Probing photons affect the mechanical properties of a force sensor.**

Fabry-Perot cavity

Effort to increase resolution (or optical power) may cause the instability of the system.

Introduction – Back-action

Back-action in opto-mechanical systems

Probing photons affect the mechanical properties of a force sensor.

Optical cooling of a micro-cantilever !
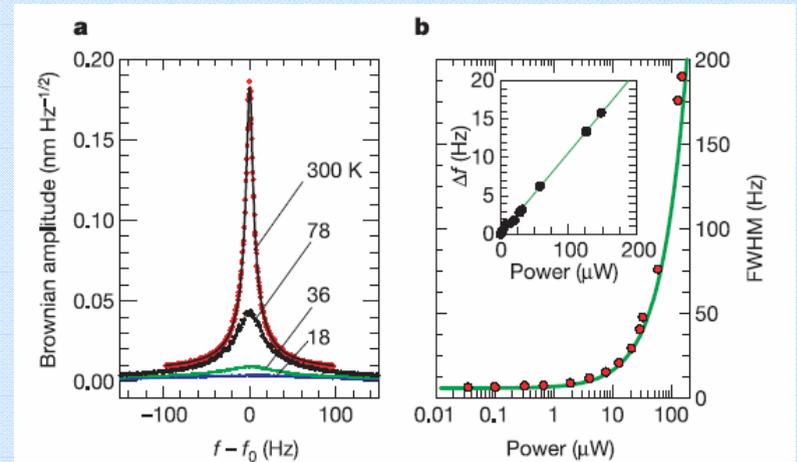

$$\frac{1}{2}k<x>^2=\frac{1}{2}k_B T$$

Figure 2 Cavity-induced cooling of the lever vibrational resonance. **a**, Brownian motion

Si microlever with k = 0.008 N/m coated with a gold film

Nature 432, 1002 (2004) Metzger & Karrai

Introduction – Back-action

Back-action in opto-mechanical systems

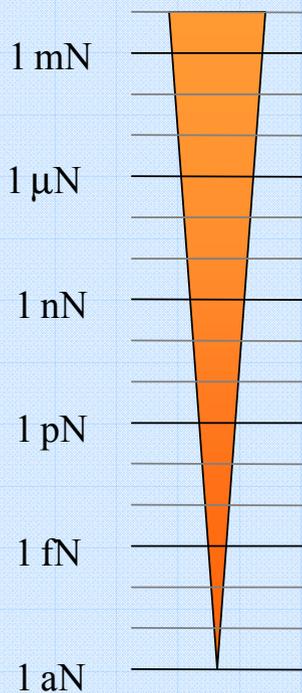**Laser Interferometer Gravitational-Wave Observatory (LIGO)**

Hanford, Washington   Livingston, Louisiana

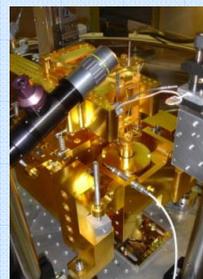# Introduction – Small Force Standard

Micro-Newton force standard

1 mN

1 μN

1 nN

1 pN

1 fN

1 aN

"Electrostatic Force balance" (NIST, PTB, NPL since 2000)

NIST

PTB

NPL
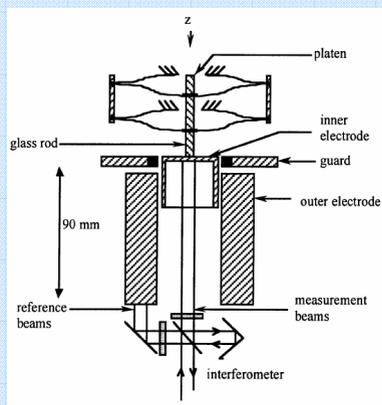
KRISS

Range: 10 nN ~ 1 μN
Target Resolution: < 1 nN

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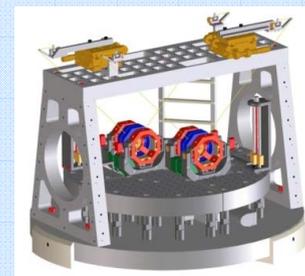
Introduction – Small Force Standard

Where to explore?

$$S_f^{1/2} = \left(\frac{k_s k_B T}{\pi f_0 Q} \right)^{1/2}$$

Vacuum

Sensitivity vs. T

Low T

NIST   PTB

KRISS

300 K
100 K
10 K
1 K

1 aN   1 fN   1 pN   1 nN   1 μN   1 mN

Single e spin (IBM, 2005)

