UNIVERSITY OF JYVÄSKYLÄ

Dielectrophoretic Trapping and Electrical Conductivity of DNA Origami Structures

Veikko Linko

Anton Kuzyk

Bernard Yurke

Seppo Paasonen

Päivi Törmä

Jussi Toppari

NSC

Nanoscience Center

TKK

Lucent Technologies
Bell Labs Innovations

BOISE STATE UNIVERSITY

Contents

- Motivation
- Basics of Dielectrophoresis (DEP)
  - DEP of DNA
- DNA Origami
- DEP Trapping of DNA Origami Structures
- Electrical Conductivity of DNA Origami Structure
  - AC Impedance Spectroscopy

Nanoscience Center

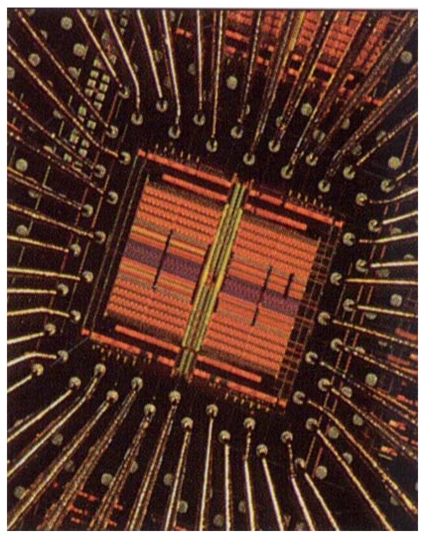
UNIVERSITY OF JYVÄSKYLÄ

Motivation

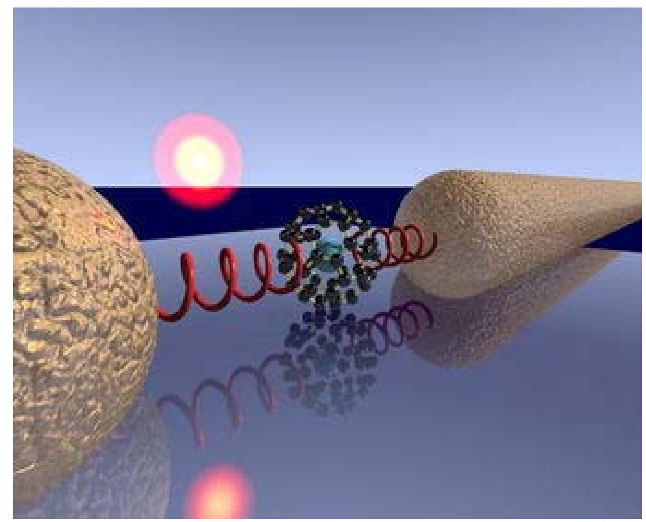
- Top-down approach
  (resolution limit, packing density)
- Nanoelectronics / molecular electronics
- Bottom-up approach (self-assembly)
- Biomolecules, CNTs, ... (1 nm - 10 μm)
- DNA: superior self-assembly properties

- Controlled positioning on the chip and connecting to other circuitry
- Manipulation of single molecules or larger constructions needed
- Use DEP!

