Single Crystal Diamond NEMS Switch

Meiyong Liao
Optical and Electronic Materials Unit
National Institute for Materials Science, Japan

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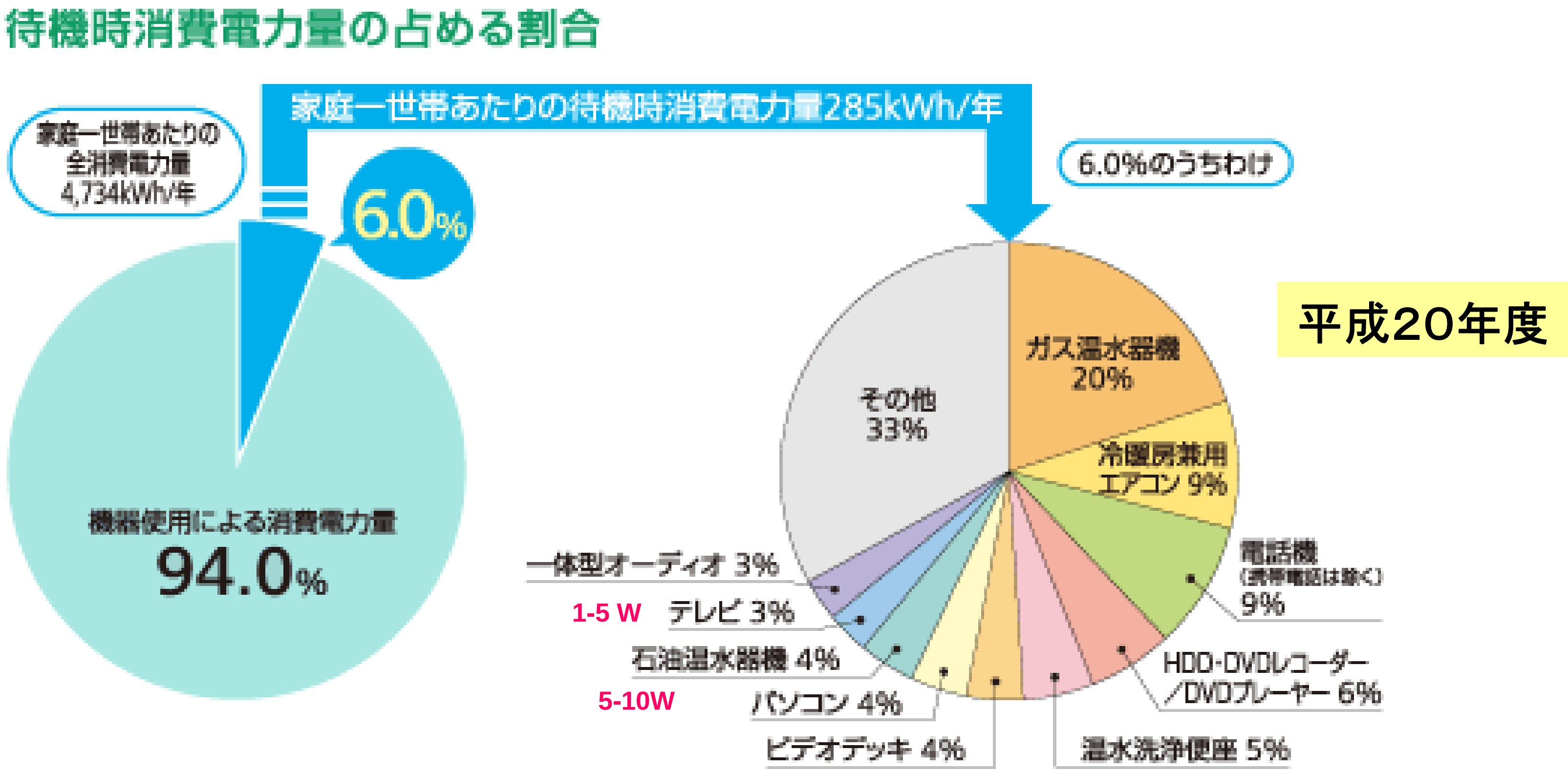
待機電力消費---半導体スイッチ

機器が非使用状態、若しくは何らかの入力(命令指示)待ちの時に定常的に消費している電力

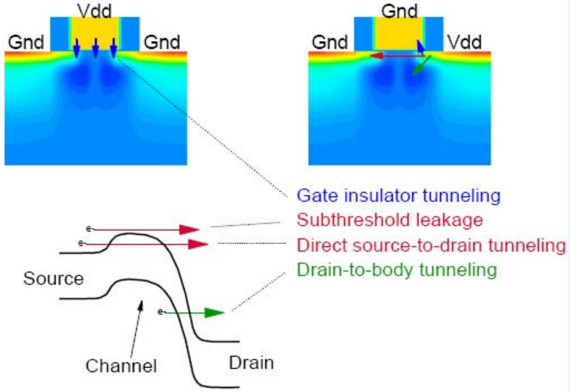


➢普段の生活のエネルギー消費を減らす必要！

✓ナノマシンスイチ:省エネルギー技術(ゼロ)として期待 。

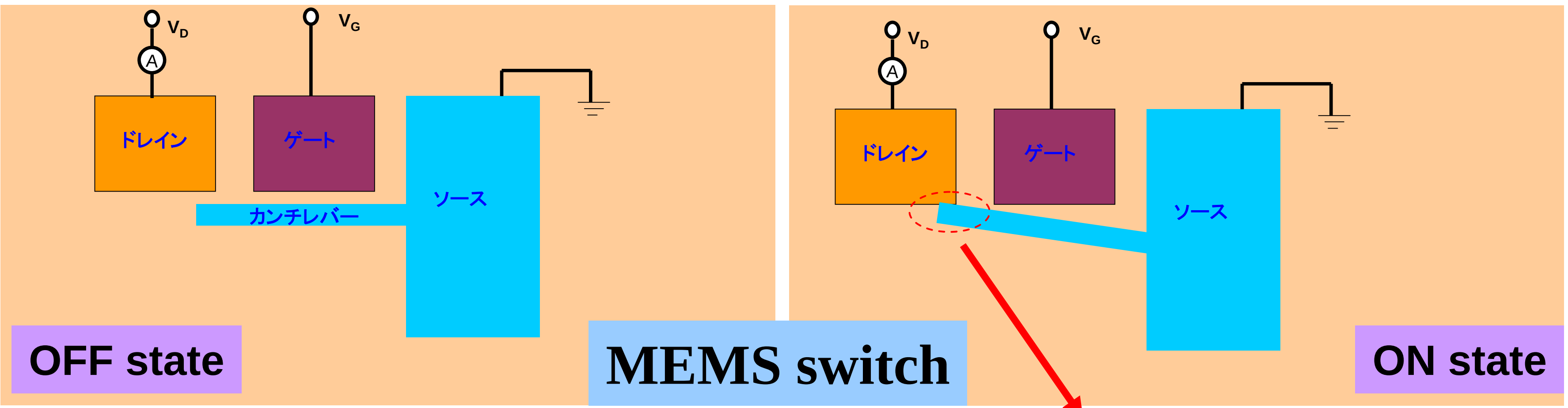
MEMS switch: Merits

Semiconductor devices consume power in OFF state!



