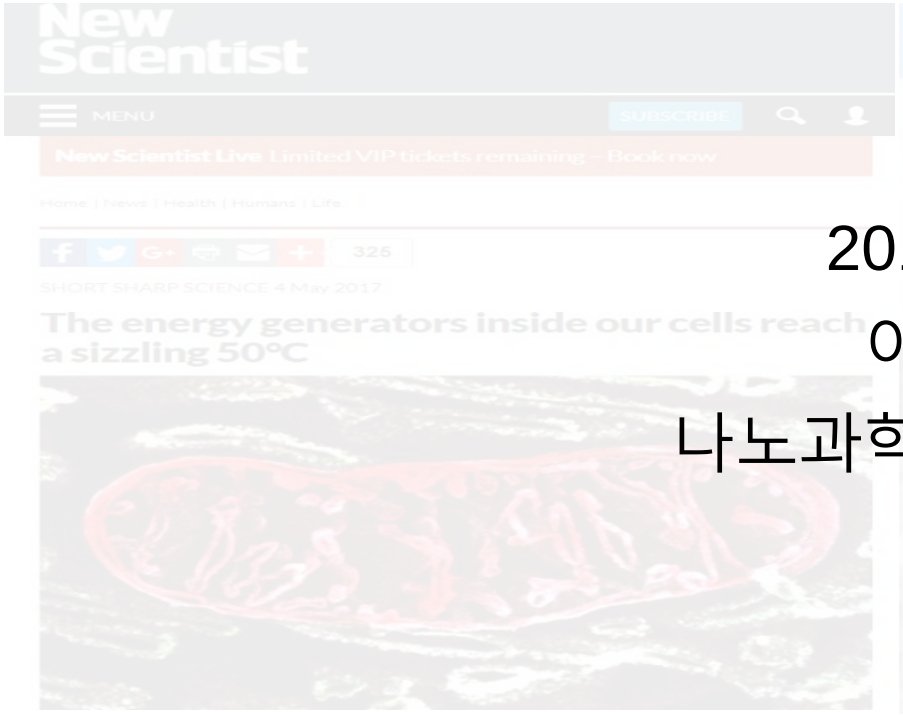
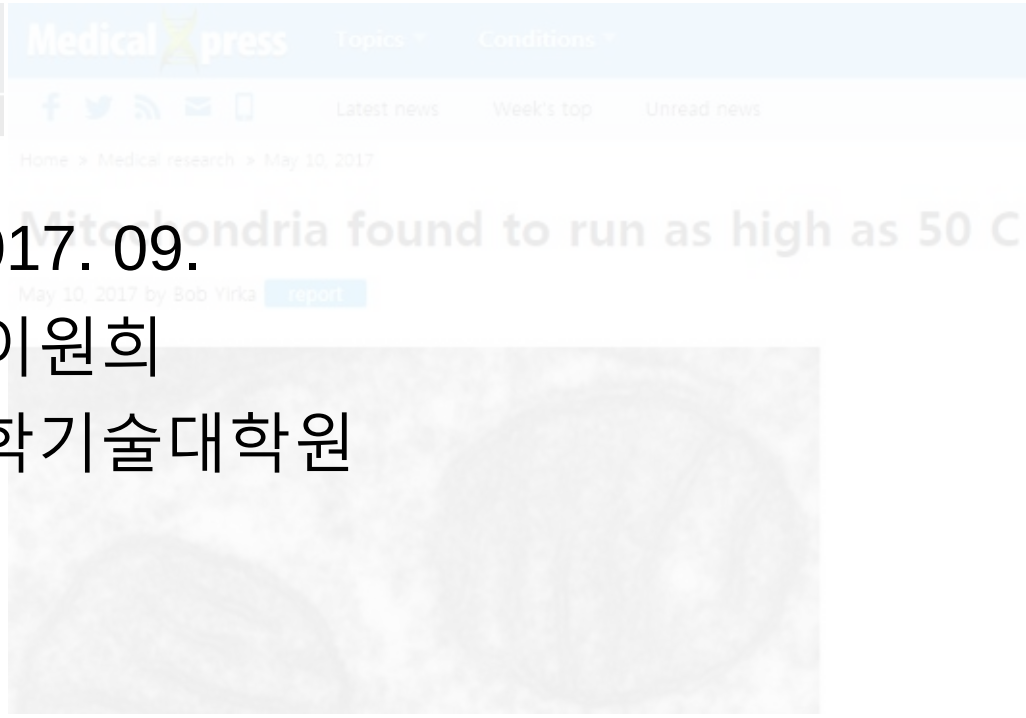
KAIST Grand Challenge 30 project

