DESIGN, ASSEMBLING AND MANIPULATION OF ELECTRIC NANOMOTORS WITH ULTRAHIGH PERFORMANCES

—for biosdelivery, tunable release, high-speed sensing, and microfluidics

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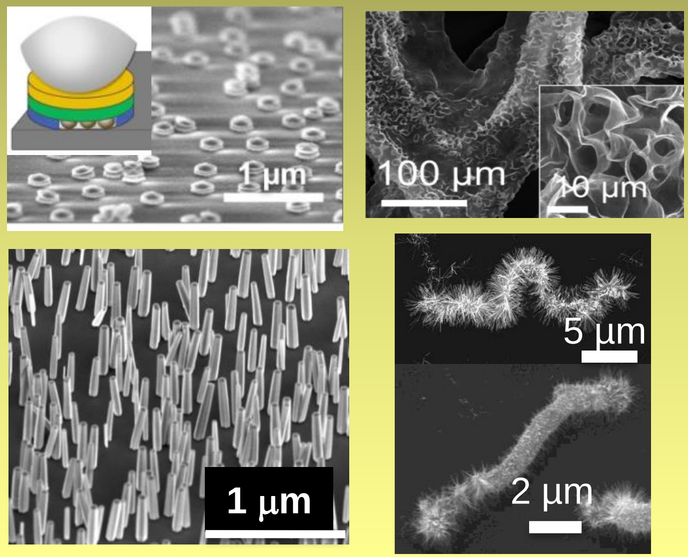
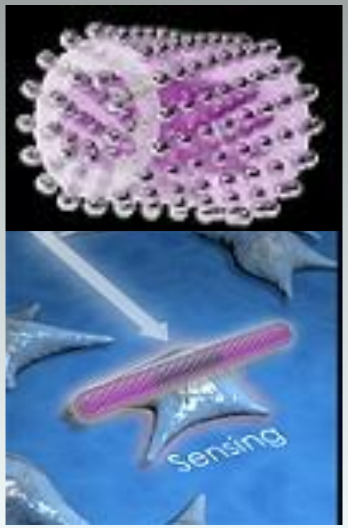
The 16th U.S.-Korea Forum on Nanotechnology, September 23, 2019

Overview

Synthesis of Nanomaterials

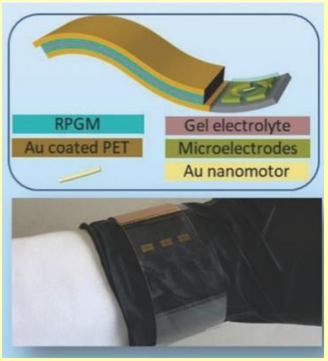


High-Performance Biochemical Sensing

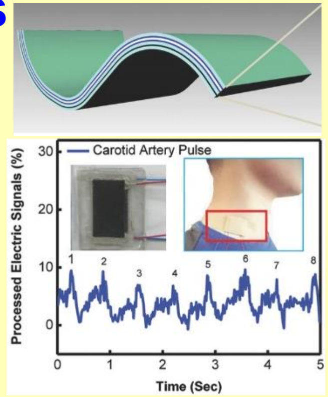


Nanorobotics: manipulation, assembly, and nanomachines

3D Porous Materials for Flexible Self-Powered Devices



Portable electric motors



Self powered strain sensors

NSF, CMMI Nanomanufacturing, CCSS, EPMD, CAREER

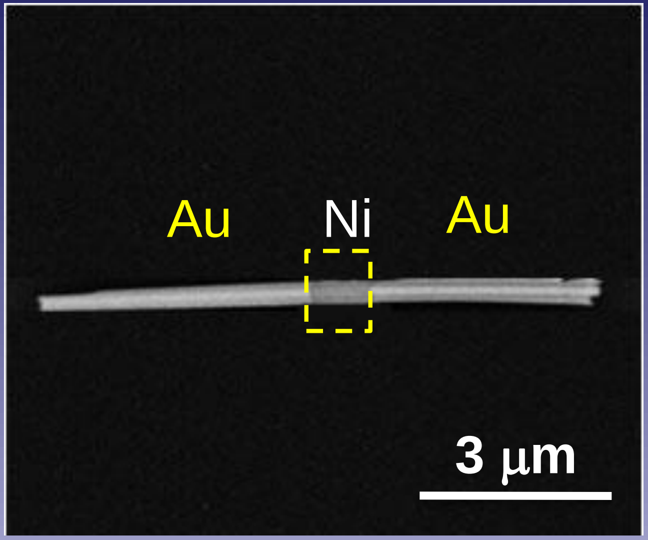
Introduction to nanowires

Features of Nanowires

- ❑ large aspect ratio

  d = 20 ~ 400 nm, L = 100 nm ~ 10 μm

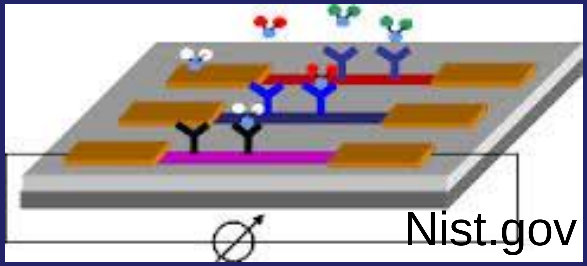
- ❑ single or multi-segment



Au-Ni-Au nanowire

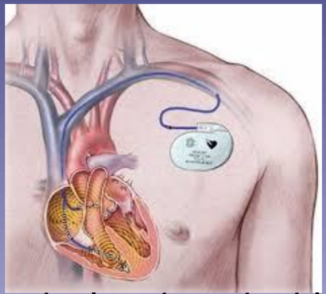
Applications of nanowires

❑ Nanosensors



Building blocks for nanocircuit & nanosensors (Harvard)

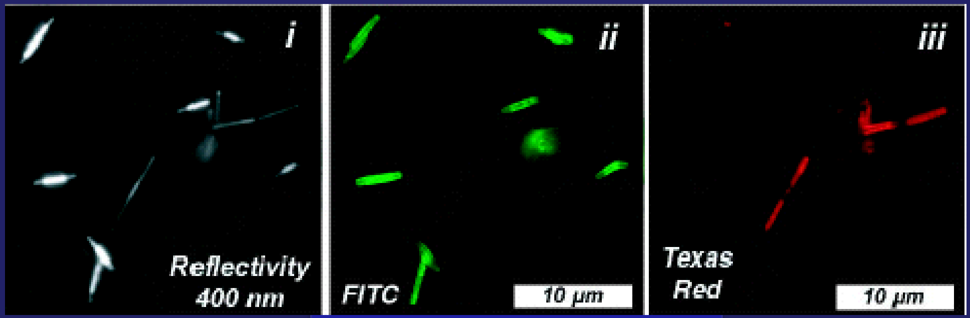
❑ Nanogenerators



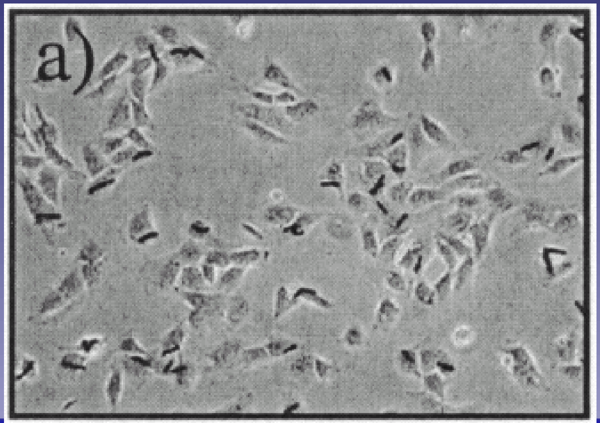
mechanicalengineeringblog.com

Convert mechanical energy into electricity for powering biodevices

❑ Bioassay



Protein diagnosis (Penn state)



Gene delivery and cell separation (JHU)