Advantages over semiconductor devices

Property	MEMS switch	Semiconductor switch
Leakage	zero	Large
Power loss	~0	>1 uW
Speed	Slow（10μs）	Fast（10ns）
Insertion loss	Small（<0.2dB)	Large（>1dB）
Isolation	Good（>30dB)	Poor（<25dB）
Linearity	Excellent	Poor
High and low temperatures	Excellent	Poor



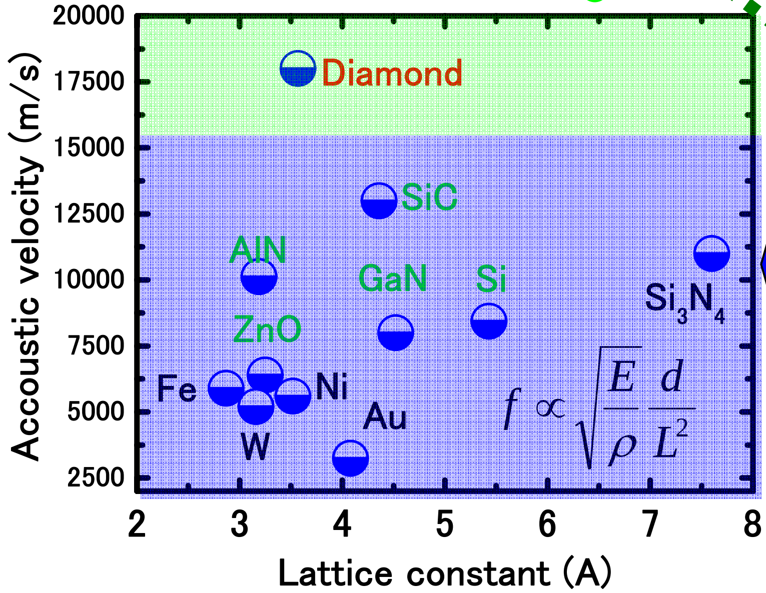
But, poor reliability due to

(i) Surface stiction
(ii) Mechanical abrasion

Diamond MEMS: route toward high reliability and high performance

Property	Diamond	SWCNT	Graphene	Si	SiC	AlN
Density (g/cm³)	3.52	1.3-1.4	>1	2.33	3.21	3.3
Young's modulus (GPa)	1200	~1000	~1000	130	450	100-400
Hardness (GPa)	100	—	—	10	33	11.8
Friction coffecient	<0.05	0.01-2	0.07-0.5	0.4-0.6	0.2-0.5	0.4
Strength (GPa)	5.3	13-55	130	1.0	5.2	0.29
Thermal conductivity($Wcm^{-1}K^{-1}$)	24	35	10-53	1.5	5	1.75
bandgap (eV)	5.5	0-2	~0	1.1	3.3	6.2
Electron moblity ($cm \cdot V^{-1}s^{-1}$)	4500	100,000	200,000	1450	900	426
Hole mobility(cms^{-1})	3800	4,000	>100,000	480	120	14
Breakdown field ($MVcm^{-1}$)	10	—	—	0.3	3.5	1.5
Dielectric constant	5.5	—	—	11.8	9.7	8.9

Current MEMS: intrinsic limitations !!



Merits

- The highest Young's modulus
- The lowest friction coefficient
- Hydrophobic surface
- Highest thermal conductivity
- Tunable electrical conductivity

The best material

Challenges and Strategies in Diamond MEMS

What process….? **What device concept……?**

Difficulties

- ❖**Batch fabrication of single crystal diamond MEMS structures.**
- ❖**Lack of device concepts compatible with the fabrication process.**

Aims

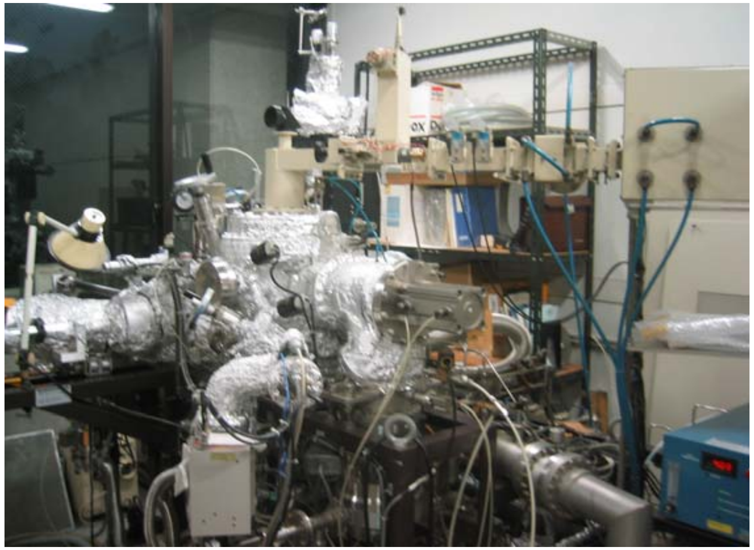
- ➢**Establish unique process for diamond MEMS structures.**
- ➢**Develop high-performance diamond MEMS/NEMS devices.**
- ➢**Create novel device concepts.**

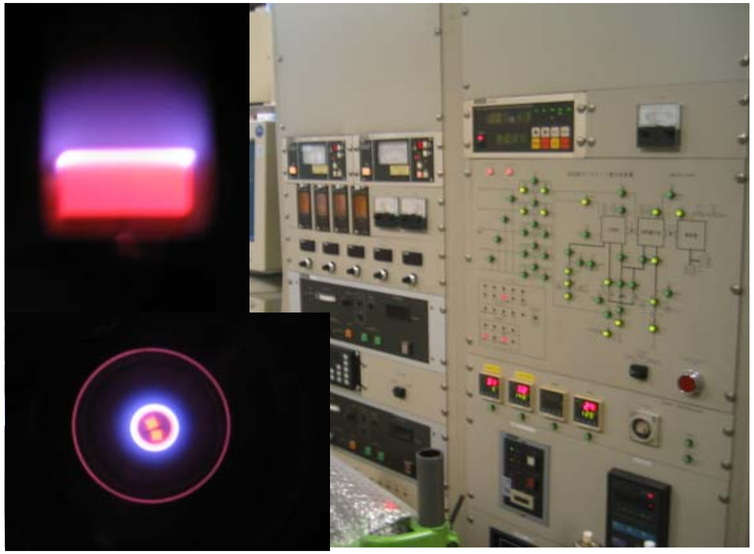
Strategies

- ●**No direct deposition of diamond on sacrificial layers.**
- ●**Diamond-on-Diamond lateral device concept.**

Diamond growth

MPCVD





Parameters:

Gas: H_2 (500 sccm), CH_4 (0.4 sccm)