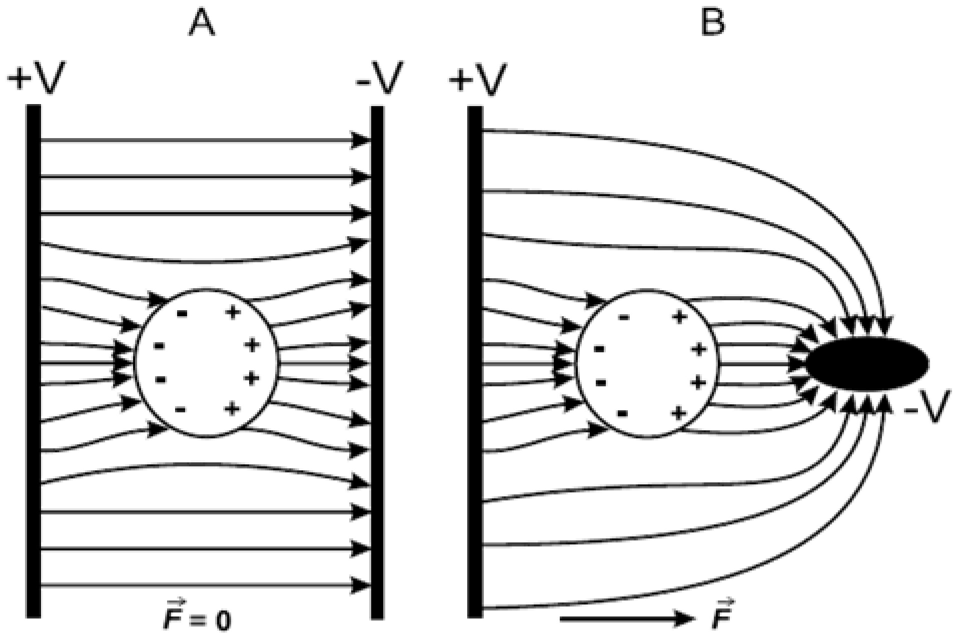
+



? =



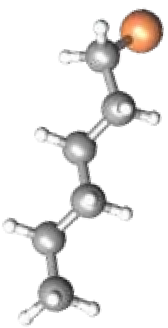
Dielectrophoresis (DEP)

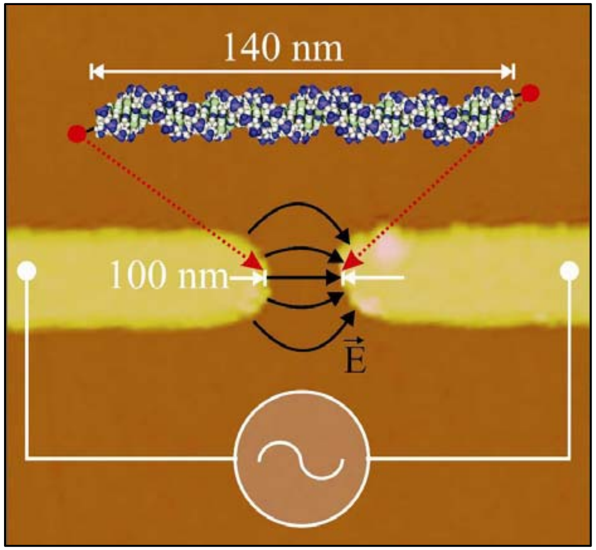


- DEP-force:
  $F = (p \bullet \nabla)E$
  $= (\alpha/2)\nabla(E^2)$
- Brownian motion:
  $F = k_B T/(2r)$

Basics of DEP Trapping of DNA

- Negatively charged DNA
- Counterion cloud in the aquatic buffer: (Hepes/NaOH, low σ)
- Polarizability increases due to the counterion cloud
- Gold fingertip-type electrodes (e-beam lithography)
- Linker molecule (S-Au bond)