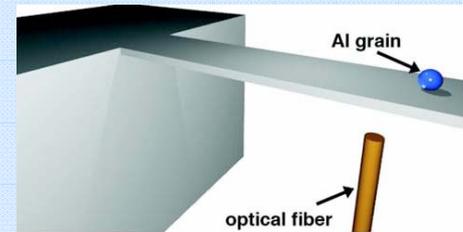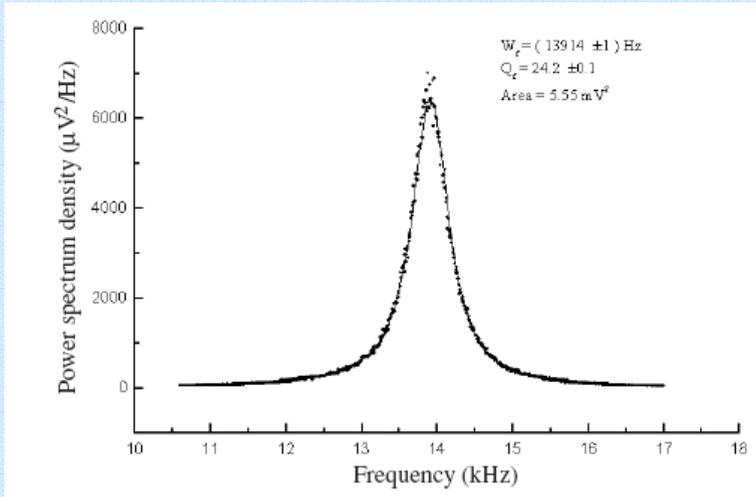Persistent current in metal ring (Yale, 2010)
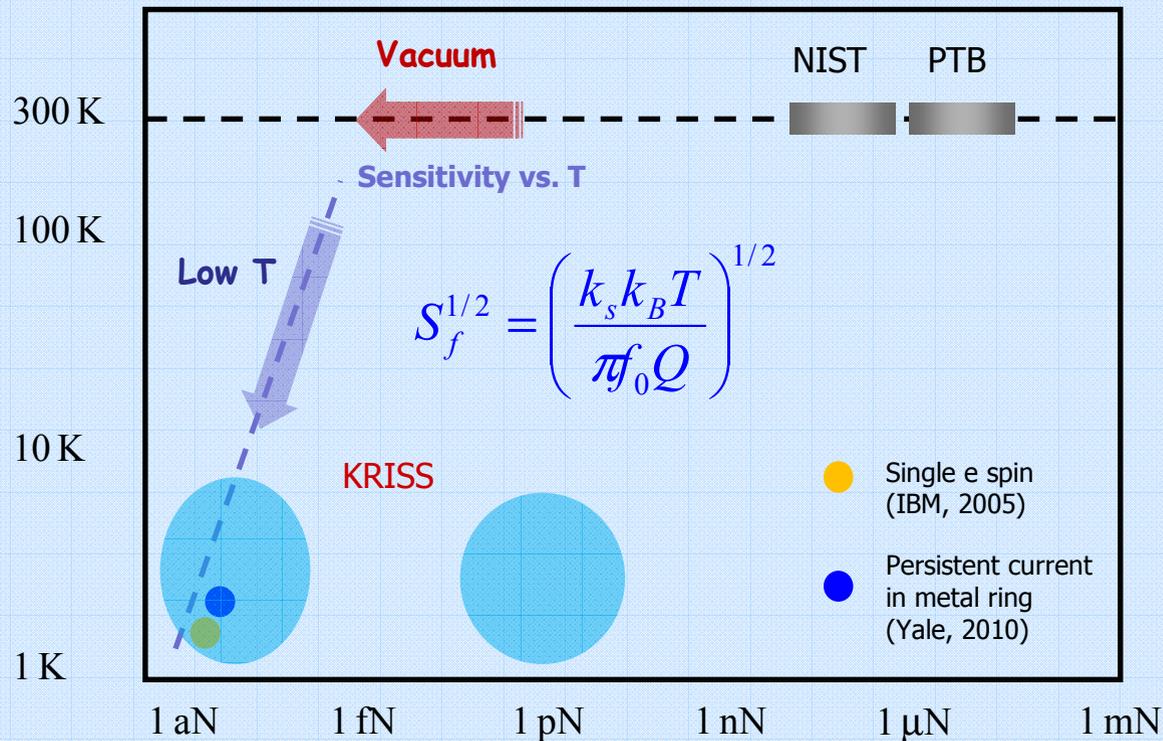
Introduction – Small Force Standard