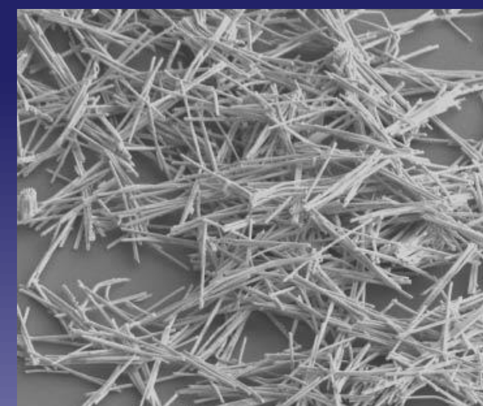
Difficulties in manipulating nanowires

- Adhere to surfaces
  - van der Waals force
  - Electrostatic force
- Extremely small Reynolds number in suspension

$$R = \frac{Dv\rho}{\eta}$$

D: size
v: speed
ρ: density
η: viscosity

Swimming human 10^4



Nanowires in water 10^{-5}

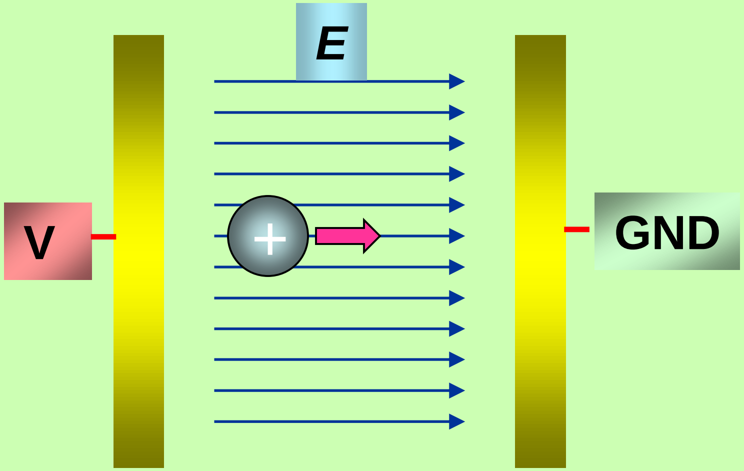
if v = 100 μm/sec
Stopping time τ ~ 1×10^{-6} sec
Stopping distance d < 1Å

Manipulation with the electric tweezers — recent invention (patents: US9044808 B2, 9718683)

Electrophoretic (EP) force:

Charged particle moves due to coulomb interaction in DC *E* field.

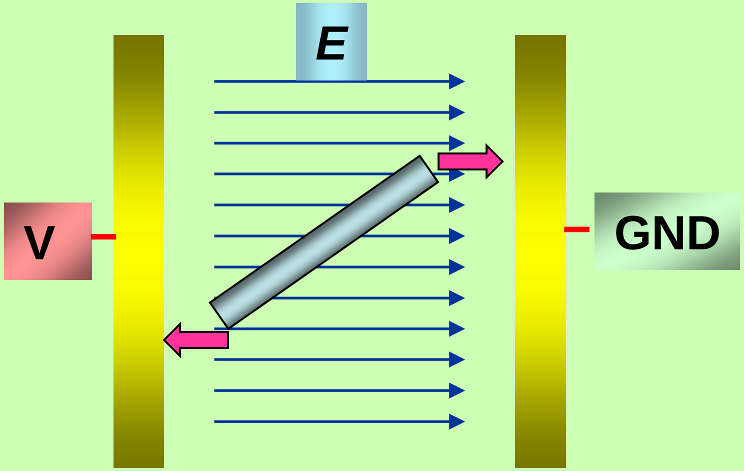
$$F_{EP} = qE$$



Dielectrophoretic force:

Neutral particle moves due to interaction between polarized particle and E field in AC *E* field.

$$F_{DEP} = (p \cdot \nabla E)E = E \cdot \nabla E$$

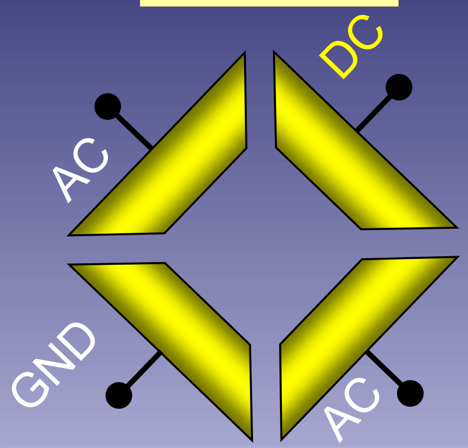


Transport of nanowires

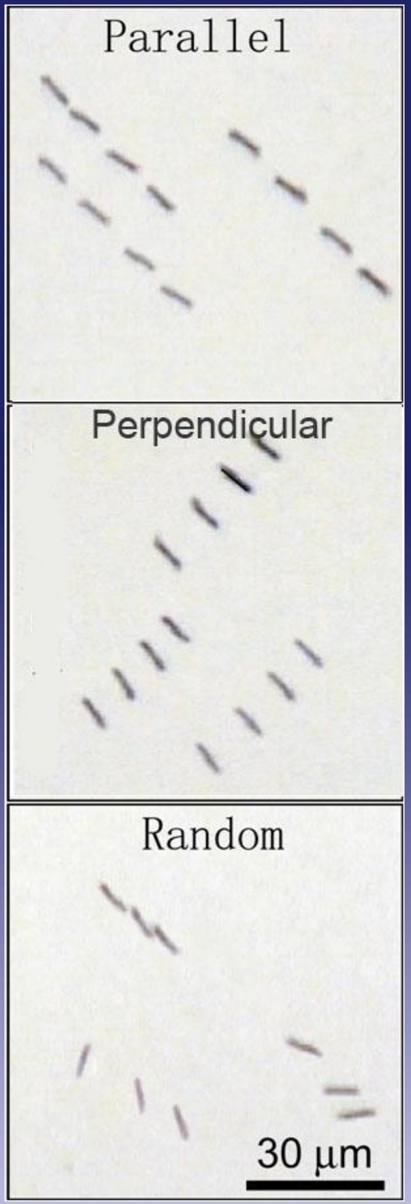
DC || AC

11s

DC ⊥ AC

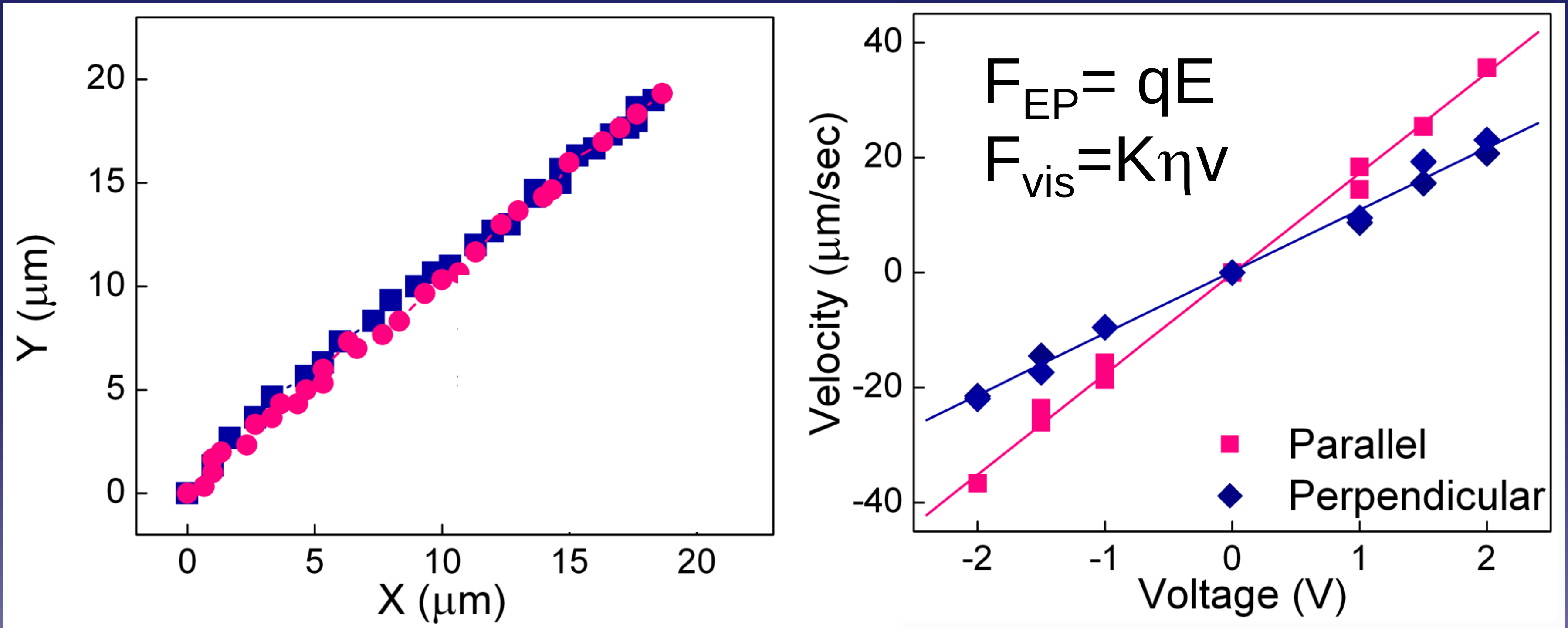


11s



Transport and orientation of nanowires can be independently controlled by the DC and AC field

