

Advanced integrated electrode architectures





Competences

Materials synthesis

- Thermal and plasma enhanced chemical vapor deposition
- Chemical vapor transport reactions
- Wet chemical synthesis and solvothermal methods
- Anodization of metal and semiconductor surfaces
- Chemical surface functionalization, decoration and crystal doping
- Physical vapor deposition processes

Assembly and microfabrication

- Optical lithography and thin film fabrication (sputtering, plasma-enhanced chemical vapor deposition of $\text{SiO}_2/\text{SiN}_x$, RIE and wet etch)
- Ink formulation and inkjet deposition
- Laser-assisted microstructuring of materials
- Surface mounting (alignment, soldering, adhesive bonding)
- FDA and SLA 3D printing
- 3 and 4 axes CNC fabrication
- 3D scaffolds for cell growth

Characterization and device testing

- TEM/ED, SEM/EDX, XRD, Raman, UV-Vis, AFM/STM
- DC analysis between 100-600 K in controlled gas environment
- Electrochemical measurements, impedance spectroscopy and high-frequency analysis up to 3 GHz
- Mechanical stress-strain and indentation measurements
- Wireless, autonomous measurements and system integration
- Thermal diffusivity (flash) and stability (TGA/DSC) measurements
- Finite-element modeling (mechanical, thermal, thermo-mechanical, electrical)



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Main contributors

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Olli Pitkänen

Niina Halonen (alumni)

Jhih-Fong Lin (alumni)

Jani Mäklin (alumni)

Collaborators

Srividya Sridhar (Rice University)

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Tomi Laurila (Aalto University)

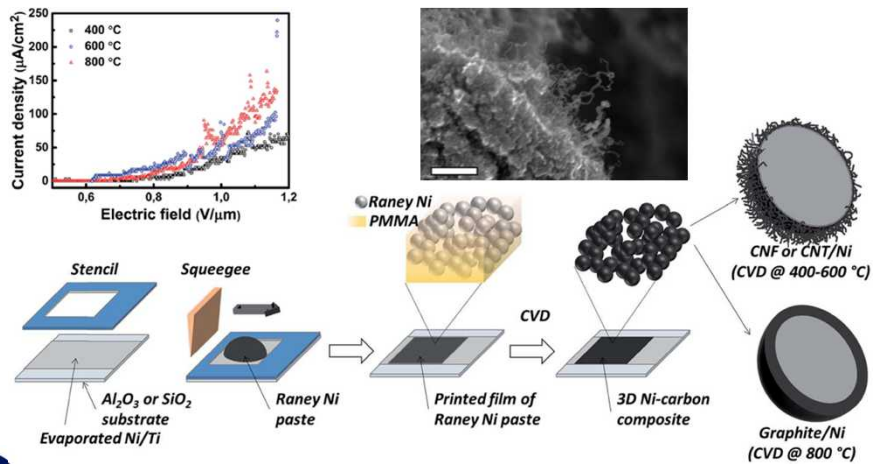
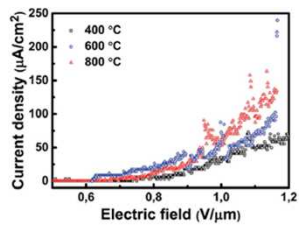
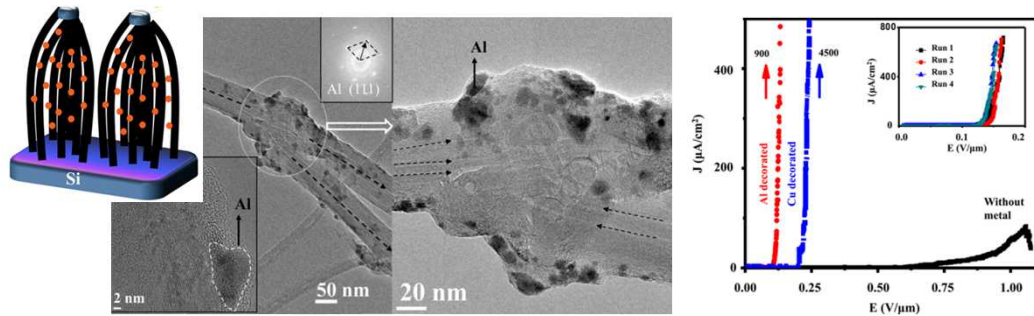
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Saikat Talapatra (Southern Illinois University)