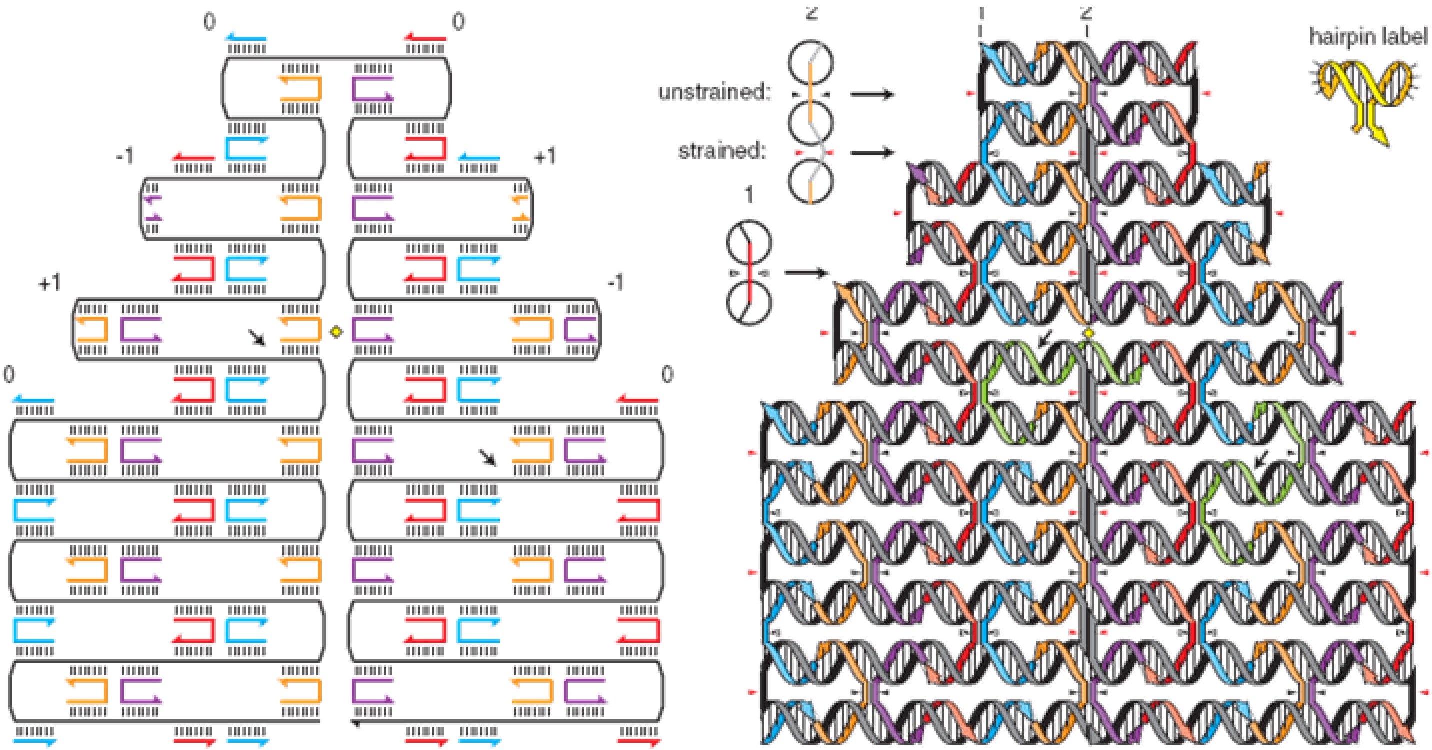




S. Tuukkanen *et al.* Nanotechnology **18,** 295204 (2007).

DNA Origami

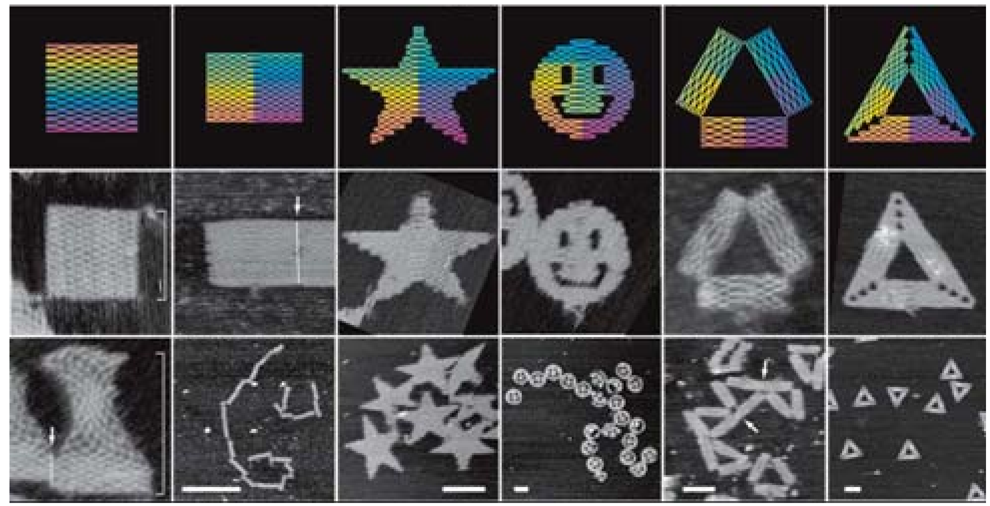
Paul W. K. Rothemund, Nature | Vol 440 | 16 March 2006