RF Power: 400 W

Pressure: 80 Torr

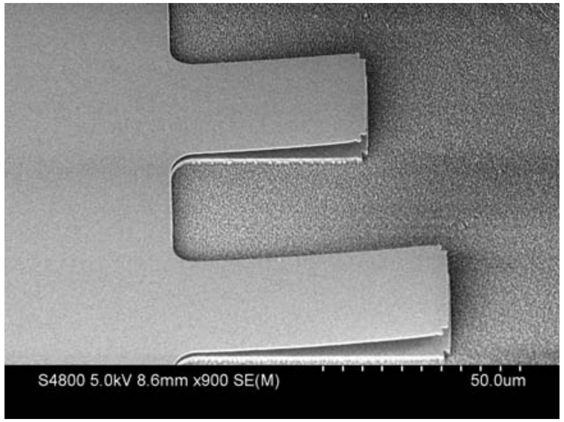
Sub. Tem: 900-950^{o}C

[B]:1000 ppm $10^{20}cm^{-3}$

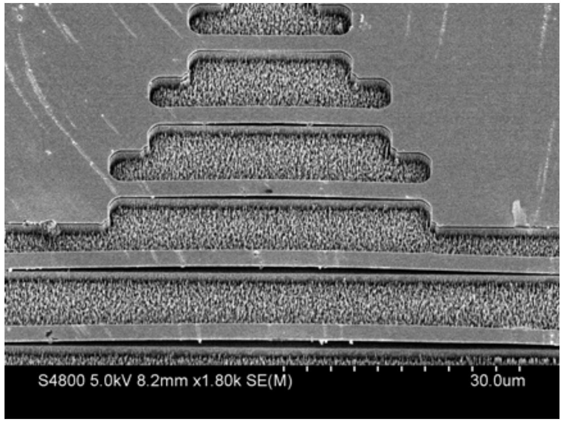
Substrate: Ib (100)---100 ppm nitrogen

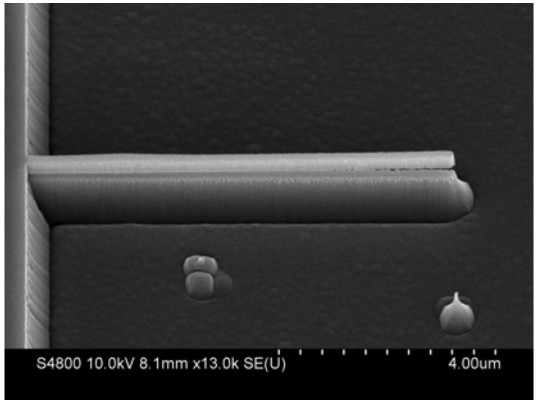
Thickness: 0.1-0.5μm

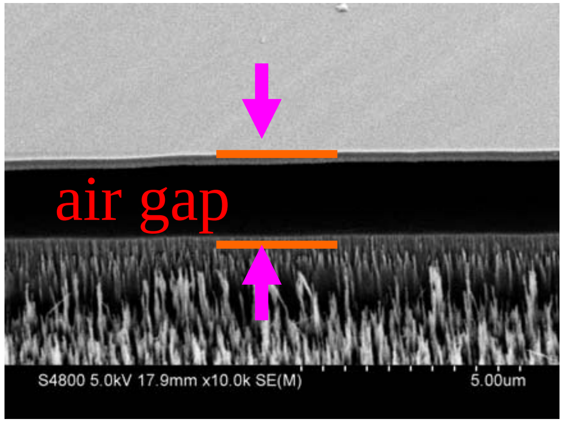
Batch production of micro-scale M/NEMS structures

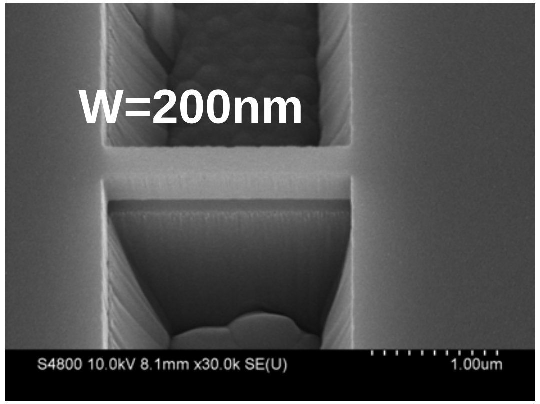


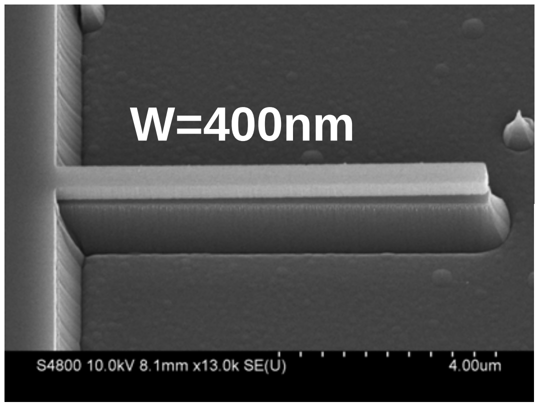
M. Y. Liao, et al,
Advanced Materials *22, 5393 (2010)*



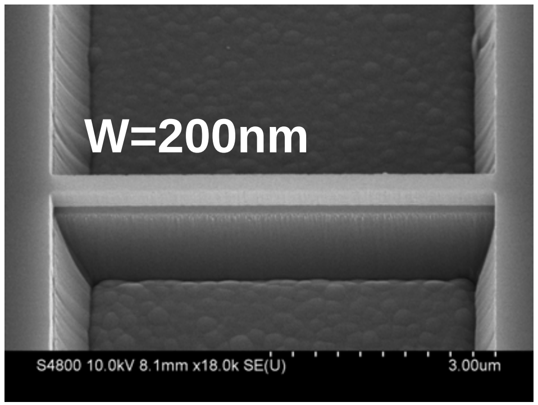




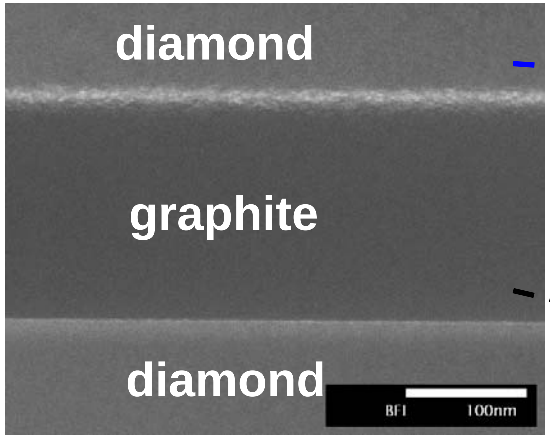


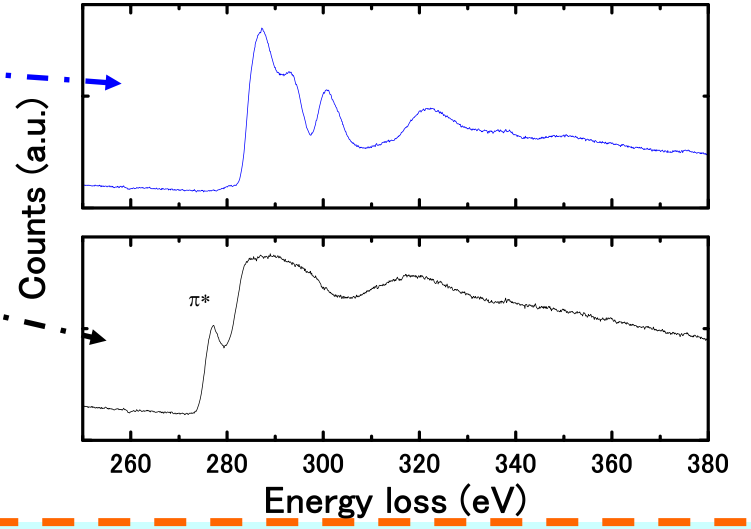


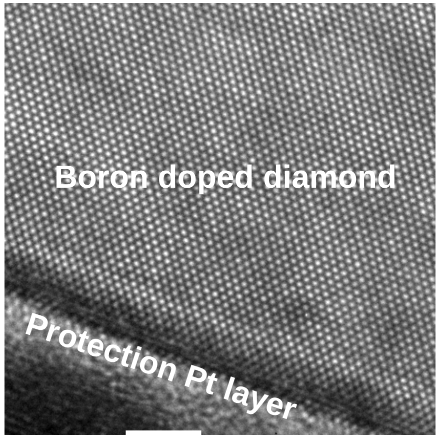
M. Y. Liao, et al,
J. Micromech. Mircoeng. 20，085002 (2010)