미토콘드리아 온도와 열생물학

Mitochondrion temperature and thermal biology



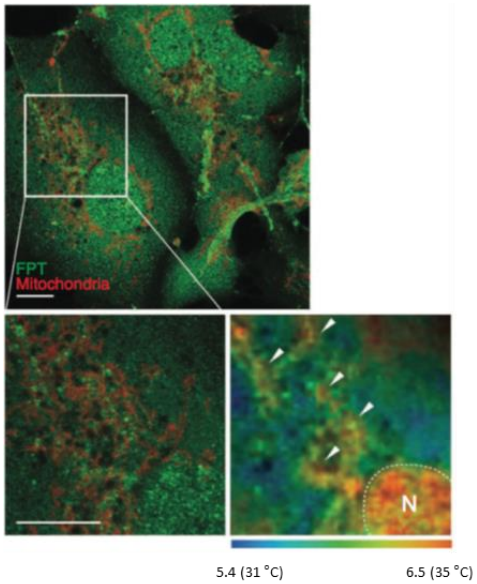


2017. 09.

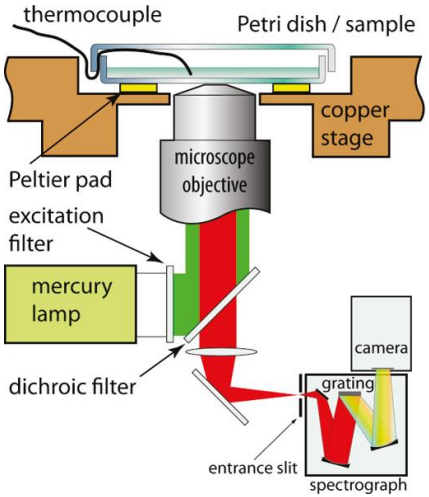
이원희

나노과학기술대학원

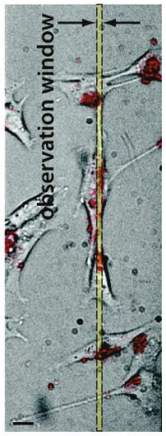
Intracellular thermometry

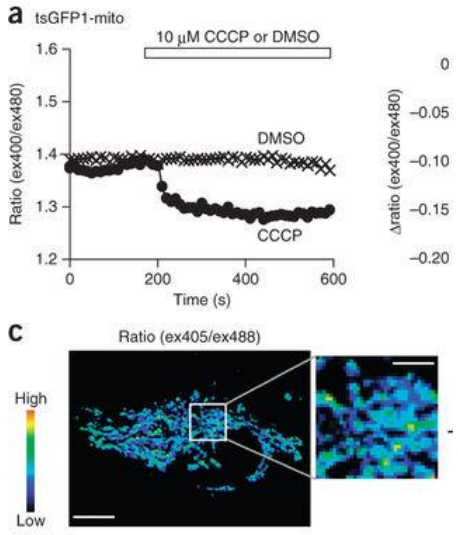


Okabe et al. *Nat Comm* 2012



Yang et al. *ACS Nano* 2011





Kiyonaka et al. *Nat Method* 2014

Nano thermometers: Fluorescence (Europium (III) thenoyltrifluoroacetonate trihydrate, Au nanoclusters, synthetic polymers, GFP), nanodiamonds spin, QD,

Local cell temperatures investigated with “nano thermometers”
→ Several results show **temperature changes > 1K**

What is the meaning of local temperature at nanoscale?