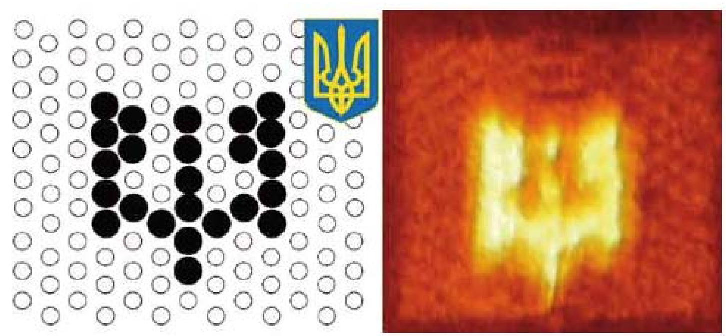
DNA Origami Structures

- DNA origami as a nanobreadboard

  - non-periodic patterning!
- How to connect origami to outer world?
- Does origami structure conduct electricity?



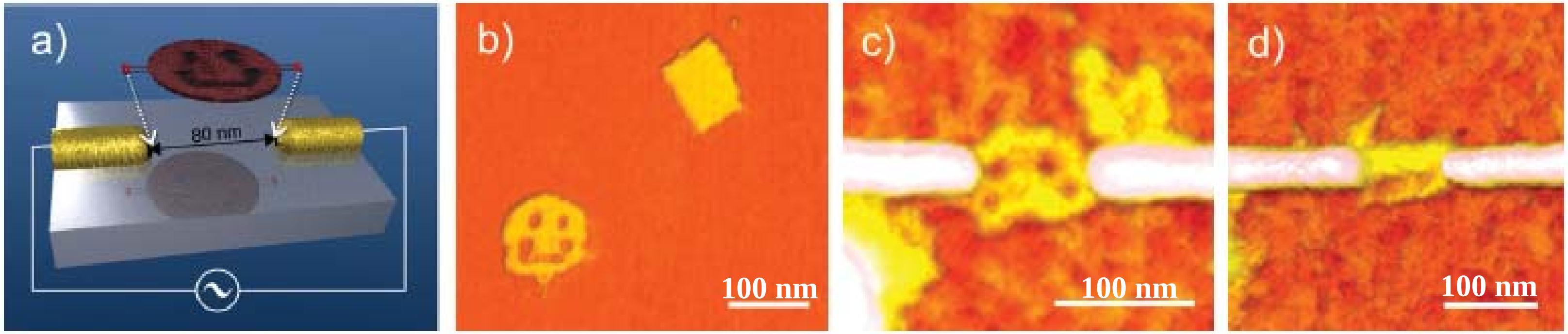
Example of patterning:
Biotin-modified staple strands + streptavidin