Ultra-bright field-emitters



- Ultra-low turn on fields
- On-chip grown devices
- Compatibility with Si CMOS, printing and ceramic technologies

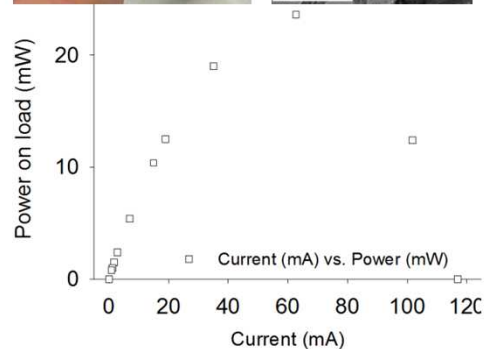
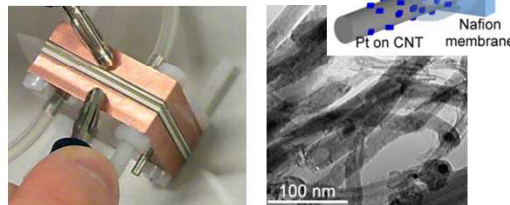
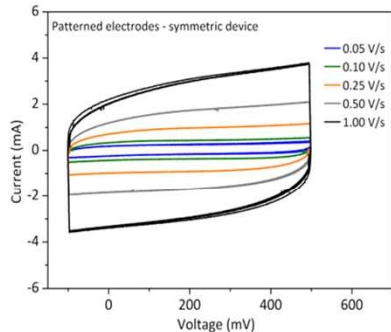
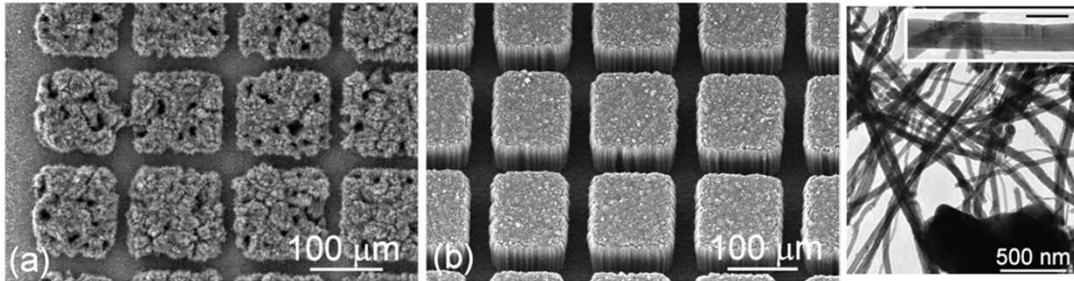
Sridhar, S; Tiwary, C; Vinod, S; Taha-Tijerina, J.J; Sridhar, S; Kalaga, K; Sirota, B; Hart, A.H.C; Ozden, S; Sinha, R.K.; Harsh, Vajtai, R. Choi, W.; Kordás, K.; Ajayan, P.M. Field Emission with Ultralow Turn On Voltage from Metal Decorated Carbon Nanotubes, *ACS Nano* **8** (2014) 7763–7770

Sridhar, S; Ge, L; Tiwary, CS; Hart, AC; Ozden, S; Kalaga, K; Lei, S; Sridhar, SV; Sinha, RK; Harsh, H; Kordas, K; Ajayan, PM; Vajtai, R., Enhanced Field Emission Properties from CNT Arrays Synthesized on Inconel Superalloy, *ACS Appl. Mater. Interf.* **6** (2014) 1986-1991.