Analysis of nanowire transport

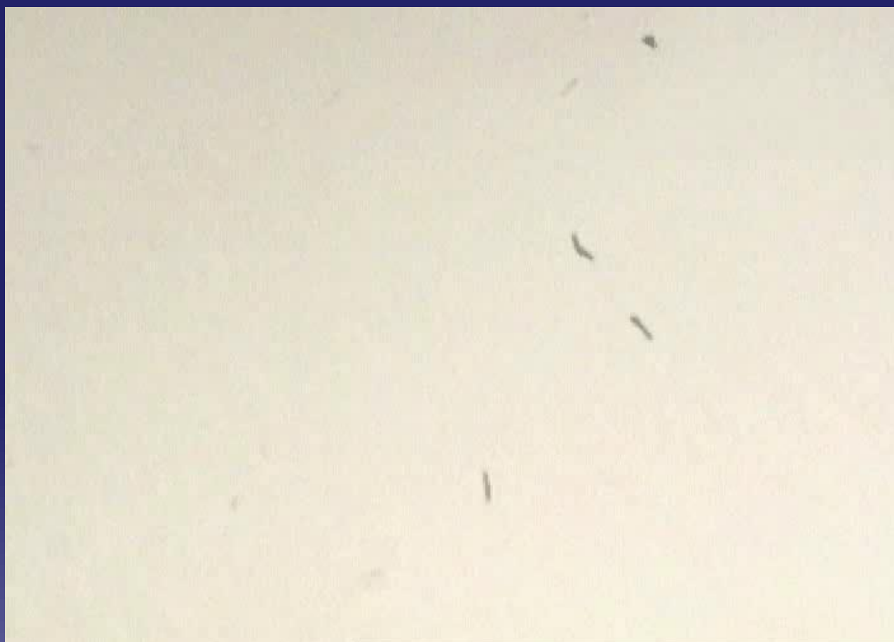


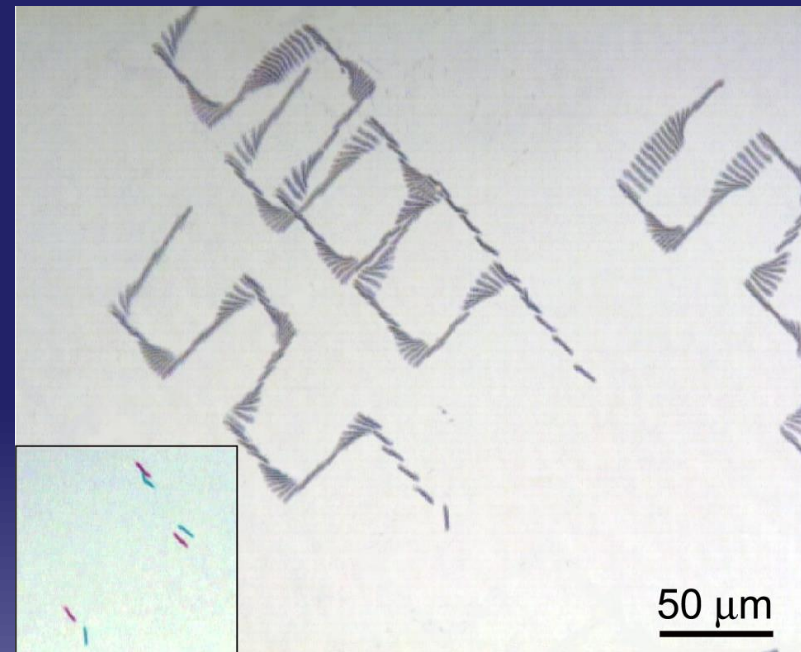
- Backward motion retrace the forward motion
- Return to the original positions

- Velocity ~ DC voltage
- Depends on nanowire orientations

Program nanowires' motion

Zigzag





19 s

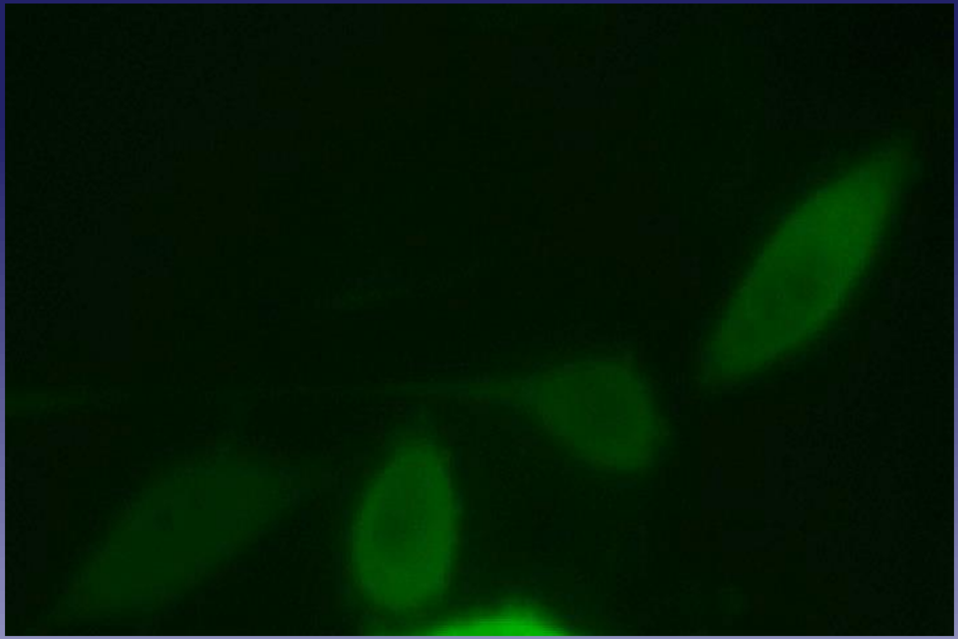
Transport in 2D, need to control motion in X and Y.

Inset shows: Nanowires return to the original positions after travel hundreds of micrometers

Application: Single-Cell Drug Delivery

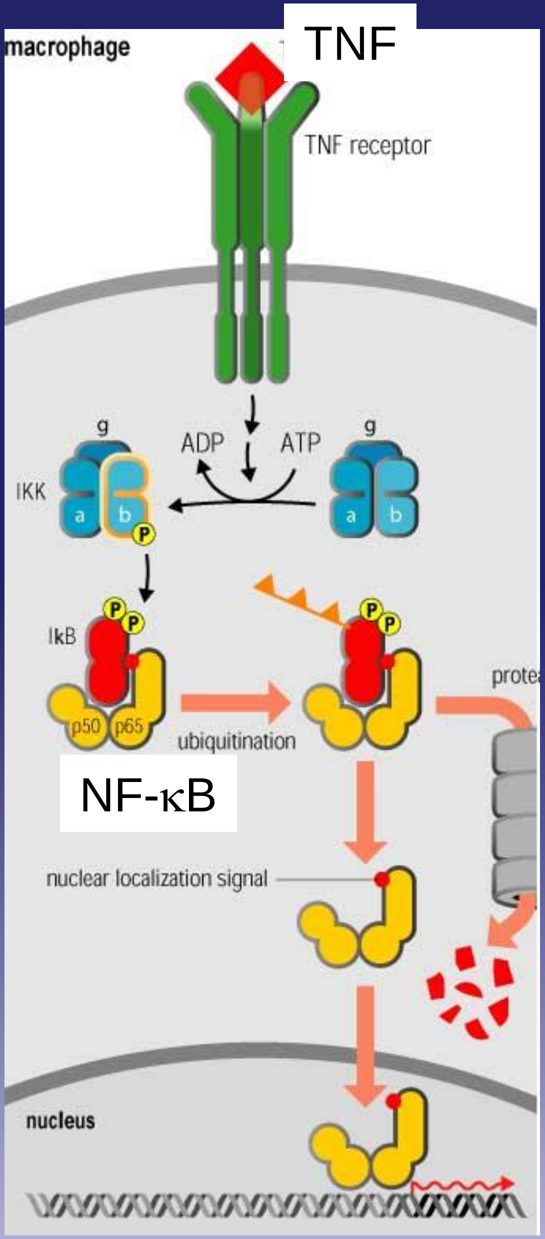
Tumor necrosis factor (TNF- α) (inflammation):

Stimulate protein (NF-κB) transfer from cytoplasm to nucleus



- Conventionally TNF-α is released to all the cells
- non- specific stimulation
- A way to release TNF-α to single cells?