A. Kuzyk, K.T. Laitinen, and P. Törmä, Nanotechnology, 20, 235305 (2009).

Nanoscience Center

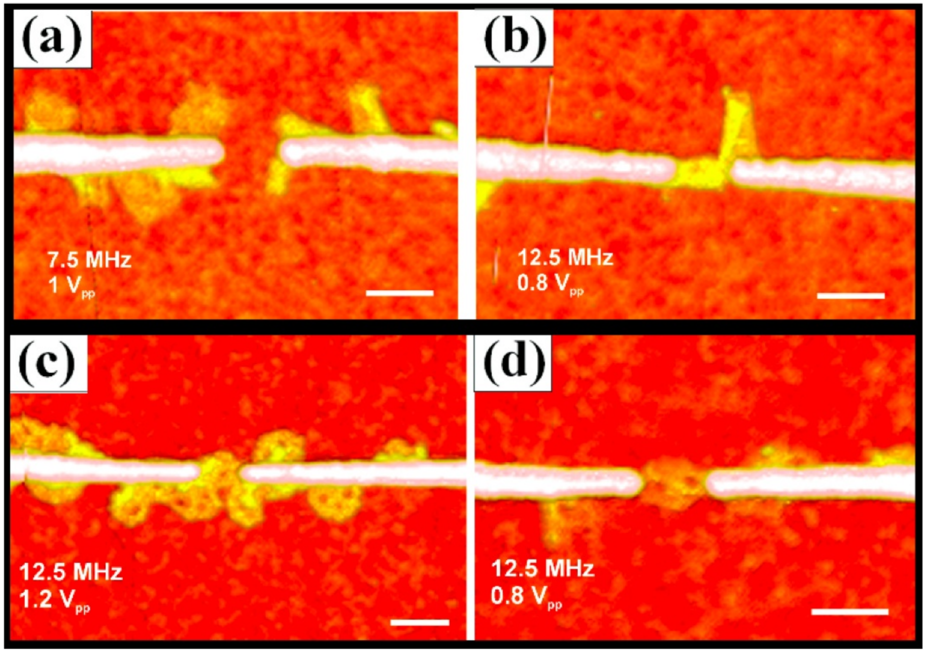
DEP Trapping of DNA Origami Structures



- Origami annealing buffer (10x TAE Mg++) changed to the buffer of lower conductivity (Hepes + NaOH + Magnesium acetate)
- Origami structures are ligated
  - Polynucleotide Kinase + DNA Ligase
- Strands with thiol groups are incorporated at each side to allow attachment to gold electrodes

More Results of DEP Trapping

- Height of origami structure: 2 nm
  - DNA sustains its natural form
- Drastic dependence on the AC-frequency and the applied voltage
- Trapping yield: ~10 %



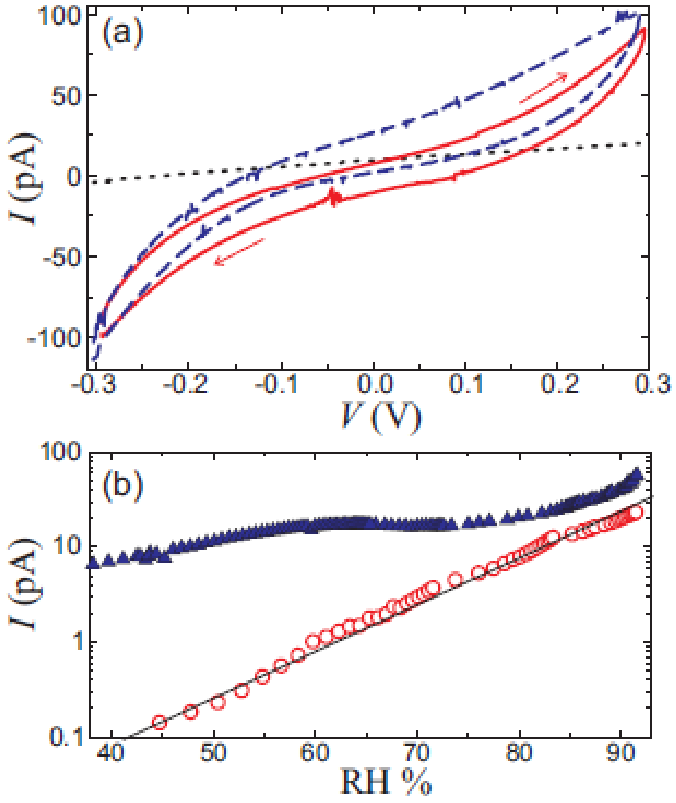
A. Kuzyk, B. Yurke, J.J. Toppari, V. Linko, and P. Törmä
Dielectrophoretic Trapping of DNA Origami, Small **4**(4), 447-450 (2008).