Lin, JF; Mohl, M; Nelo, M; Toth, G; Kukovecz, A; Konya, Z; Sridhar, S; Vajtai, R; Ajayan, PM; Su, WF; Jantunen, H; Kordas, K; Facile synthesis of nanostructured carbon materials over Raney® nickel catalyst films printed on Al₂O₃ and SiO₂ substrates, *J. Mater. Chem. C* **3** (2015) 1823-1829



Energy applications



- Aligned micropatterned multifunctional CNT forests on conductive substrates
- Low series resistance, efficient and high capacity electrodes for fuel cells, supercapacitors and pseudocapacitors
- Compatibility with Si CMOS, printing and ceramic technologies

Rautio, AR; Pitkanen, O; Jarvinen, T; Samikannu, A; Halonen, N; Mohl, M; Mikkola, JP; Kordas, K; Electric Double-Layer Capacitors Based on Multiwalled Carbon Nanotubes: Can Nanostructuring of the Nanotubes Enhance Performance? *J. Phys. Chem. C* **119** (2015) 3538-3544.

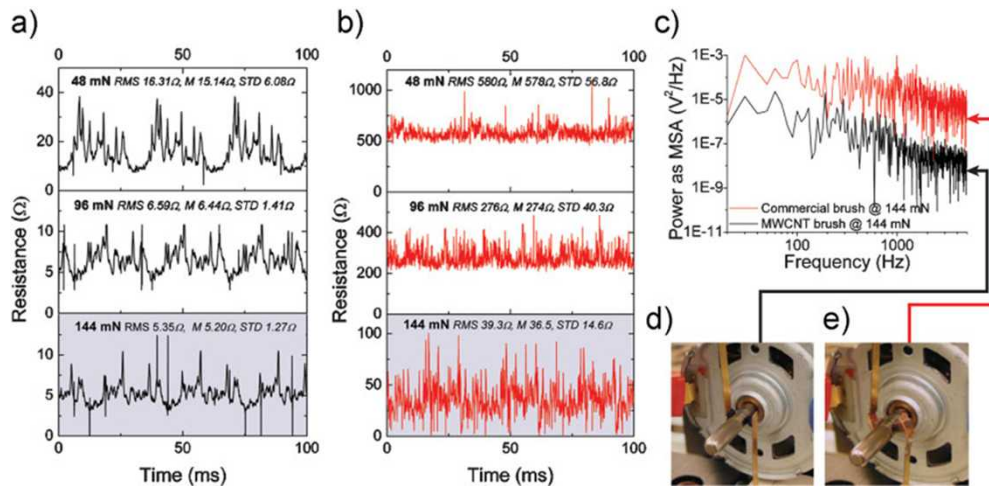
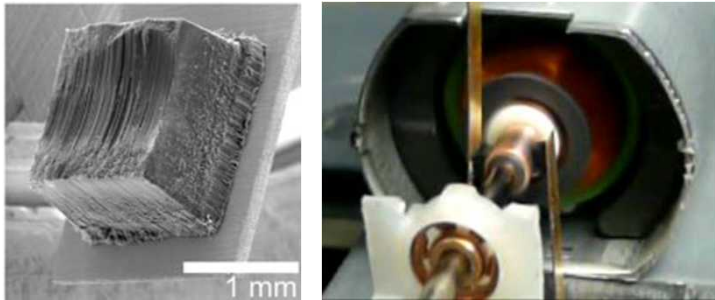
Halonen, N; Maklin J; Rautio A-R; Kukkola J; Uusimaki A; Toth G; Reddy LM; Vajtai R; Ajayan PM; Kordas K; Thin micropatterned multi-walled carbon nanotube films for electrodes, *Chem. Phys. Lett.* **583** (2013) 87.