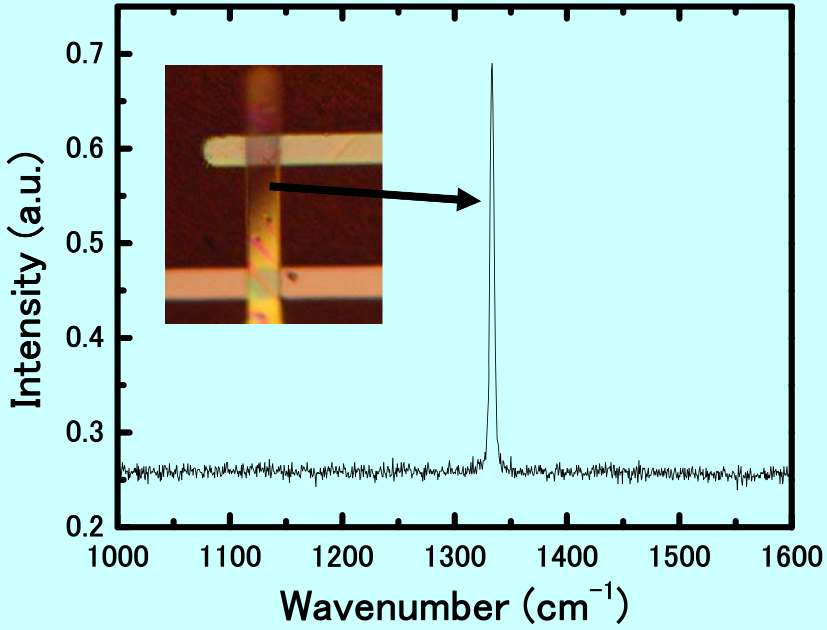


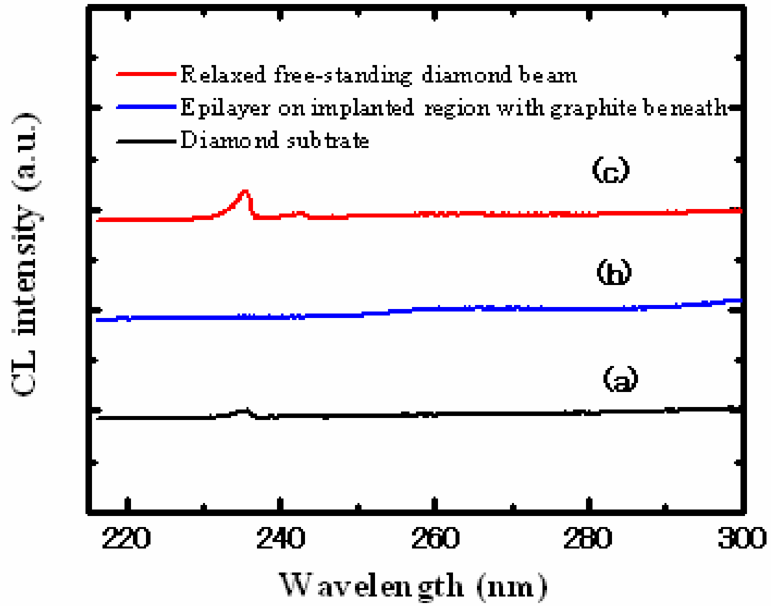
Quality of the MEMS/NEMS structure



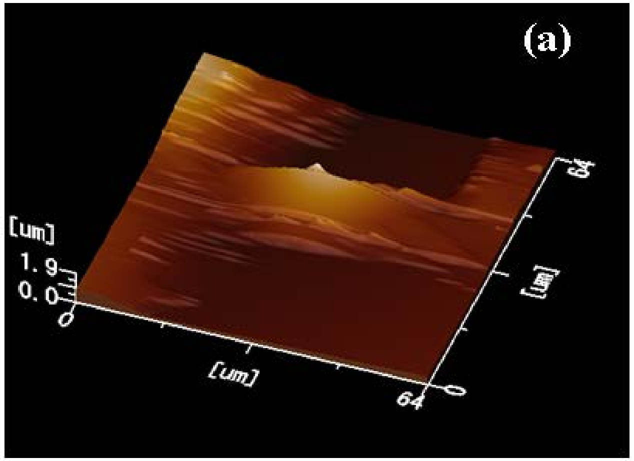


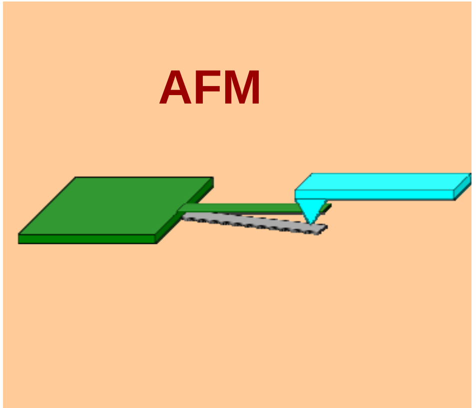


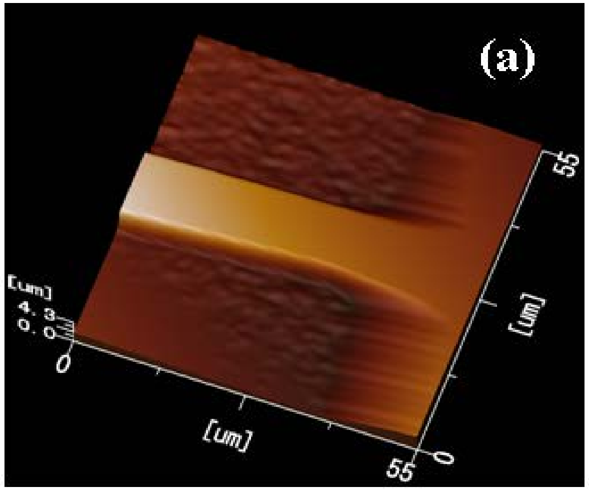


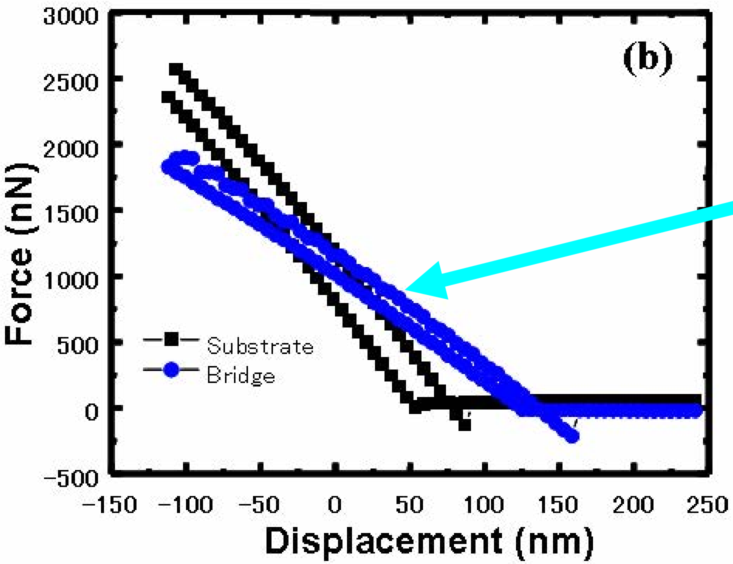


Nanoindentation of MEMS structures

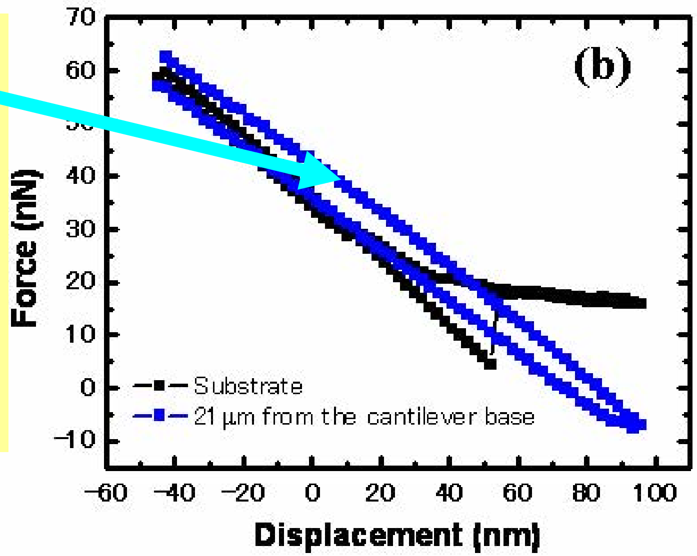