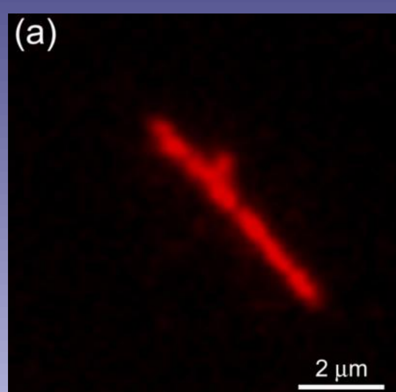
5 s



www.ixtenet.com

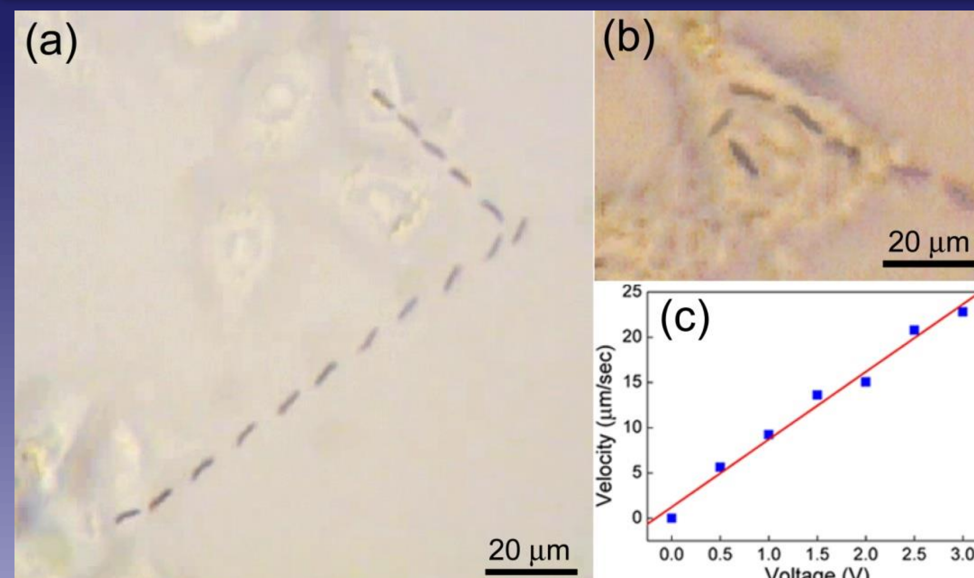
Precision delivery of drug to a single cell by nanowire vehicle

24 s



Conjugation of TNF-α onto the surface of nanowires

- Nanowires transported on top of cells
- Nanowires can be precisely positioned onto any places of a cell



Transport nanowires one by one

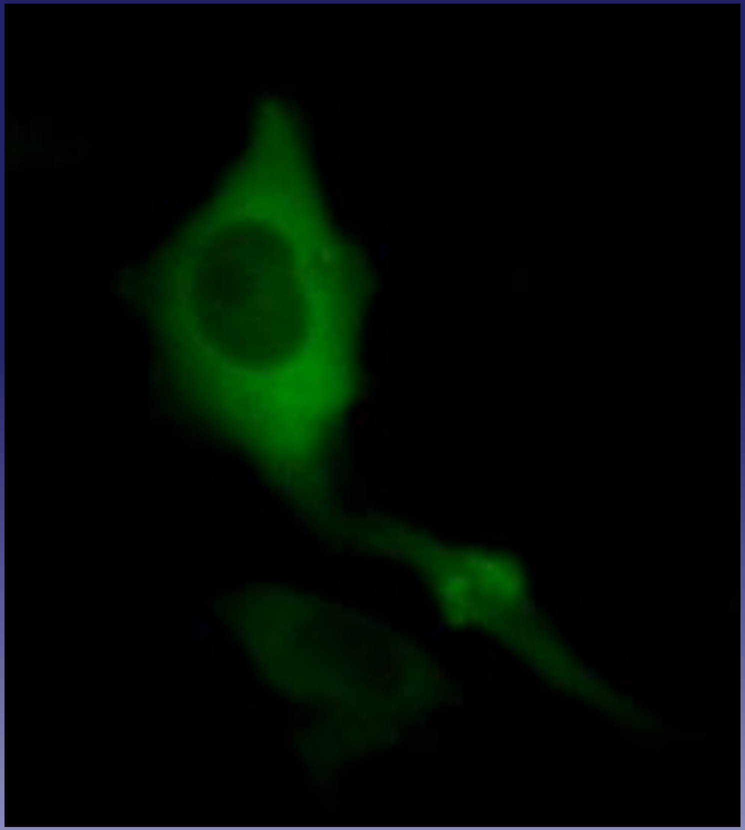
1 nanowire

2 nanowires

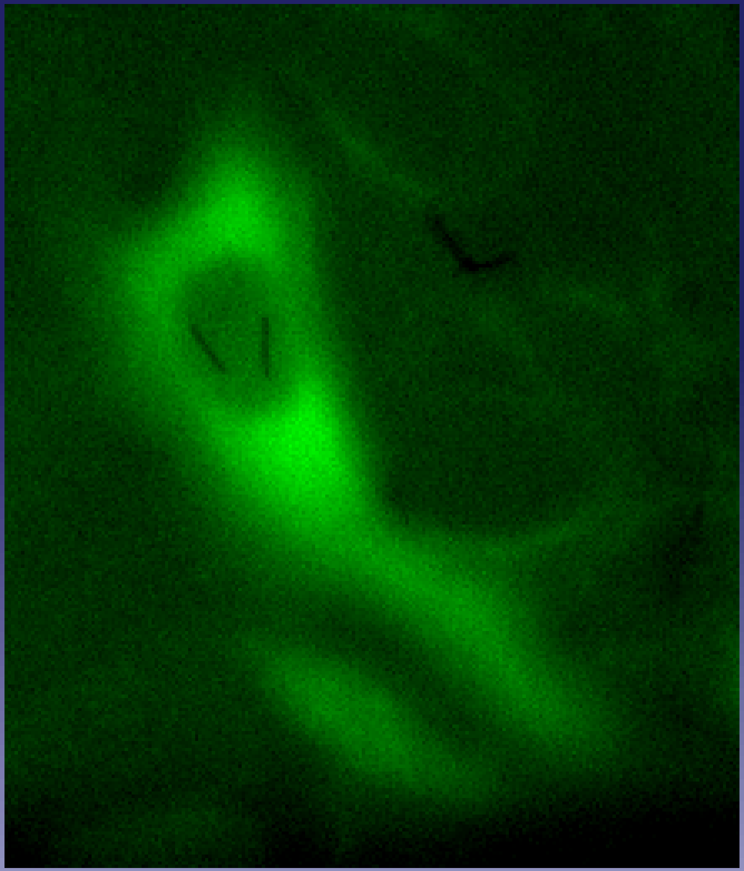
3 nanowires

The amount of dosage of drugs can be controlled by the number and the size of the nanowires.