Al-Asadi, L.A. Henley, M. Wasala, B. Muchharla, N.-P. Lopez, V. Carozo, Z. Lin, M. Terrones, K. Mondal, K. Kordas, S. Talapatra, Aligned Carbon Nanotube/Zinc Oxide Nanowire Hybrids As Supercapacitor Electrodes, 2016, submitted for publication

O. Pikänen, T. Järvinen, H. Cheng, G. S. Lorite, G. A. Dombovari, S. Talapatra, G. Tóth, K. Kordás, On-Chip Pseudocapacitors with CNT-MnO₂ electrodes, 2016, to be submitted.



Contact brushes

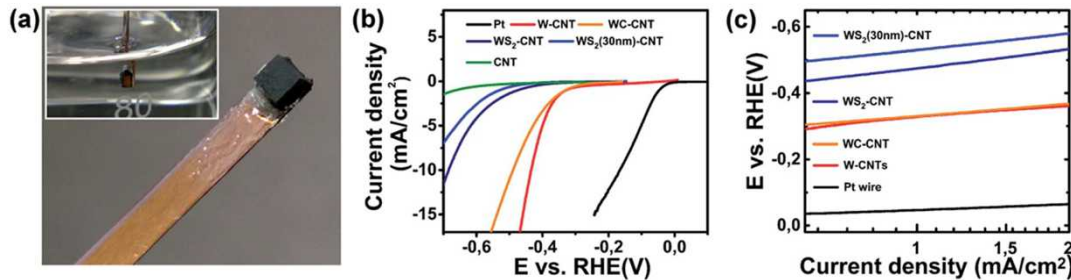
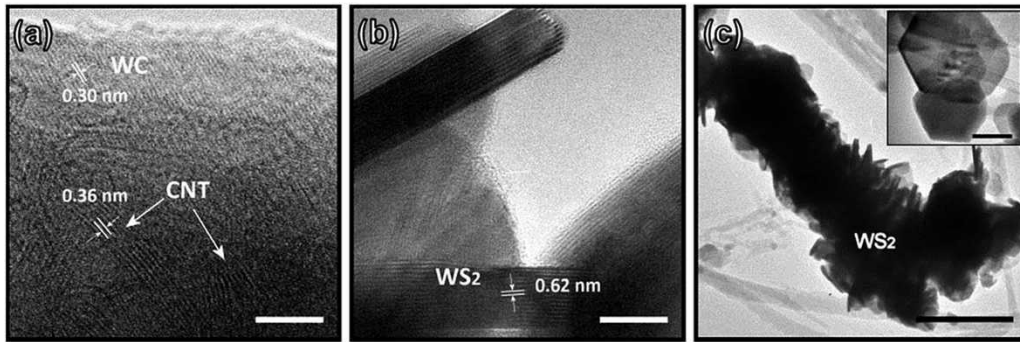


- Aligned CNT forests solder mounted on conductive flexible cantilevers
- Low series resistance, mechanical flexibility and vibration damping

G. Toth, J. Mäklin, N. Halonen, J. Palosaari, J. Juuti, H. Jantunen, K. Kordas, W. G. Sawyer, R. Vajtai, P. M. Ajayan, Carbon Nanotube Based Electrical Brush Contacts, *Adv. Mater.* **21** (2009) 2054.