$$\frac{1}{k_{m-x}} = \frac{1}{k_{si}} + \frac{1}{k_{dia-x}}$$



Young's modulus: 800±200 GPa (Calibrated by Si cantilever)

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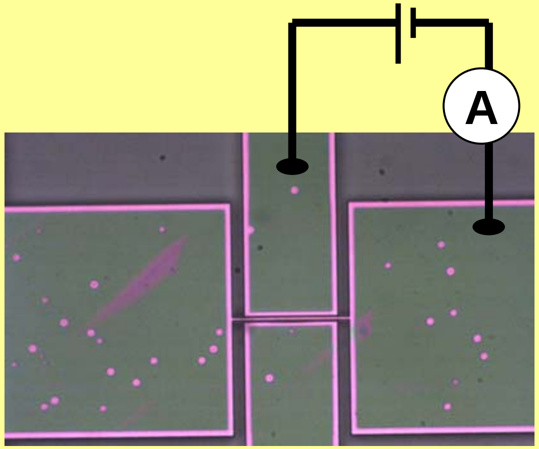
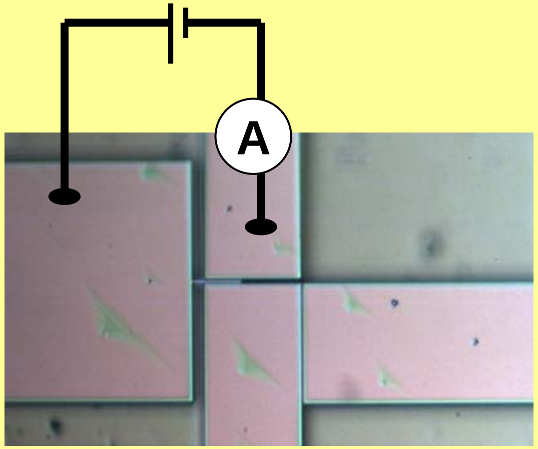
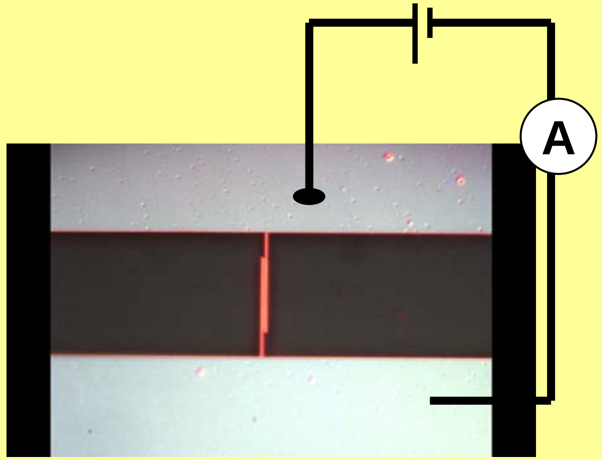
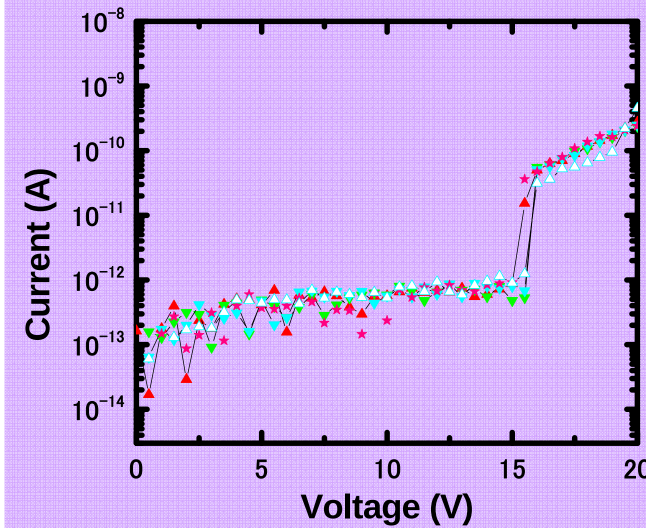
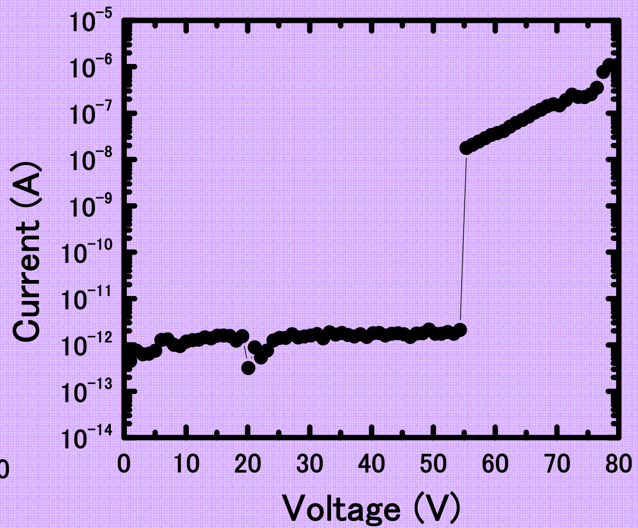
Nanoelectromechanical switch: 2-terminal