Difficulties in calibrating pN-aN force sensors
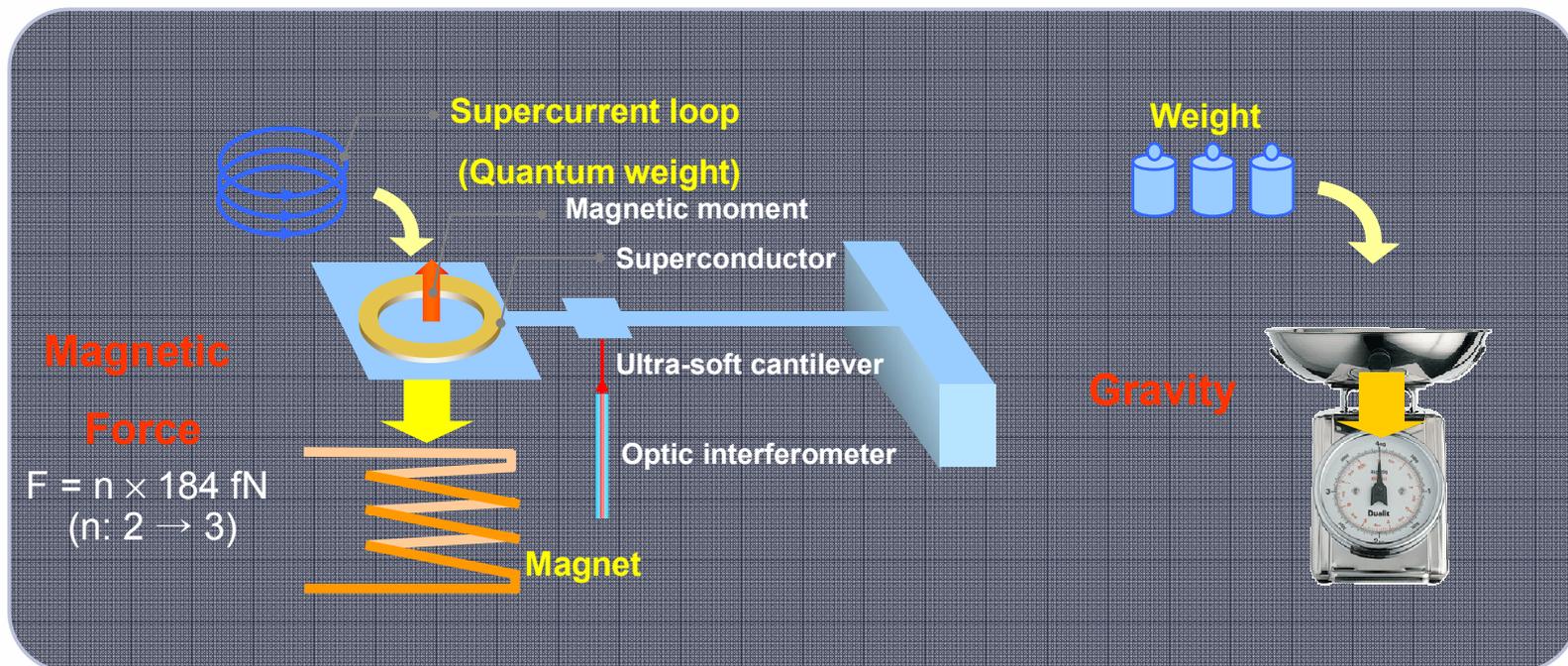
Noise spectrum method is the only method available.

$$\frac{1}{2}k<x>^2=\frac{1}{2}k_BT$$

$\checkmark$ $T_{cantilever} = T_{fridge}$ assumed
$\checkmark$ 10 ~ 20 % uncertainty
$\checkmark$ No other method to confirm it

Principle of flux-quantum based force realization

Magnetic flux quantums in a superconducting ring

Supercurrent loop
(Quantum weight)
Magnetic moment
Superconductor

Weight

Magnetic Force

$F = n \times 184$ fN
(n: 2 → 3)

Ultra-soft cantilever

Optic interferometer

Magnet

Gravity

~ 0.2 pN (static) for each flux quantum

Quantum-by-quantum

$$F = n \times m_Q \frac{dB}{dz} = n \times k\ \Delta z$$

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Rough estimation

◆ **Quantum force standard**

$$F = n \frac{\pi}{2\mu_0} \frac{h}{2e} R \left(\frac{dB}{dz} \right) g(R, w, \Lambda)$$