Electrical Measurements: DC-conductivity

- Rectangular structures
- Relative humidity ~90 %
- Non-linear *IV*-curves
- DC-resistance: 2 GΩ – 10 GΩ

  - for control sample: over 10 GΩ
- Current vs. Humidity

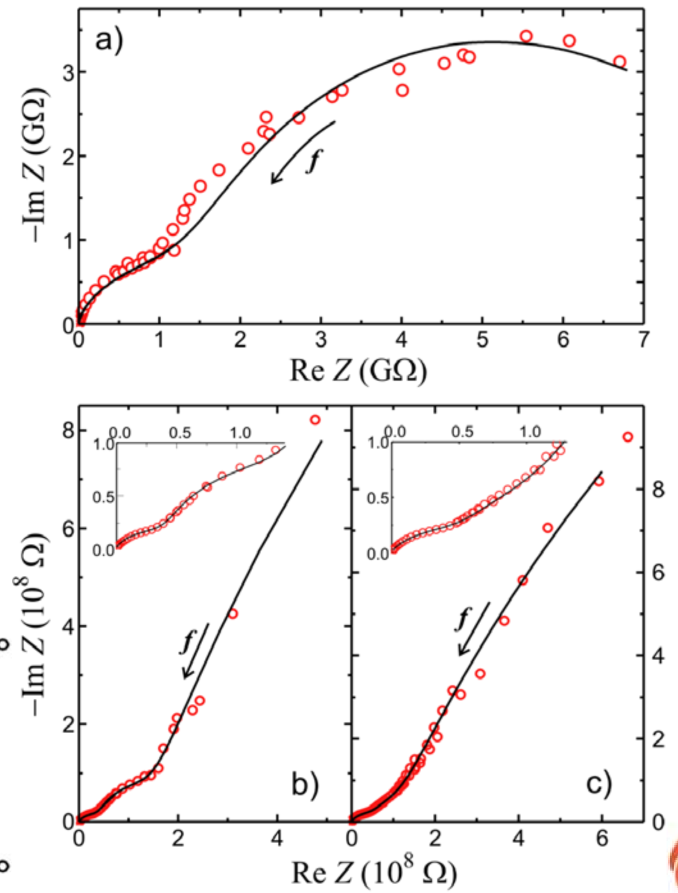
  - ionized water molecules main charge carriers
- Linker molecule has a large resistance
- No information about the electronic conductivity



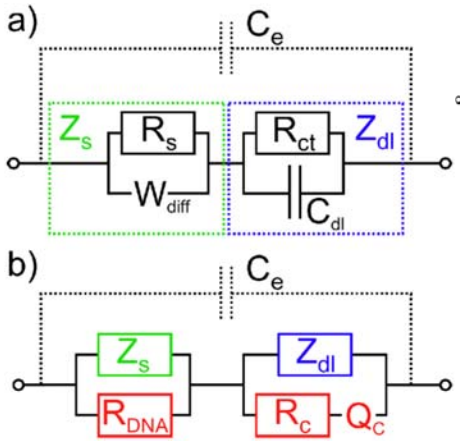
Nanoscience Center

AC Impedance Spectroscopy

- RH = 90 %
- Frequency range: 0.01 Hz -100 kHz
- Amplitude: 50 mV
- Control sample
  -> Modified Randles circuit
- DNA origami structure
  -> R_{DNA}, R_C and Q_C have to be added



- R_s = resistance of ”electrolyte”
- W_{diff} = diffusion of ions
- R_{ct} = charge transfer resistance through double-layer
- C_{dl} = double-layer capacitance
- C_e = self-capacitance
- R_c and Q_c modify the double-layer