Electrocatalytic electrodes for OER and HER



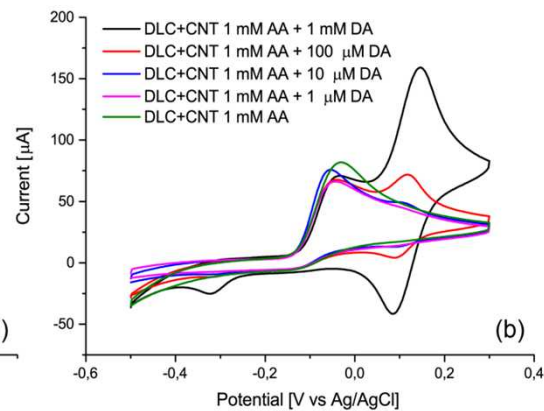
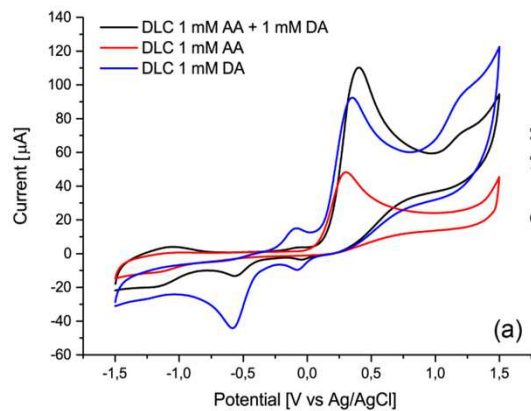
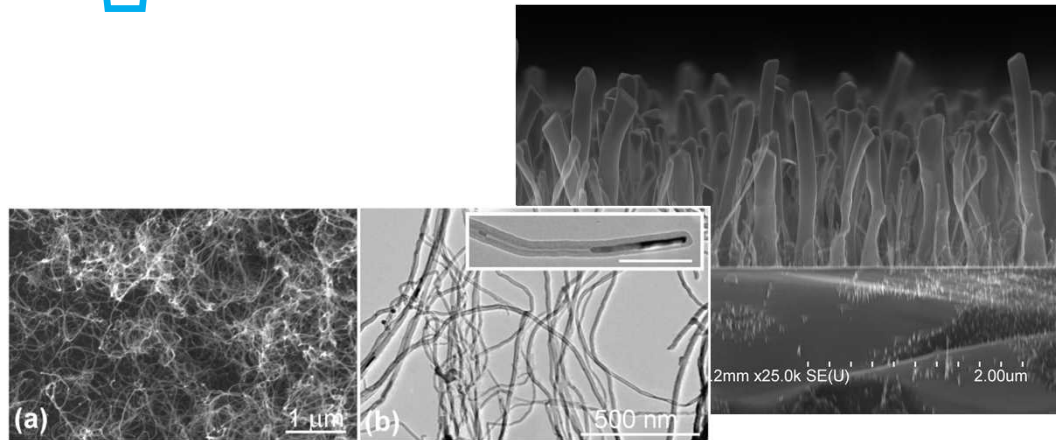
- Nanocomposites of aligned CNT forests and WS₂ solder mounted on conductive leads
- Hierarchical structures of carbon foams and nanotubes decorated with Co₃O₄
- Gas evolution at low overpotentials
- Compatible with integration techniques

Lin, JF; Pitkanen, O; Maklin, J; Puskas, R; Kukovecz, A; Dombovari, A; Toth, G; Kordas, K Synthesis of tungsten carbide and tungsten disulfide on vertically aligned multi-walled carbon nanotube forests and their application as non-Pt electrocatalysts for the hydrogen evolution reaction, *J. Mater. Chem. A*, **3** (2015) 14609-14616.

Pham, TN; Sharifi, T; Sandström, R; Siljebo, W; Shchukarev, A; Kordas, K; Wågberg, T; Mikkola, JP; Robust hierarchical and cost-efficient 3D carbon foam electrode for efficient water electrolysis, submitted for publication, 2016.



Sensor devices



- Diamond-like carbon and carbon nanotube hybrid structures grown on Si substrates
- Synergy leading to enhanced amine sensitivity
- Detection of biogenic amines

Sainio, S; Palomaki, T; Tujunen, N; Protopopova, V; Koehne, J; Kordas, K; Koskinen, J; Meyyappan, M; Laurila, T; Integrated Carbon Nanostructures for Detection of Neurotransmitters, *Molecular Neurobiology* **52** (2015) 859-866.