2.584792 fN/(μm·T/m)

Constant Force Steps

◆ **Quantum voltage standard**

$$V_n = n \frac{h}{2e} f$$

(0.4835979 GHz/μV)⁻¹
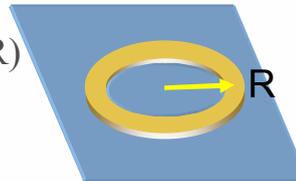
Constant Voltage Steps

$$F = m \frac{dB}{dz}$$

Magnetic Moment $m = I_s \cdot \pi R^2$ (R : hole radius)
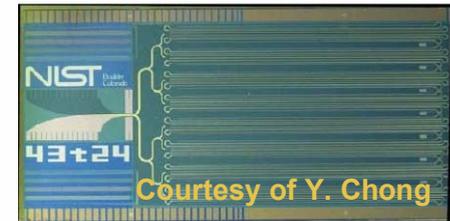
Current $I_s = \Phi / L$

Inductance $L = \mu_0 R$ (for width > 2R)

$\mu_0 = 4\pi \times 10^{-7}$

R

Josephson effect

Sinusoidal driving frequency f

NIST

Courtesy of Y. Chong

You can find details of the theory in APL **90**, 073117(2007)
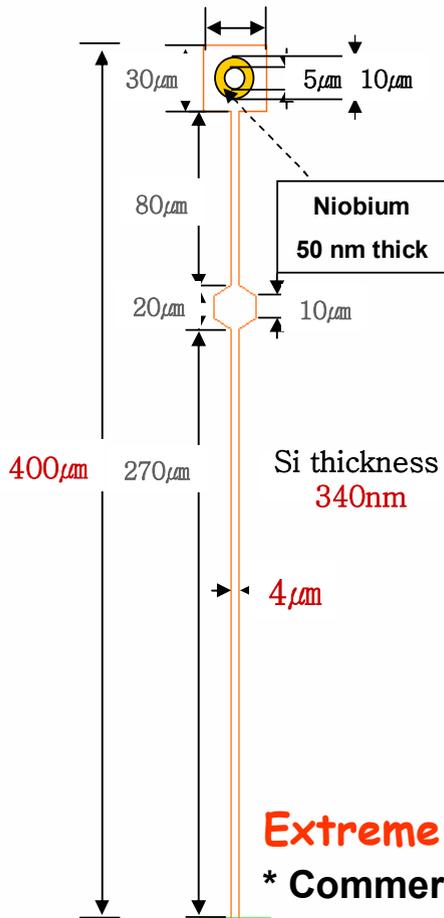
Contents

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Better Standards, Better Life!