Highly complex nanostructure
Material inhomogeneity
Mass transport
Non-equilibrium, active biochemical reactions

Debates

ΔT*~ a few *K does not make sense 

Heat diffusion equation

$$c\partial_t T(\boldsymbol{r},t) - \kappa\nabla^2 T(\boldsymbol{r},t) = p(\boldsymbol{r},t)$$

$$\rightarrow \Delta T = \frac{P}{\kappa L} = \frac{Heat\ power}{thermal\ conductivity \cdot size\ of\ heat\ source}$$

p ~100 pW, L = 10 μm, κ ~ 1 W /m·K

ΔT ~ 10^{-5} K

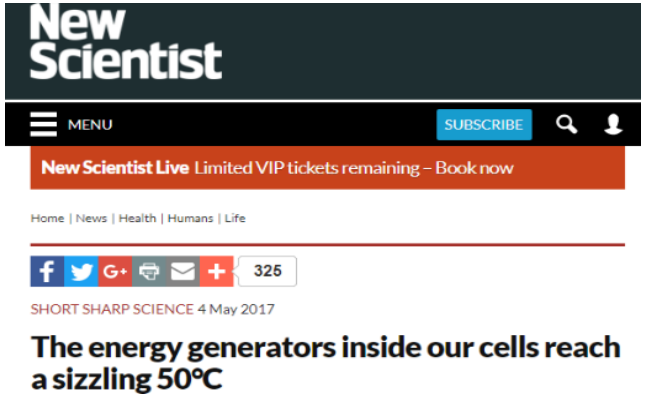
Even with consideration of smaller L, short burst of energy, membrane surface thermal resistance, required power is ~ 1 μW. 10^5 discrepancy cannot be explained!

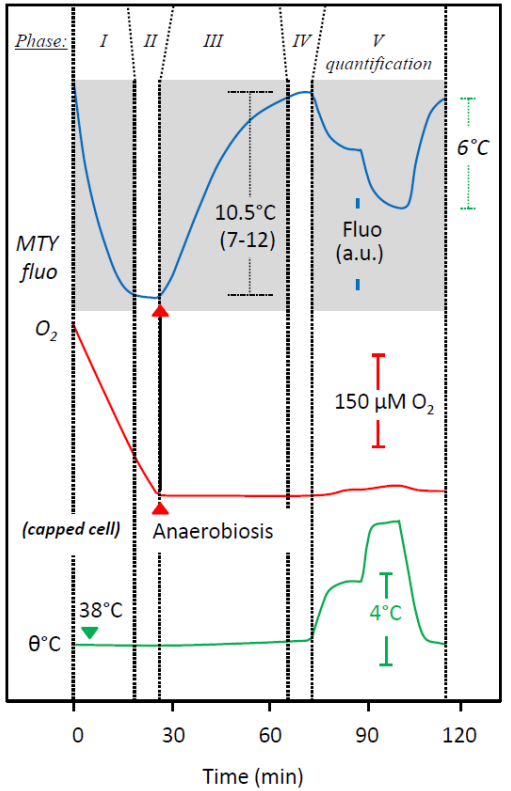
(Baffou *et al. Nat. Methods* 2014)

Rebuttal

- κ ~ 0.6 (W /m·K) for water and 0.1-0.2 for proteins
- Size of heat source in mitochondria < 100 nm
- If Heat dissipation in short time (1s), required energy will be ~ 10 nJ
- + Heterogeneity in the conductivity of intracellular component
- + Complexity in the nanostructures (membranes mostly) of organelles
- + Heat capacity can change with complex and highly organized structure

Abnormally high T of mitochondria

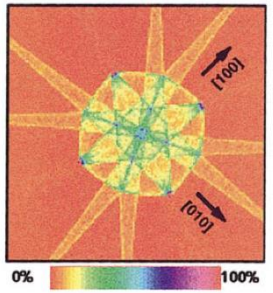




- **Metabolism at 50 °C?**
- Protein stable at 50 °C?
- Is it true? Maybe mistake?
- Can we make use of it?