Stimulation of cells by drugs delivered by nanowires



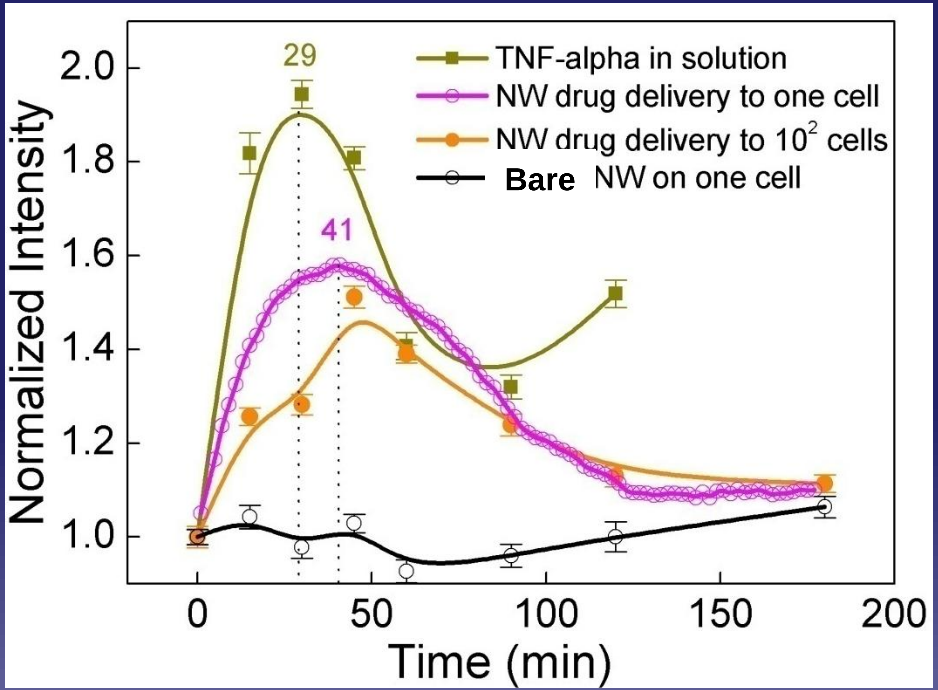
12 s NFkB Protein transfer

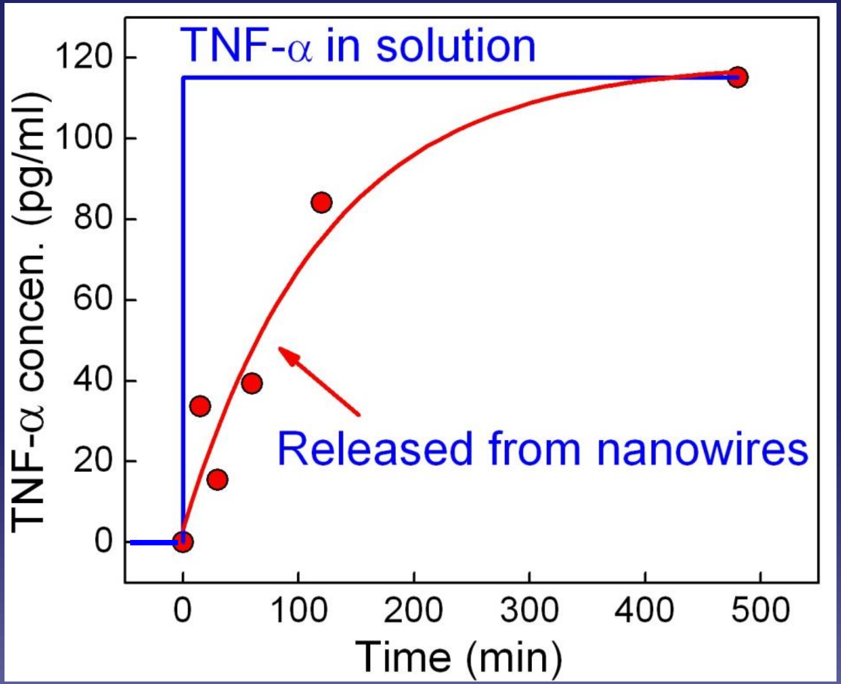


Nanowires on top of the cell

Cell specific drug delivery

Time controlled drug release



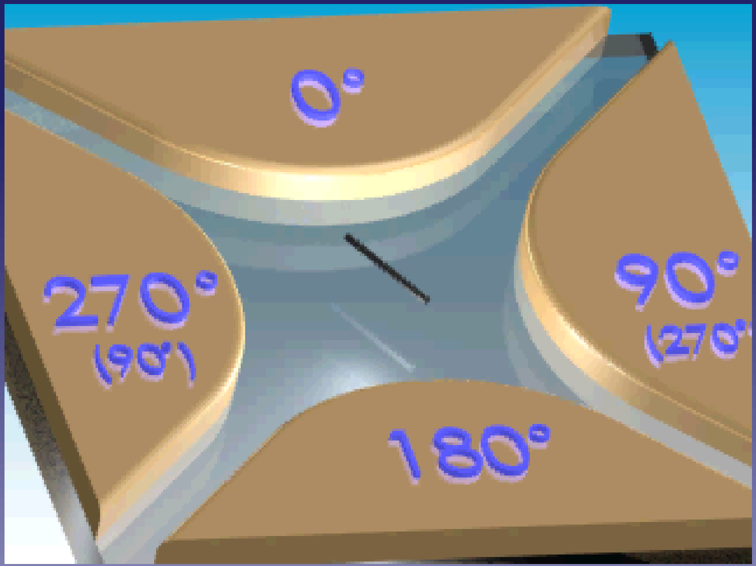


- Delivery on single cellular level
- Time controlled drug release: gradual release, delay 12 min
- Low amount of dosage: 13k drug molecules, ~ number and size

Fan et al., ***Nature Nanotechnology***. 5, (2010), pp. 545 - 551

Rotation of nanowire by Electric field

DEP force aligns nanowires in the direction of ***E*** field



Create a rotating *E* field

35 s

controlled speed & chirality

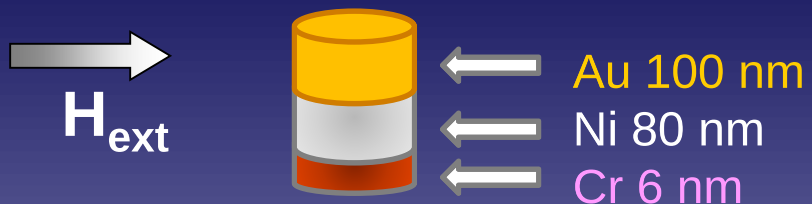
Investigate New Mechanisms for Rotary Nanoelectromechanical Devices

- Fabrication with high efficiency
- Nanoscale dimensions
- Reliable performances: speed, control, life time
- Low cost

Innovative Rotary NEMS

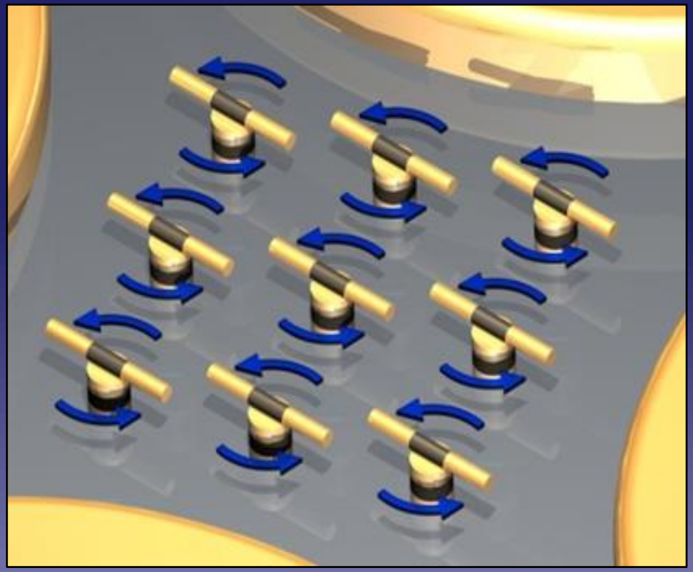
Device Design:

- Multisegment nanowires as rotors
- Patterned nanomagnets as bearings
- Quadruple microelectrodes as stators



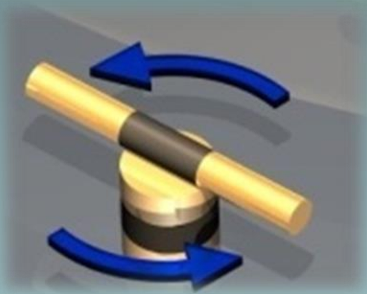
Au/Ni/Au nanowires

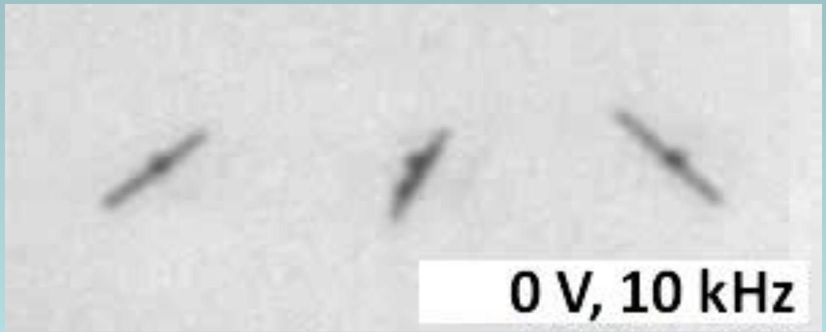
Arrays of Rotary Nanomotors



Assembling of Rotary NEMS

Various Arrays of Nanomotors





1. Controlled synchronous rotation in two directions
2. Rotate stably, start and stop instantly
3. First assembly of ordered arrays of nanowire rotary motors
4. Continue for 80 hr, 1.1 million cycles
5. All dimensions less than 1 μm