Device Fabrication – 1st Generation

30μm   5μm   10μm

Niobium
50 nm thick

80μm

20μm   10μm

400μm   270μm   Si thickness
340nm

4μm

Cantilever 2007

detach   crack

Cantilever 2008

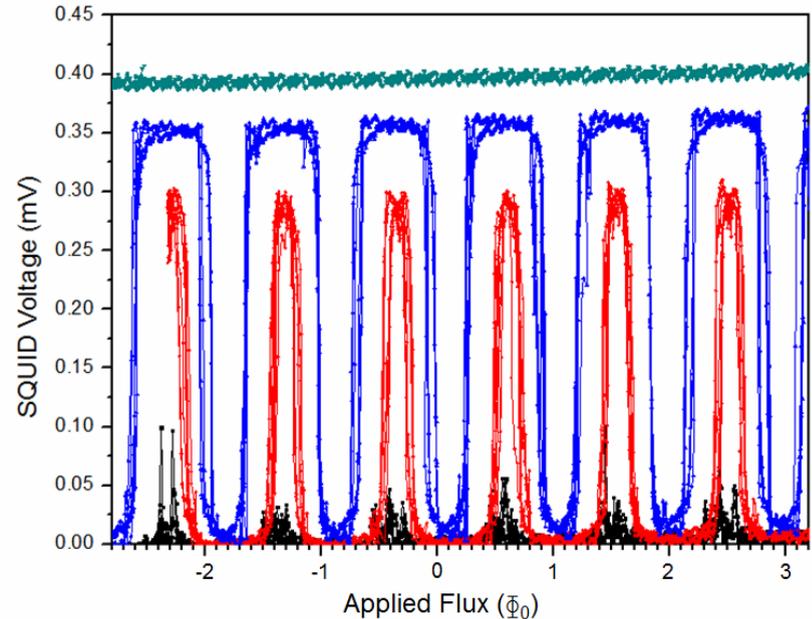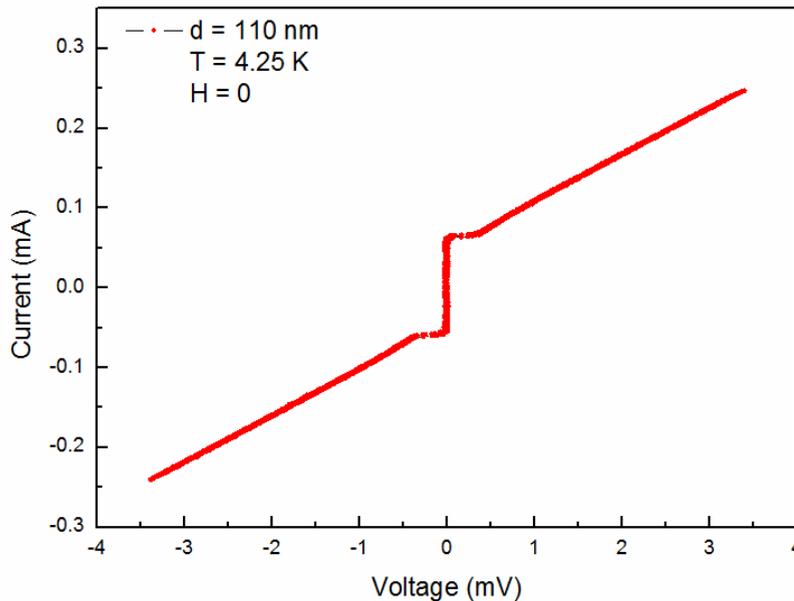**To confirm**
superconductity
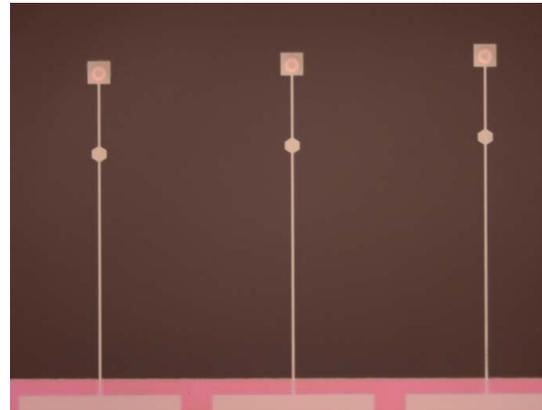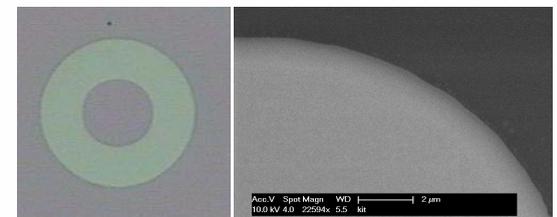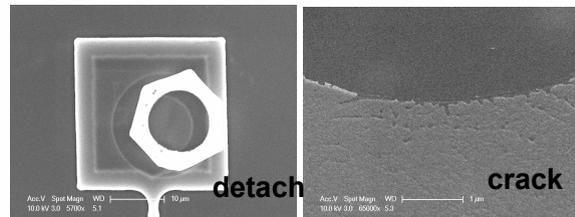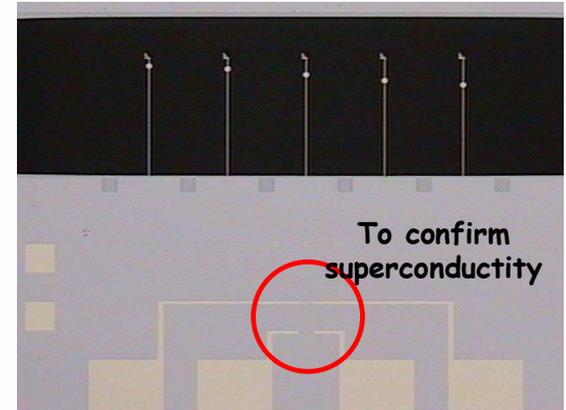
Extreme Dimension for 10^{-4} N/m !!!

* Commercial cantilever: 0.1~50 N/m, 2~4 μm thick

Device Fabrication –2nd Generation

Toward counting flux quantums: SQUID-on-cantilever

Characteristics of a fabricated SQUID on a bulk Si

Electrical counting of flux quantums !