Nanoscale temperature

- Kapitza thermal resistance
- Coherent Phonon experiments



Msal et al. PRL 2000

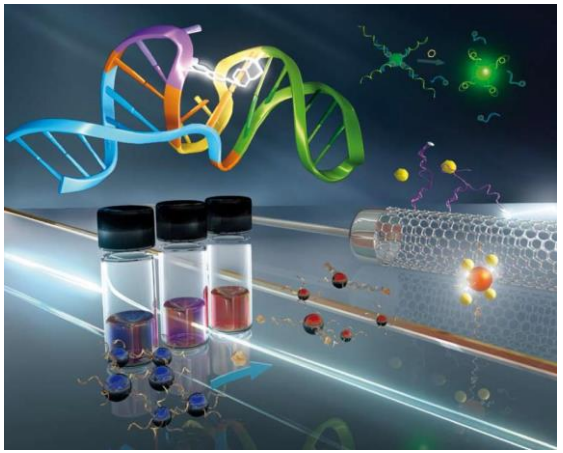
- **What it TEMPERATURE?**

"Average energy of a system of particles" $\langle K.E._i \rangle = \frac{m}{2N}\sum_n^N v^2(t_n) = \left\langle \frac{1}{2}mv_i^2 \right\rangle$

$\left\langle \frac{1}{2}mv_i^2 \right\rangle = \frac{3}{2}k_B T_i$ or $\left\langle \frac{1}{2}mv_i^2 \right\rangle = \frac{1}{4N}\sum_{\lambda,q}\hbar\omega_\lambda(q)\xi^{(i)2}(\lambda,q) \times \left(\frac{2}{e^{\hbar\omega_\lambda(q)/k_B T_{i-1}}} + 1\right)$

Temperature defined locally vs. Length scale < phonon wavelength

- Nanoscale structure and materials
  Thin films & superlattices
  Nanotubes & nanowires
  Graphene & 2D materials
  Nanoparticles & QD



Questions and Goals

Big question: What is Temperature at nanoscale?

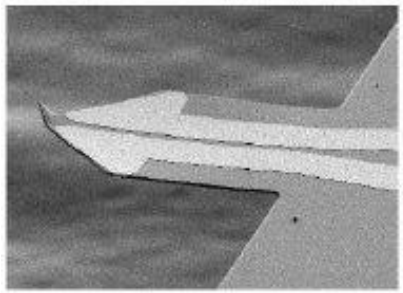
1. Is the >1K temperature change by mitochondria possible?
   - Confirmation of the results
   - If not, what was wrong ?
   - If so, how is that possible ?

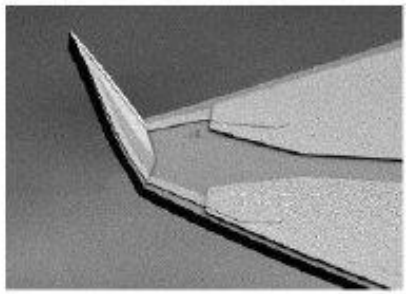
2. How to formulate effective T of molecules, or organelles?
   - Provide a *useful method* to describe T at nanoscale

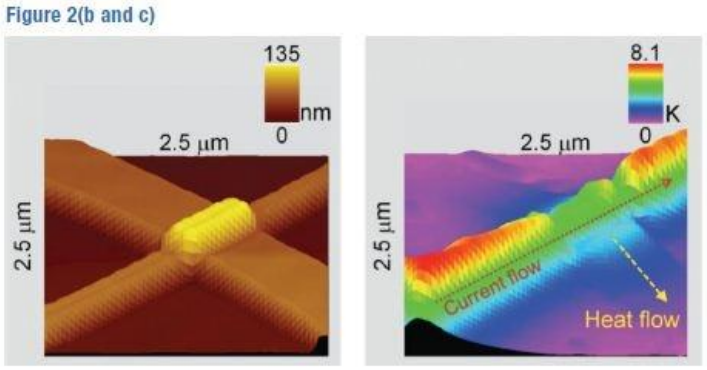
3. Can we control nanoscale T in unusual manners?
   - Construct nanostructure with unusual heat transfer characteristics, such as super insulator.