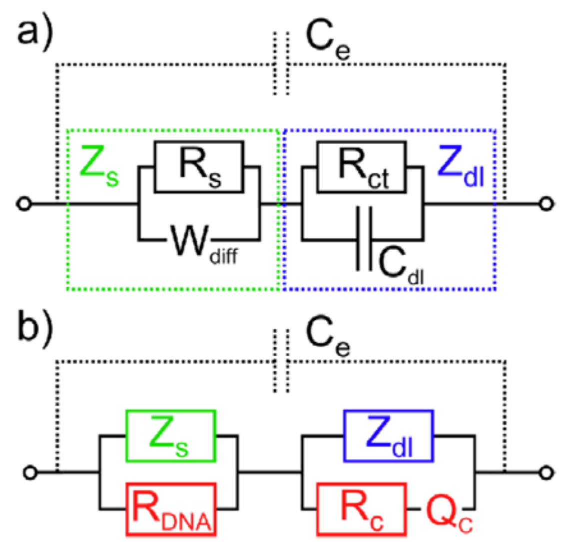


Nanoscience Center

UNIVERSITY OF JYVÄSKYLÄ

More AC-IS Results

- Linker molecule does not conduct directly, but there is a charge transfer process in AC -> Measurement of electronic conductivity
- R_{DNA} ~70 MΩ
  - Electronic conductivity
- R_{ct} dominates in DC, $R_{s,}$ R_{ct} ~ GΩ
  - $R_s + R_{ct} \approx 10$ GΩ (DC-path)
- W_{diff} increases due to mobile counterions around DNA
- Over 90 % relative humidity increases diffusivity, Q_C -> W



$$Z_{CPE} = 1/[Q(j\omega)^n];\ Z_W = 1/[W(j\omega)^{1/2}]$$

V. Linko, S.-T. Paasonen, A. Kuzyk, P. Törmä, and J.J. Toppari, *Characterization of the Conductance Mechanisms of the DNA Origami by AC Impedance Spectroscopy*, to appear in Small (2009).

Conclusions

- DEP is a feasible tool for controlled positioning and immobilization of DNA origami structures

  - First example of trapping of a complex self-assembled molecular structure

  - DEP as a bridge between top-down and bottom-up approaches

- AC Impedance spectroscopy:

  - Individual structures measured

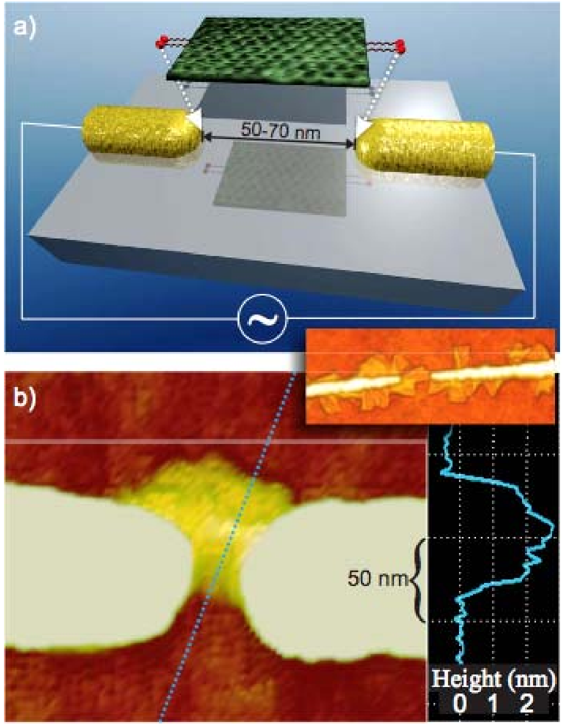
  - Nature of conductivity (electronic and ionic)

  - High impedance of linker molecules

  (DC-measurement is not enough)

  - Conductivity is sufficiently low (for applications: locally conducting parts by doping?)

  - Good approximation for pure dsDNA also



Nanoscience Center

UNIVERSITY OF JYVÄSKYLÄ

Acknowledgements

This work was supported by:

- Academy of Finland
- EURYI scheme awards (www.esf.org/euryi)
- National Graduate School in Nanoscience
- Tekniikan Edistämissäätiö

- Finnish Academy of Science and Letters (Väisälä Foundation)
- Finnish Cultural Foundation (Central Finland Regional Fund)

Thanks to P.W.K. Rothemund, E. Winfree, R. Barish, and R. Hariadi for useful discussions, J. Ylänne and M. Vihinen-Ranta for help with lab facilities.

Nanoscience Center

UNIVERSITY OF JYVÄSKYLÄ

Thanks for your attention!

Nanoscience Center

UNIVERSITY OF JYVÄSKYLÄ


UNIVERSITY OF JYVÄSKYLÄ