Contents

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Better Standards, Better Life!

Low T Characterization

Atto-Newton force sensitivity at 3.0 K

Thermal noise spectrum of cantilever vibration

$k \sim 7.13 \times 10^{-5}$ N/m
$f_0 \sim 1250$ Hz
$Q \sim 31000$

Force sensitivity

$$F_{min} = (2kk_BT/\pi f_0 Q)^{1/2}$$

$$= 6.9 \text{ aN} / \text{Hz}^{1/2}$$

Laser

Low T Characterization

Optical back-action

Optic fiber

x

cantilever

Reflectivity

$\lambda/2$

x
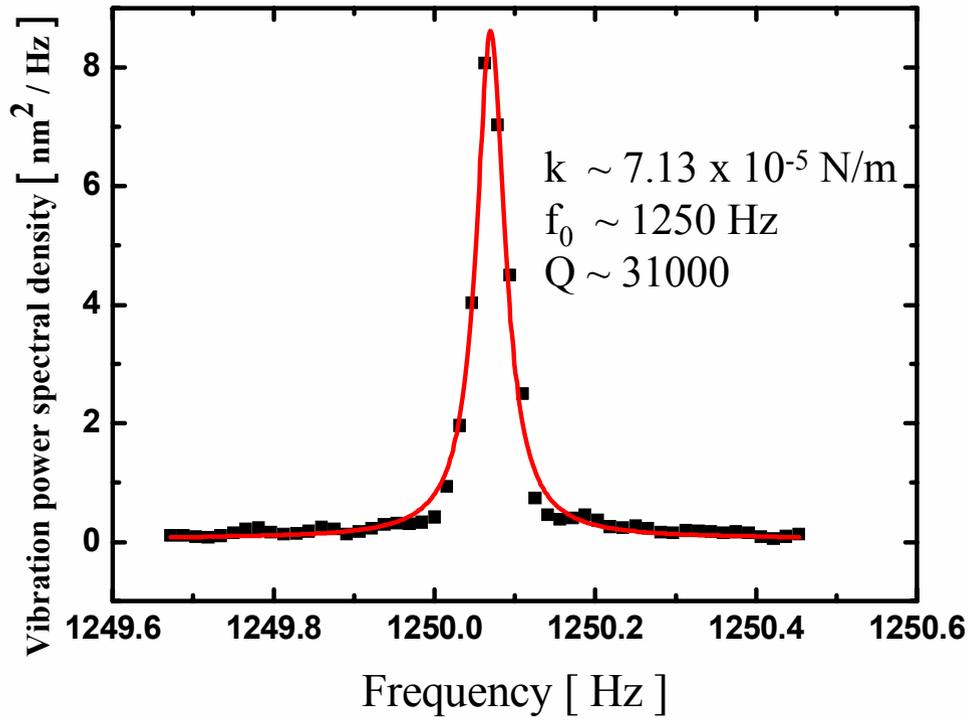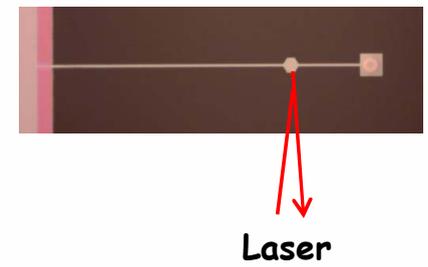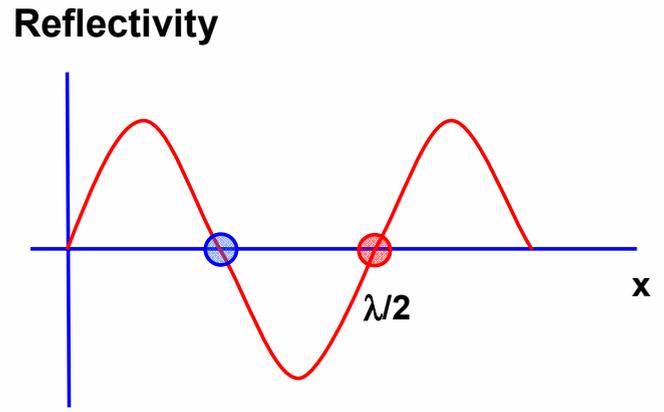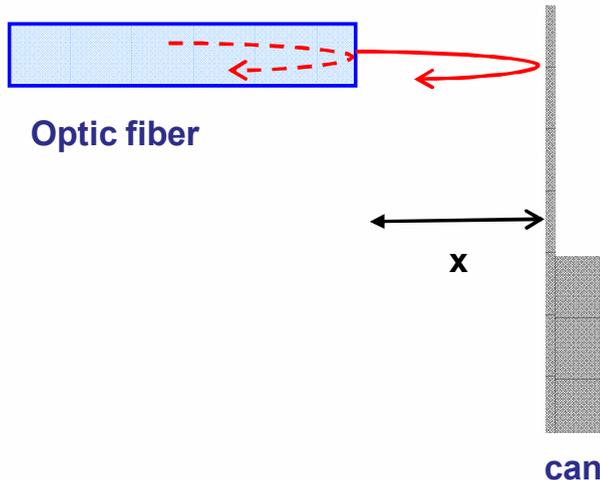
* Our strengths