Ultrahigh Performance of Rotary NEMS

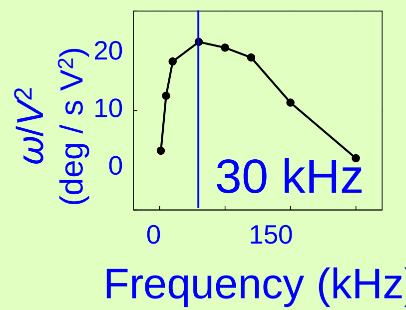
—Ultrahigh Speed Rotation

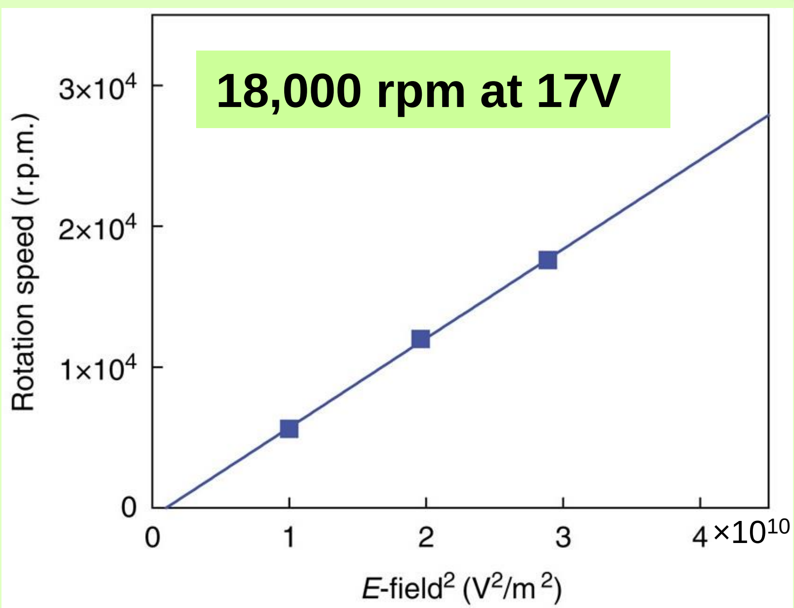
Small electrode gaps

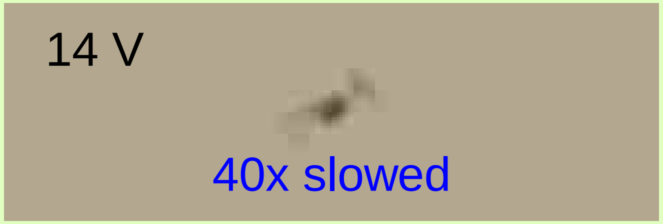
(100 μm)

High E-field intensity

Optimized AC frequency





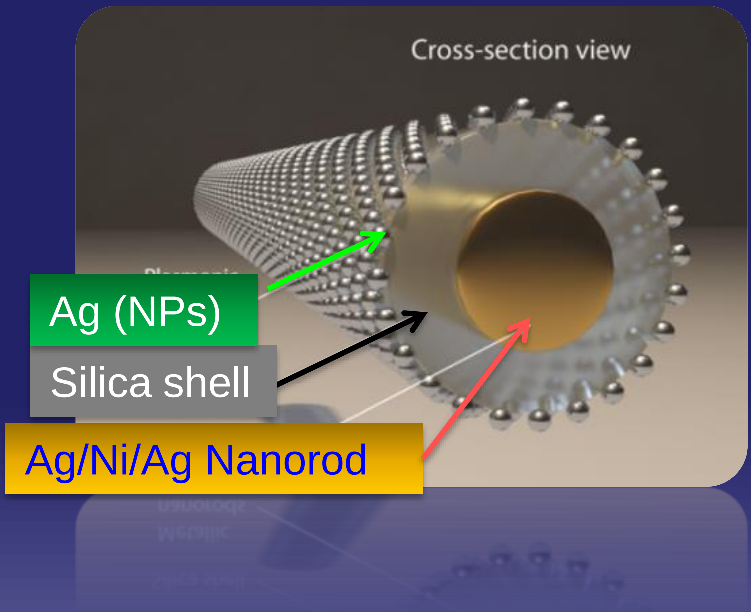


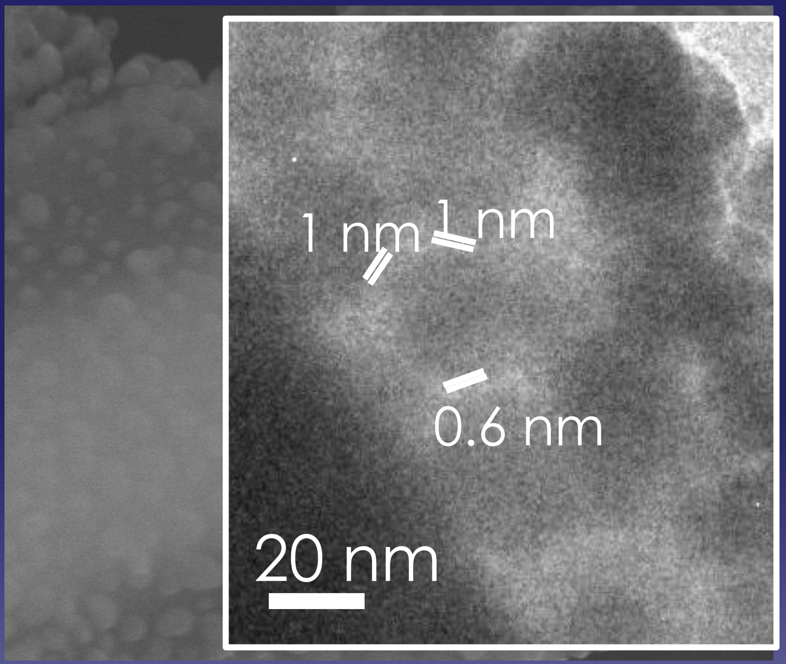
Real-time video

- Rotation speed over 18,000 rpm
- Nanomotor with highest speed at a fixed position – Same magnitude of jet engines

K. Kim, X. B. Xu, J. H. Guo and D. L. Fan, ***Nat. Commun.*** 5, 3632 (2014)

Plasmonically-Active Nanomotors for Applications in Controlled Drug Release





Tri-layer structure:

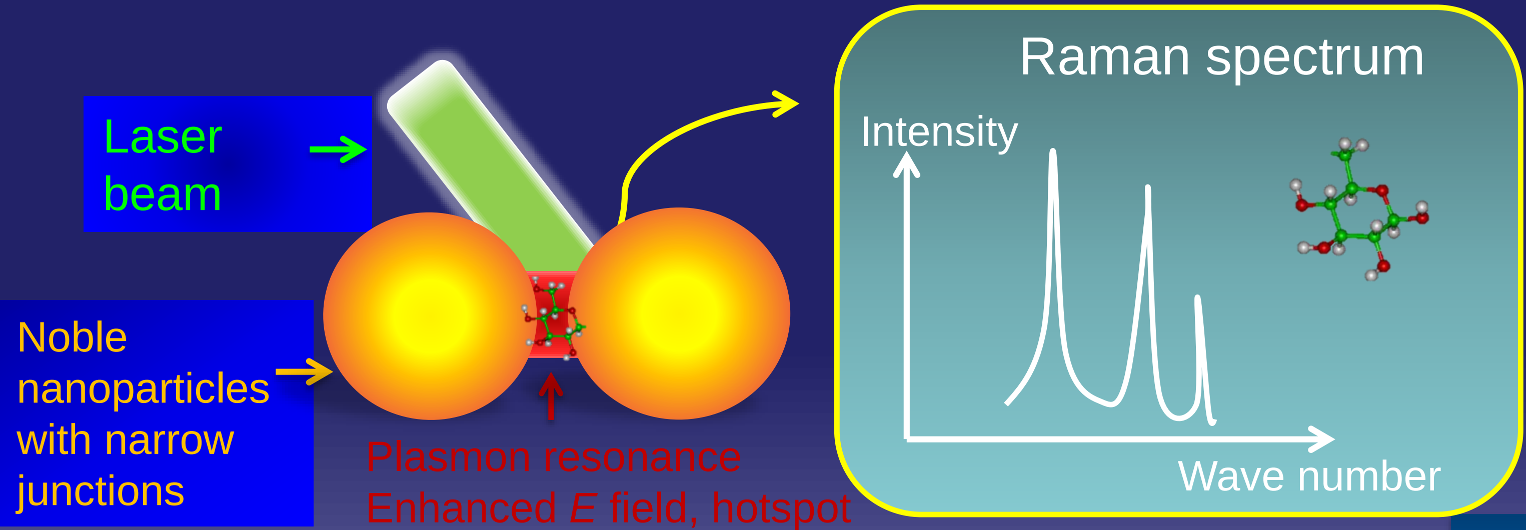
Metallic nanorod as the core: electric polarized and manipulated by electric tweezers