Methods

- Scanning thermal microscope

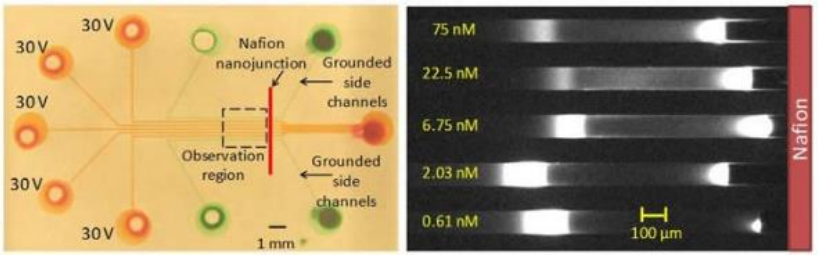




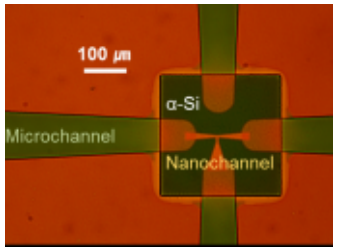


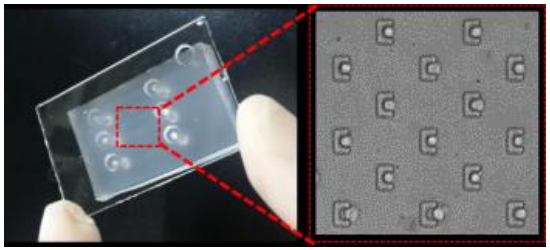
Courtesy of www.azonano.com

- Micro-, nanofluidics & nanofabrication (artificial cell, organelle)

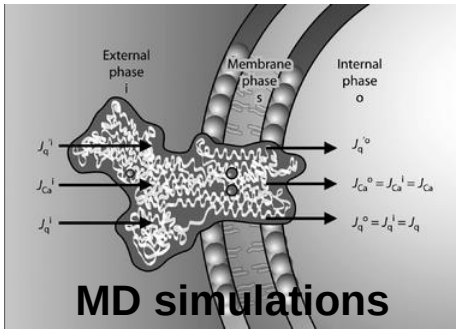


Chen et al. JACS 2011

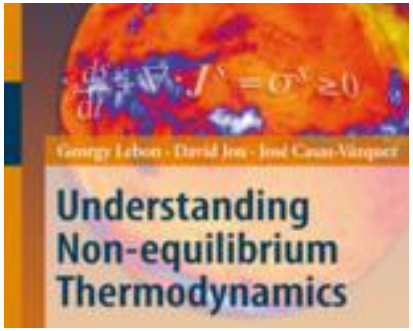


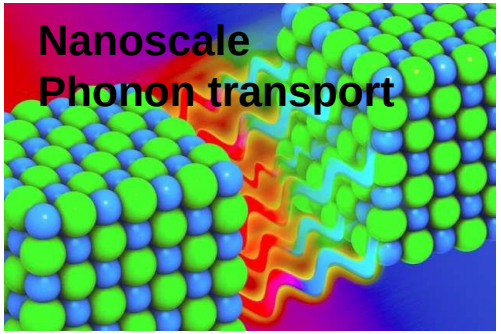


- Active Collaborations



Bedeaux et al. PCCP 2008





Why Grand challenge?

- Temperature is one kind of basic physical parameter regulating life, yet poorly understood !!
- Difficulty in defining Nanoscale Temperature
- Importance of understanding nanoscale heat-transport : Nanodevice, nanomaterials, biology!
- Huge impacts on various fields, including nanoscale electronics, high-ZT, insulating material, cancer treatment etc.
- Not likely to be funded
- Not active, current research project of the lab