- Got nano-stages and techniques to align laser at an exact target position.

- Low cryogenic T capability

Optical back-action

So, the best way is to use the smallest laser power for cantilever calibration?

Not always.
In that case, you have to fight with bad SNR from a detector.

Get better detectors, or develop a novel small force standard and calibration methods.

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Better Standards, Better Life!

Superconductivity of a Nb ring on a SiN cantilever

H_{ext} = 20 Oe

T_c ~ 8.7 K
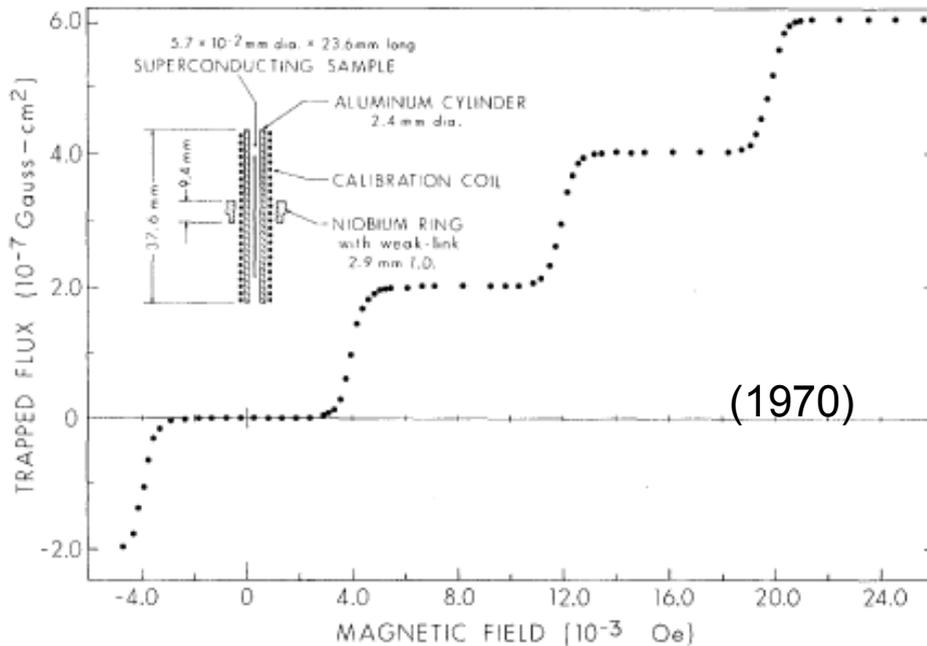
Operating T

Coil for magnetic excitation
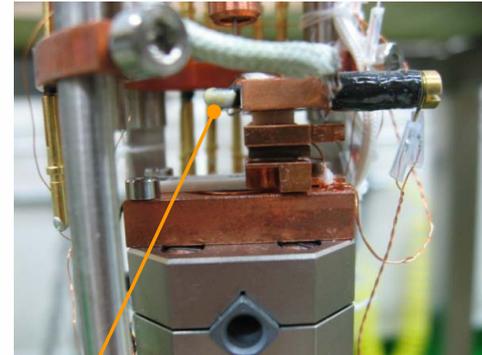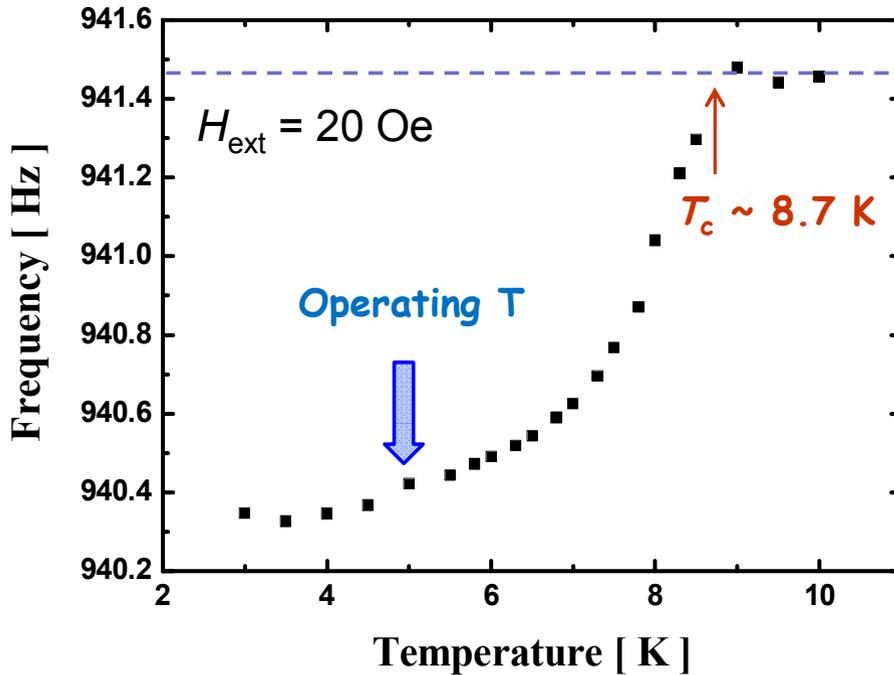
- Meissner effect at $T < T_c$

Proof-of-principle Experiment

Flux trapping and mechanical detection

Early demonstration of flux quantization in an aluminum cylinder

- **Magnetic detection**

- **T ~ 1 K**

(1970)

Proof-of-principle Experiment

Flux trapping and mechanical detection

Detection scheme

1. At T = 12 K (> T_c), apply an external magnetic field at a target value

2. Field-cool the device from 12 K to 5 K (<< T_c)