Center silica layer: supporting substrate for Ag NPs and separate Ag NPs from nanorods

Outer Ag NPs: optimized sizes , junctions , and high density of hotspots for ultrasensitive SERS sensing

Fan, et al., ***Chemistry of Materials***, 29, 4991–4998 (2017). ***ACS Sensors***, 2, 346–353 (2017) ***Adv. Mater***., 24, 5447 (2012), ***Adv. Funct. Mater***., 23, 4332 (2012)

Surface Enhanced Raman Scattering (SERS) for Detection of Molecules

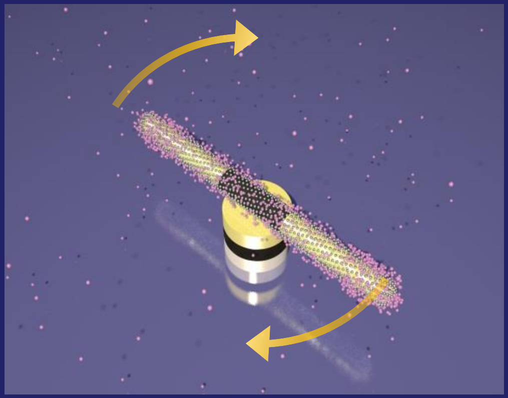


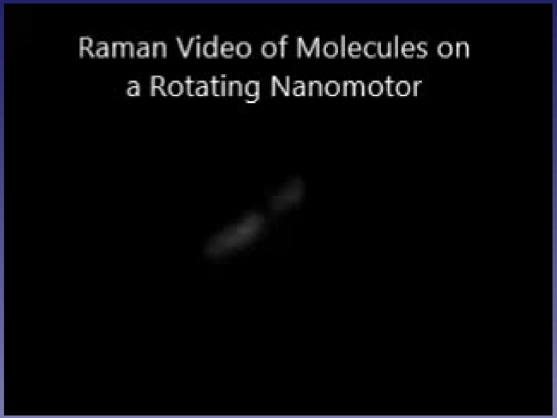
$$EF \approx M_{Loc}(\omega_L) M_{Raman}(\omega_R) \approx \frac{|E_{Loc}(\omega_L)|^2}{|E_{Inc}|^2} \frac{|E_{Loc}(\omega_R)|^2}{|E_{Inc}|^2} \approx |E_{Loc}(\omega_L)|^4 / |E_{Inc}|^4$$

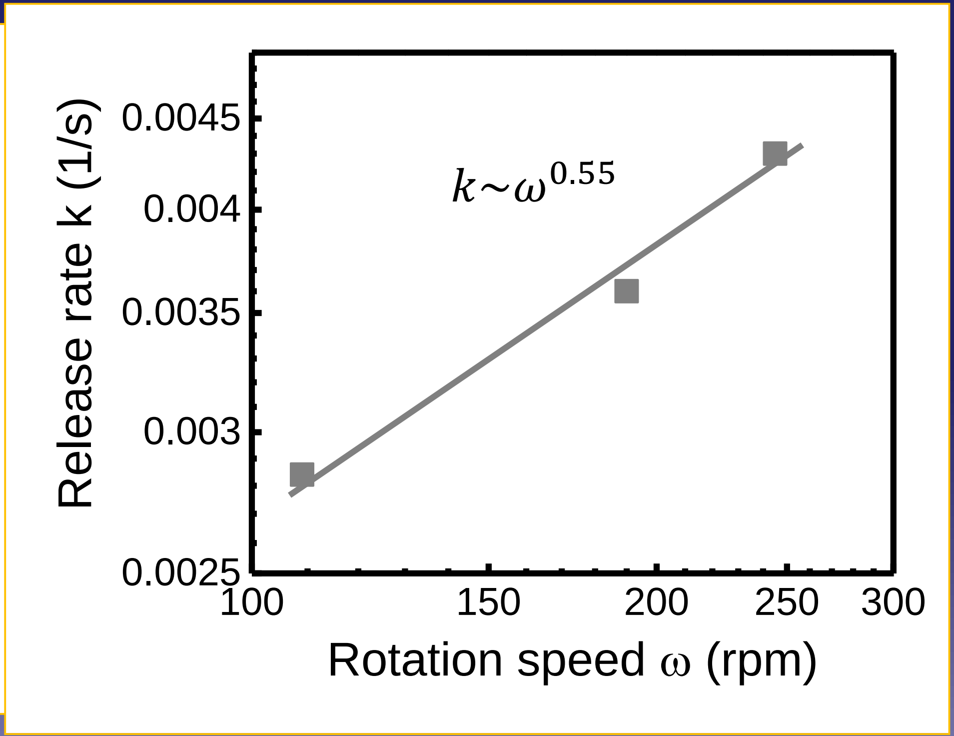
- EF as high as 10^{10}
- Single-molecule detection

Only molecules in the vicinity of the surface of the plasmonic particles can be substantially enhanced

Rotary Nanomotors for Controlled Molecule Release & its Real Time Monitoring







- Detected real-time release of molecules by Raman spectroscopy
- The higher the rotation speed, the higher the release rate

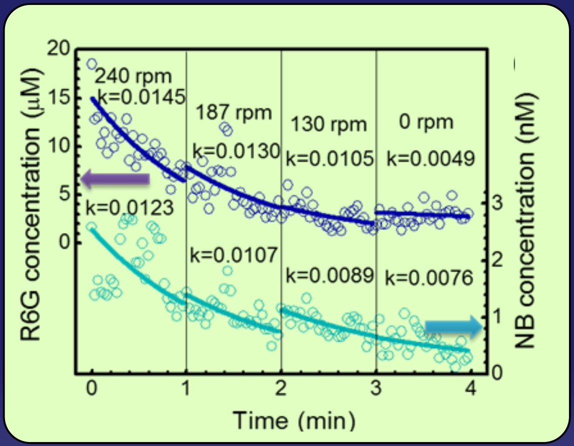
According to the Fick's law

Exponential decay function

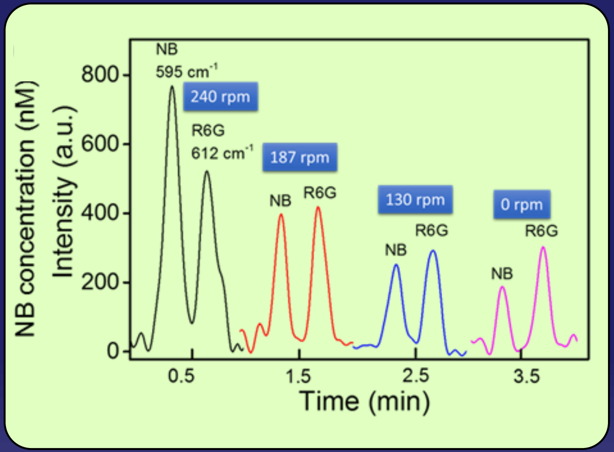
$$C = C' \cdot e^{-kt} + C_0$$

Fan, et al., ***Angew. Chem. Int. Ed***., 127, 2555 (2015)