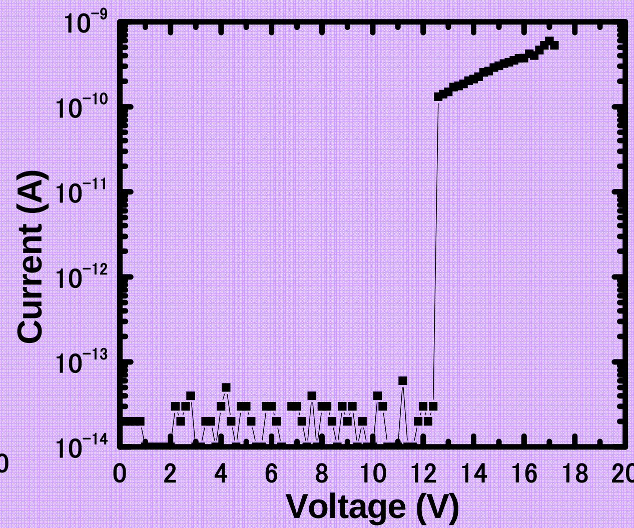




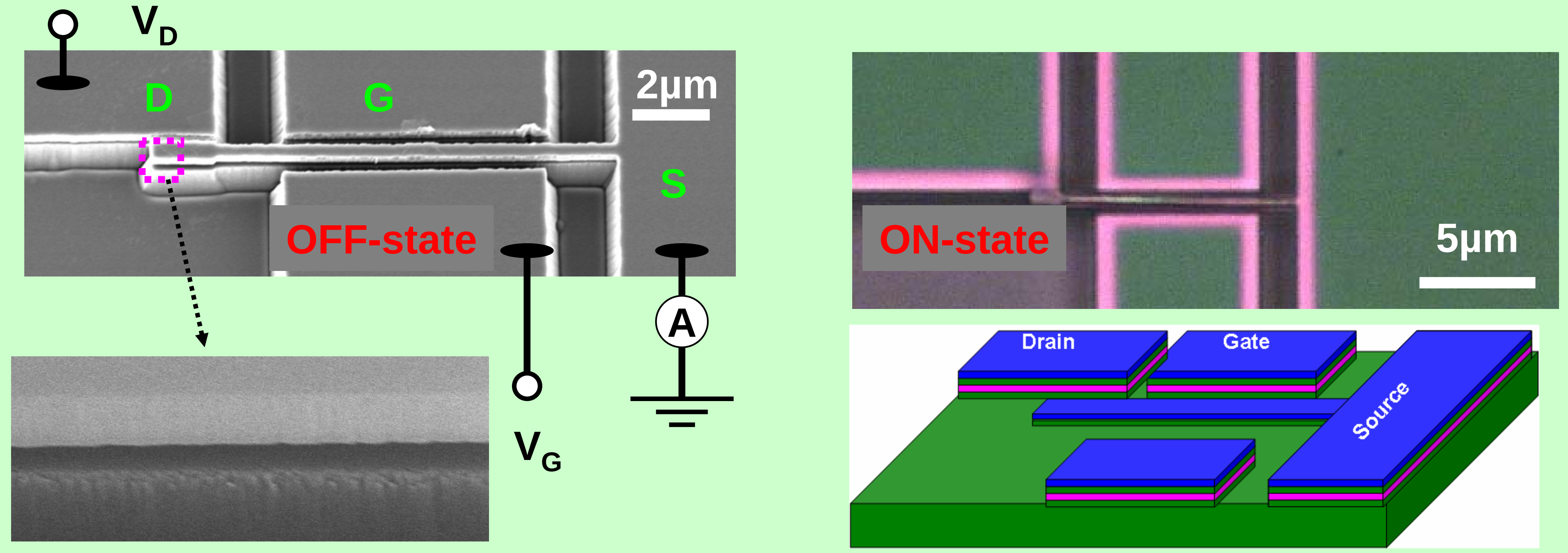


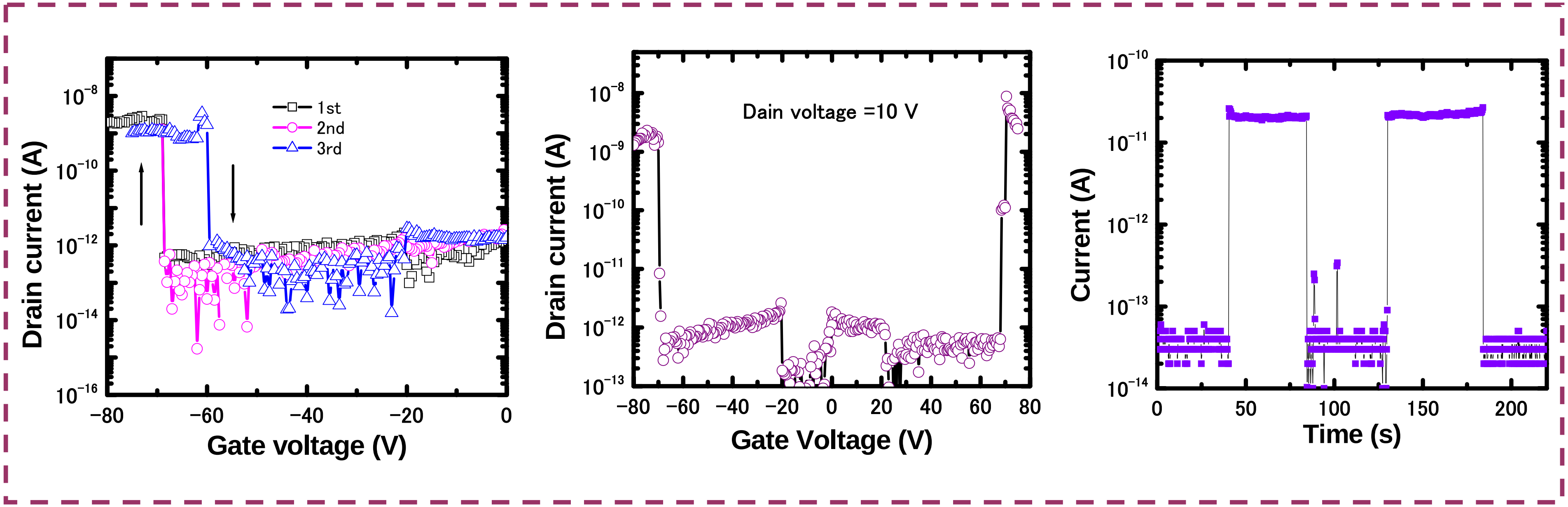




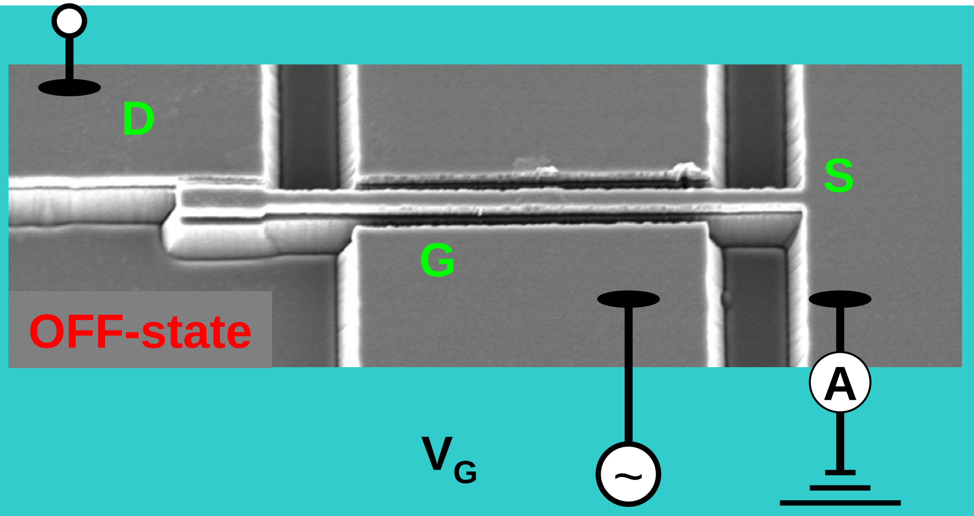


Nanoelectromechanical switch: 3-terminal



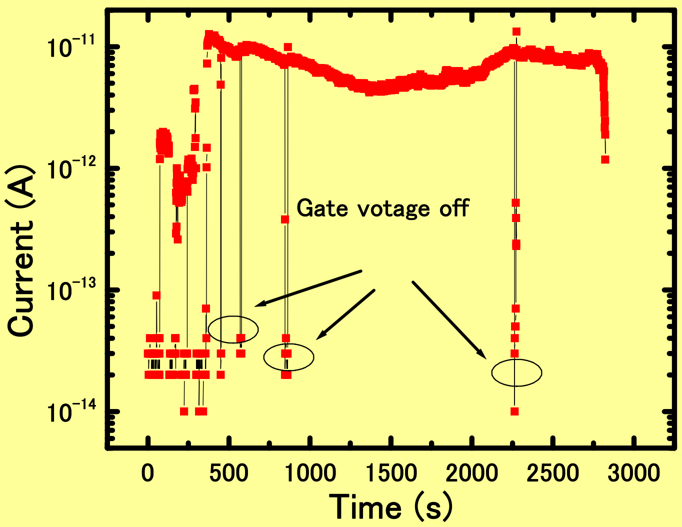


3-T NEMS switch: Reliability

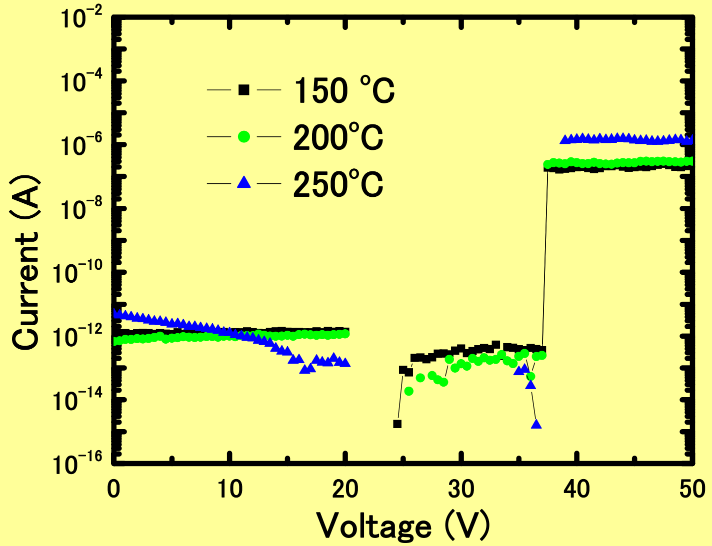


10^5 switching cycles

100Hz AC V_G



High temperature operation



Modeling and simulation of NEMS switch

$$-\nabla \cdot (\varepsilon \nabla V) = 0$$