Laurila, T; Sainio, S; Jiang, H; Palomaki, T; Pitkanen, O; Kordas, K; Koskinen, J; Multi-walled carbon nanotubes (MWCNTs) grown directly on tetrahedral amorphous carbon (ta-C): An interfacial study, *Diamond and Related Materials*, **56** (2015) 54-59.

Sainio, S; Palomaki, T; Rhode, S; Kauppila, M; Pitkanen, O; Selkala, T; Toth, G; Moram, M; Kordas, K; Koskinen, J; Laurila, T; Carbon nanotube (CNT) forest grown on diamond-like carbon (DLC) thin films significantly improves electrochemical sensitivity and selectivity towards dopamine, *Sensors and Actuators B* **211** (2015) 177-186.



Projects

Ongoing

- ❑ Surface plasmons at work: Visible and infrared light enhanced catalysis and gas sensing - Academy of Finland (PI: K. Kordas)
- ❑ Hybrid nanocarbon materials for biosensors - Academy of Finland (PI: K. Kordas)
- ❑ More-than-Moore research community - University of Oulu (PI: K. Kordas)
- ❑ 3D hierarchical scaffold based on bio-decorated carbon nanotubes for bone and cartilage tissue engineering – Academy of Finland (PI: Gabriela S. Lorite)
- ❑ High-power Impulse Plasma Process Operations for the Creation of Advanced Metallic Parts - European Union FP7 (PI: G. Toth)

Completed

- ✓ Optimal production of bioethanol from macroalgae via photo-chemo-enzymatic processing (2013-2015) - Academy of Finland (PI: K. Kordas)
- ✓ Smart and sustainable food packaging utilizing flexible printed intelligence and materials technologies (2012-2014) - European Union FP7 (PI: G. Toth)
- ✓ Implementation of highly efficient TiO₂ based photocatalytic nanomaterials (2011-2014) - Finnish Funding Agency for Technology and Innovation (PI: K. Kordas)
- ✓ Autonomous R2R systems (2011-2014) - Finnish Funding Agency for Technology and Innovation (PI: K. Kordas)
- ✓ Nanoscale thermal management of multi-scale electrical components using carbon nanotubes grown by CCVD and PECVD (2009-2011) - Academy of Finland (PI: G. Toth)
- ✓ Thermal management with carbon nanotube architectures (2010-2012) - European Union FP7 (PI: K. Kordas)
- ✓ Nanotechnology Platform for Electronics and Photonics (2010-2013) - European Union FP7 (PI: K. Kordas)
- ✓ Novel catalyst materials based on robust CNT membranes (2009-2012) - Academy of Finland (PI: K. Kordas)
- ✓ Invisible electric tagging with nanomaterials (2008-2010) - Finnish Funding Agency for Technology and Innovation (PI: K. Kordas)
- ✓ Hydrogen for fuel cells by bioethanol reforming 2, - Finnish Funding Agency for Technology and Innovation 2007-2009 (PI G. Toth)
- ✓ Nanomaterials in wireless tags based on printed electronics (2005-2008) - Finnish Funding Agency for Technology and Innovation (PI: H. Jantunen)
- ✓ Integrated self-adjusting nano-electronic sensors (2006-2009) - European Union FP6 (PI: K. Kordas)



Doctoral dissertations

Anne-Riikka Rautio (2016): On the stability of carbon nanotube and titania nanowire based catalyst materials

Jhih-Fong Lin (2015): Multi-dimensional carbonaceous composites for electrode applications

Jani Mäklin (2014): Electrical and thermal applications of carbon nanotube films

Niina Halonen (2013): Synthesis and applications of macroscopic well-aligned multi-walled carbon nanotube films

Jarmo Kukkola (2013): Gas sensors based on nanostructured tungsten oxides

Tero Mustonen (2009): Inkjet printing of carbon nanotubes for electronic applications