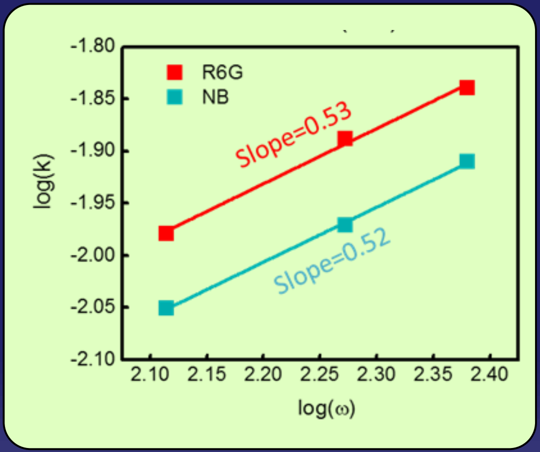
Release of Multiplex Molecules & its Real Time Monitoring



Releasing of multiplex molecules
(R6-G, Nile Blue)



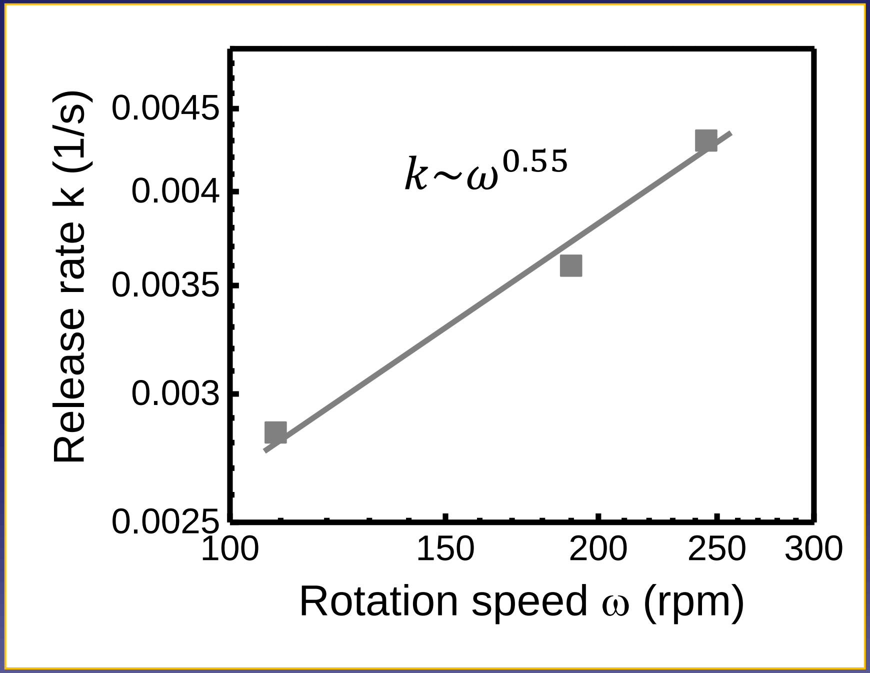
Chemistry and quantity can be simultaneous detection with Raman spectroscopy

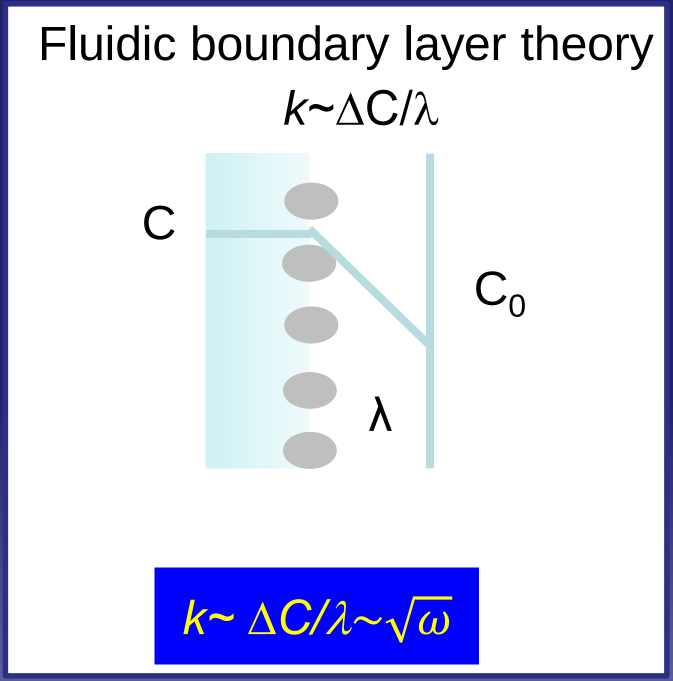


Both release rates show ~ 0.5 power-law dependence

Fan, et al., ***Angew. Chem. Int. Ed*.**, 127, 2555 (2015)

Understanding of Mechanically Controlled Release





Fluidic boundary layer theory: the thickness of diffusion layer (λ) becomes thinner with higher flow speed ($\lambda \sim \frac{1}{\sqrt{\omega}}$)

- We can precisely tune molecule release on nanoparticles by mechanical rotation
- The release rate $k \sim \sqrt{\omega}$ is understood quantitatively
- First of its kind

Fan, et al., ***Angew. Chem. Int. Ed***., 127, 2555 (2015)

Rotating Nanomotors next to a Live Cell

- Work in biomedia next to a live cell
- Tunable release to single live cell
- Unprecedented study on cell-cell communications

Summary

— Linear nanomotors for drug delivery to a single cell with distinct bioresponses

— High-performance rotary nanomotors (ultrahigh speed and durable operation)

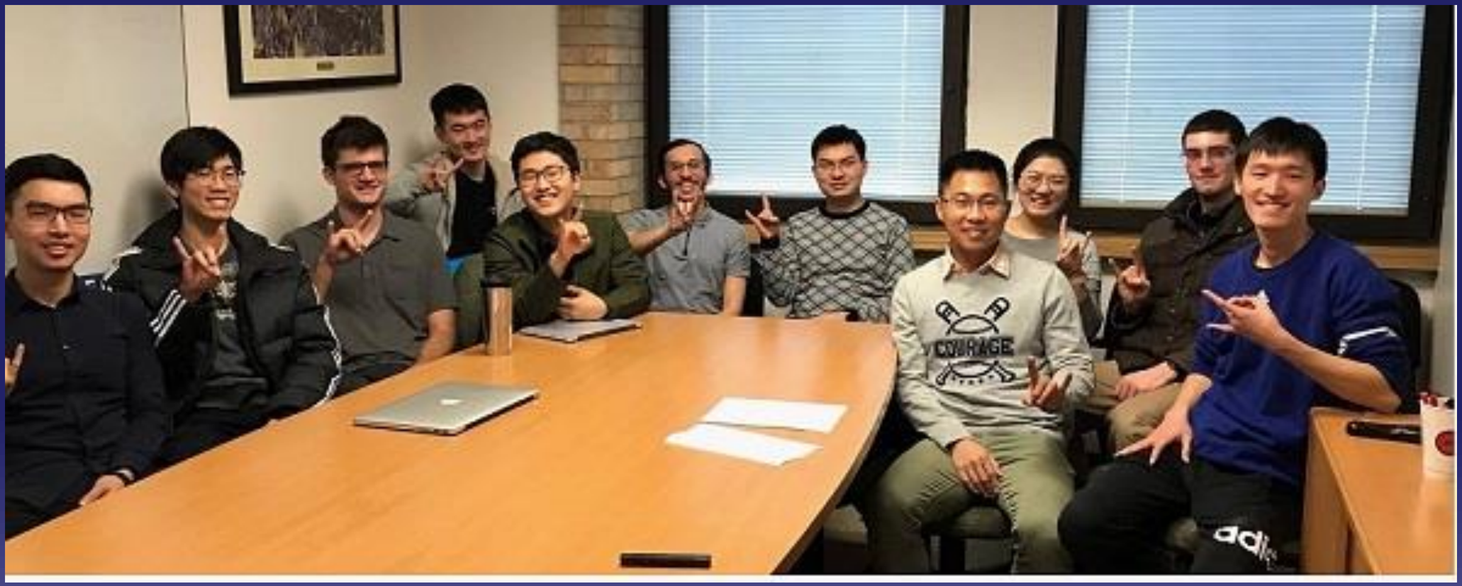
— Plasmonic active nanomotors

  — Tunable biochemical release rate

  — Integration of micromotors in microfluidics

  — Enhanced DNA capture and sensing speed with mechanical rotation

Acknowledgement



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To Jianhe Guo

Thank you!