Potential in the air around the beam

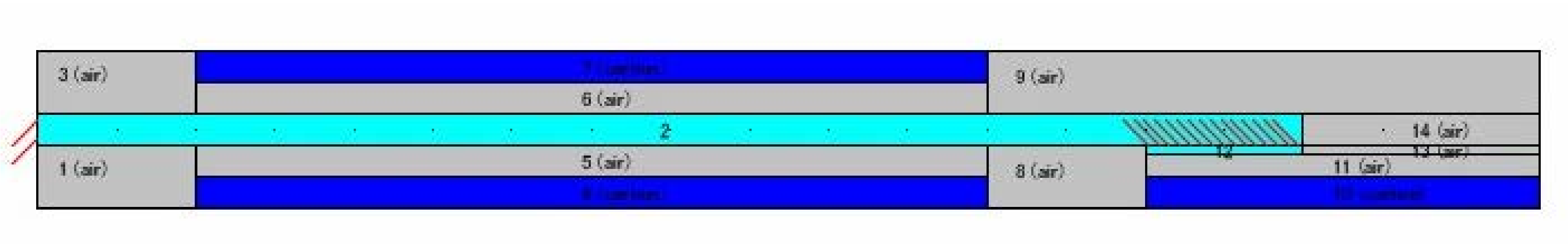
$$F_{es} = -\frac{1}{2}(E \cdot D)\,n + (n \cdot E)\,D^T$$

F_{es}: Electrostatic force density of the beam
E: electric field, D: displacement vector

$$V_{pull-in} = \sqrt{\frac{4c_1 B}{\varepsilon_0 L^4 c_2^2 (1 + c_3 \frac{g}{W})}}$$

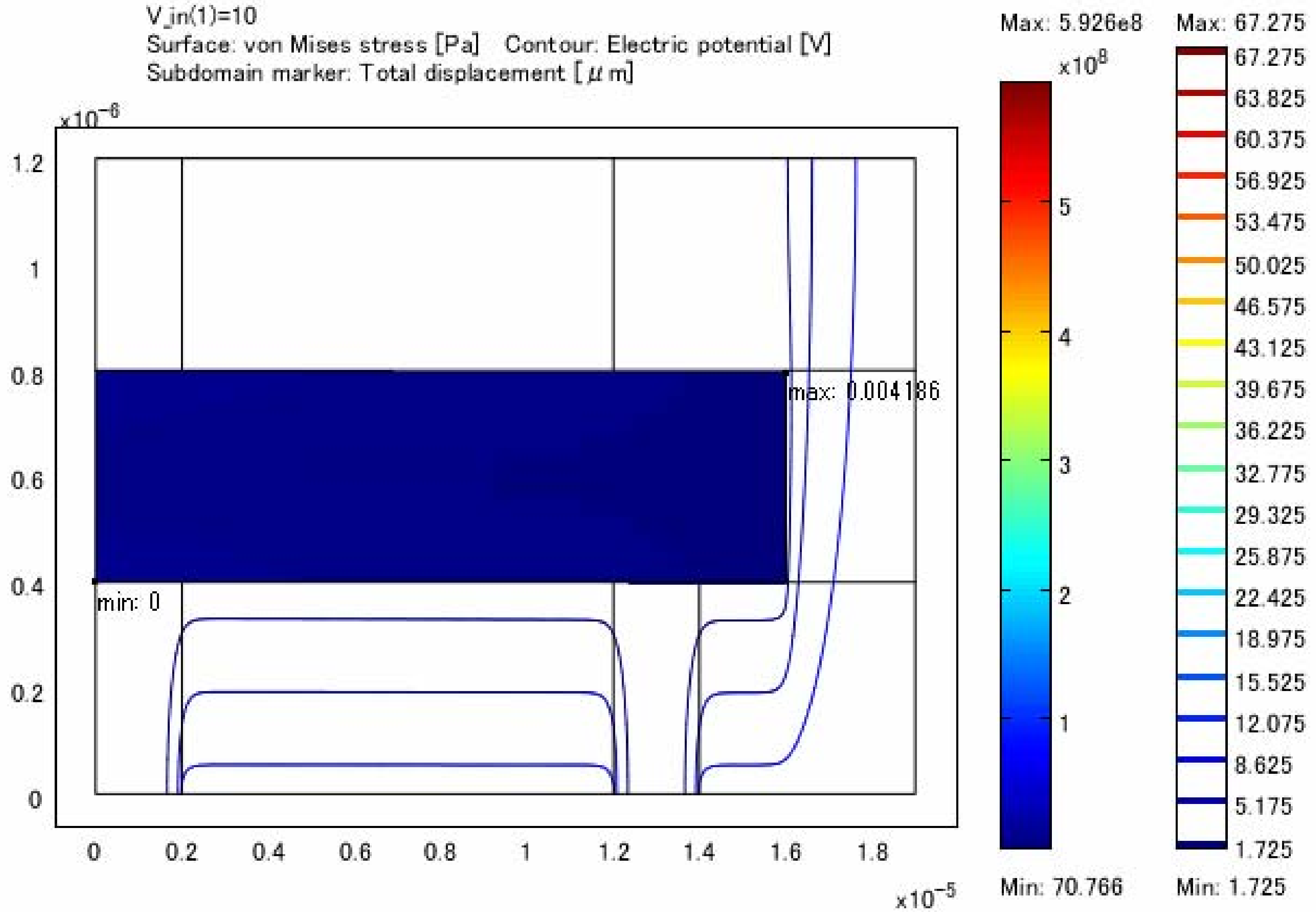
Pull-in voltage: defined as the beam contact to the gate.
L: length, W: width, t: thickness