3. Turn off the external field

4. Drive the device using a magnetic excitation coil with AC current

5. Measure a resonance frequency shift

6. Increase T to 12 K

7. Repeat steps from 1 to 6 with a different field value
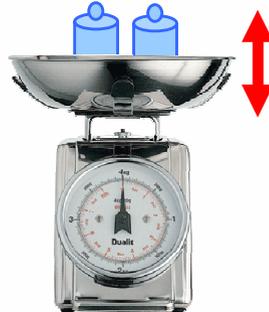
Proof-of-principle Experiment

Flux trapping and mechanical detection

What we did, and what we will do in next steps:
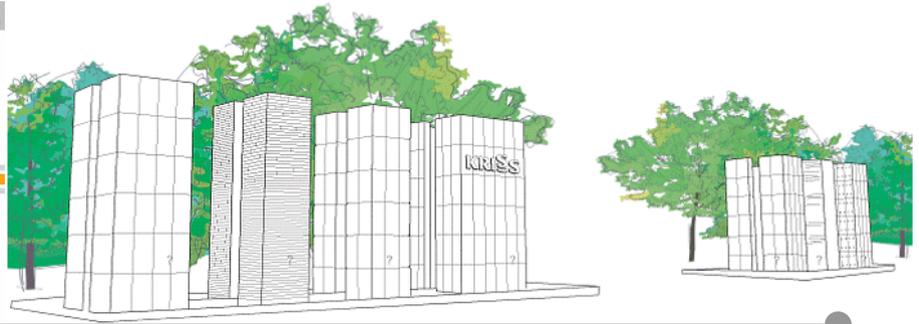
Quantum Weight
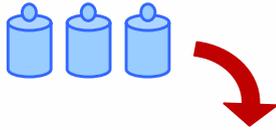
Weight Loading   Weight Counting   Gravity ON

Contents

1. Introduction

2. pN Realization Set-up

3. Device Fabrication

4. Low T Characterization

5. Conclusion

Conclusion

◆ **We must keep pushing the limit of small force standard, being patient and supportive.**

◆ **Deep understanding of coupling between a micro-mechanical system and a probe (photon, qubit,…), or back-action, is required.**

◆**The KRISS project for flux-quantum-based small force standard made big steps this year: 1) electrical counting of flux quantums, 2) flux trapping and mechanical detection.**

Thank you, IMEKO colleagues !

Special thanks to Dr. Dae-Im Kang
and Dr. Y. K. Park, and Dr. M. S. Kim