$B = E_0 t^3 g^3$

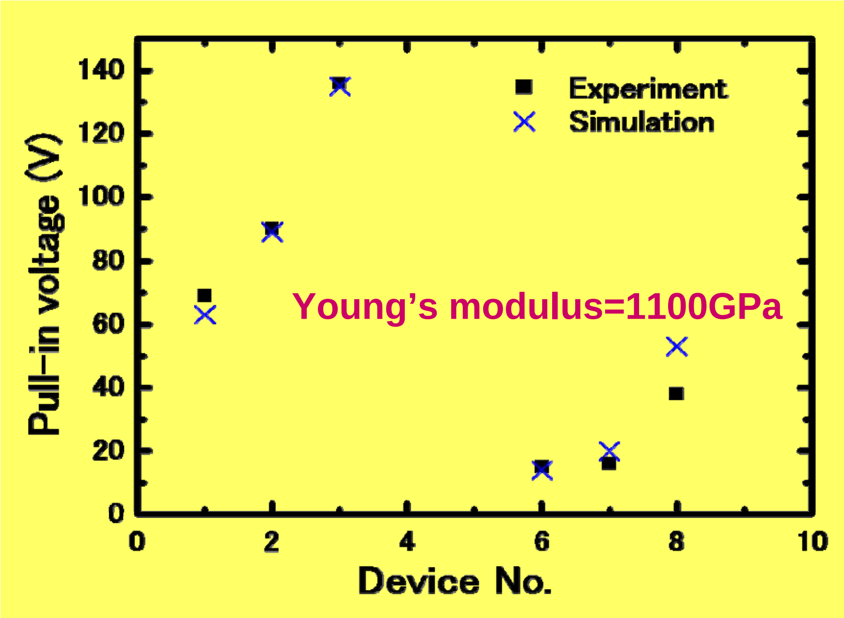


Source **Gate** **Drain**

Modeling and simulation of NEMS switch

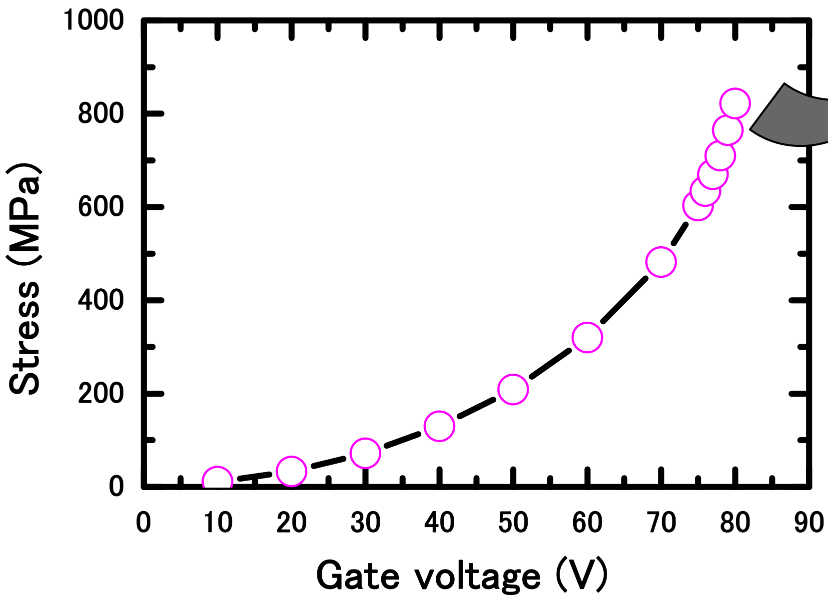


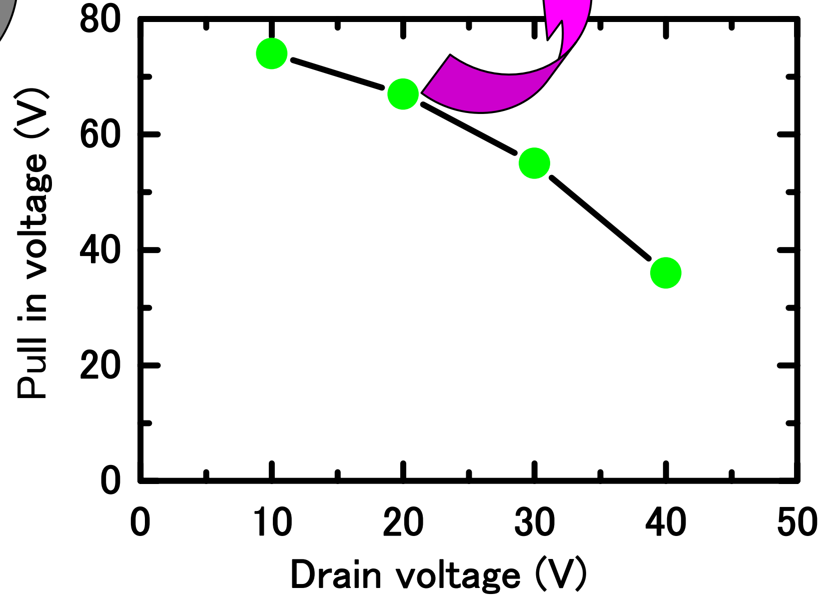
Comparison between experiment and simulation:



- High Young's Modulus
- Good reproducibility
- Consistence between experiment and simulation

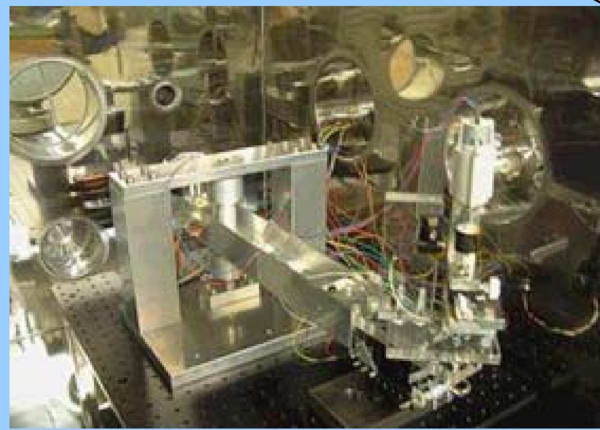
- Joint stress much lowerthan fracture strength
- Drain voltage affecting pull-in voltage



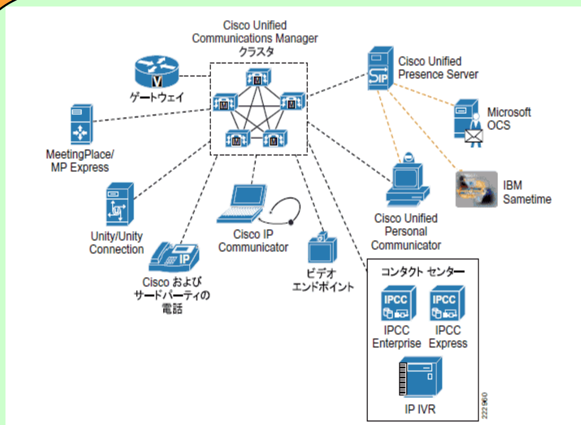


Applications of diamond M/NEMS Switch: H^4

(待機ゼロ)電源制御装置



耐環境デバイス:高温論理回路



携帯電話や*無線LAN*などの無線通信

メモリ

ナノ・マクロマシン
スイッチ

High power

High temperature

High frequency

High reliability

Summary

For the first time

- **Single-crystal diamond NEMS switch was fabricated.**
- **Batch production of SCD MEMS/NEMS structures were developed.**

- **The diamond NEMS switches exhibit high performance.**
  (1) High controllability .
  (2) High reproducibility.
  (3) Good reliability.

- **Modeling and simulation were made and were consistent with experiments**