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Nanoparticle Monitoring – Present Technology and Future Developments

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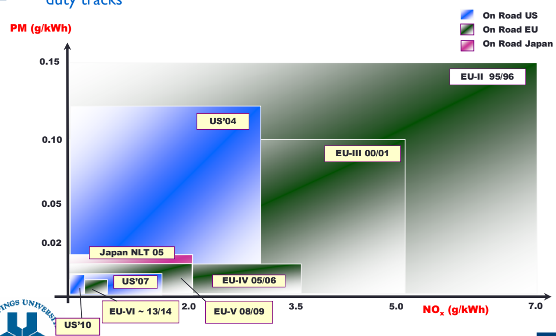
Outline:

1. Motivation for the nanoparticle measurements
2. Some present commercial solutions
3. Research trends in nanoparticle sensors
4. Chempack project
5. Smart sensors

1. Motivation for the nanoparticle measurements

Legislation for particulate matter (PM) and NO_x-emissions from heavy duty tracks



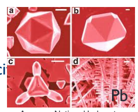
1. Motivation for the nanoparticle measurements: nanotoxici

Nanoparticles show adverse health effects according to:

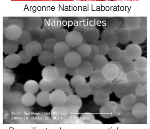
- Size (by definition ϕ < 100 nm)
- Shape (sperhical, cubic, stars, fibers,...)
- Content
- Concentration
- Nanoparticles damage cells: oxidative effect on cells

➡ Nanoparticle sensors should be able to measure all that?!!!

➡ First approach will be so called "smart sensor": an integrated collection of separate sensors!



Argonne National Laboratory

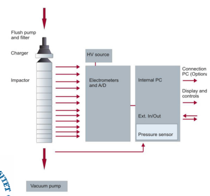


Borosilicate glass nanoparticles
Martin Gijs, EPFL

Kathryn M Mayer *et al* 2010 *Nanotechnology* **21** 255503 doi: 10.1088/0957-4484/21/25/255503

2. Some present commercial solutions

- DEKATI ELPI (Electrical Low Pressure Impactor)
- Particles are first charged to a known charge level in a specific charger
- Then in a cascade impactor, they are divided according to their aerodynamic diameter and very sensitive electrometers measure the real-time currents of the particles.
- The currents are proportional to particle number concentration and size. The measurement scale is 6 nm – 10 µm.



2. Some present commercial solutions

- PARTICLE MEASUREMENT SYSTEMS
- Nano-ID™ NPS500 based on DMA (Differential Mobility Analyzer) technology
- DMA is a system with two electrodes which generates an electric field. The particles are then separated in the field according to their electrical mobility from which the particle diameter can be calculated.
- The portable particle measurement device is capable of defining the size distribution of particles in the range of 5 nm – 500 nm.

2. Some present commercial solutions

•NANOSIGHT
- provides optical methods to measure the size
- uses a laser light source to illuminate a 0.3 ml
- typical range is 10 nm - 1000 nm

•BECKMAN COULTER
- determines the particle size by measuring the scattering of laser light of a fluid with nanoparticles
- for size analysis electrophoretic light scattering (ELS)

•LIGHTHOUSE WORLDWIDE SOLUTIONS
- different kinds of handheld and portable particle counters
- minimum sensitivity of 200 nm

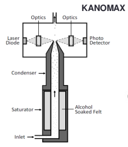
•AIRMODUS
- uses condensation to grow even 1 nm diameter nanoparticles to optically detectable sizes

•KANOMAX
- measures optically condensed particles even 15 nm in diameter

AIRMODUS

BECKMAN COULTER

KANOMAX MODEL 3800

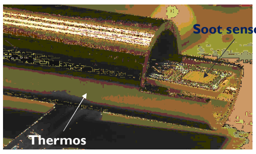


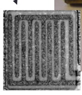
NANOSIGHT LM10

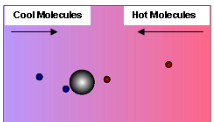
LIGHTHOUSE HANDHELD 2016

3. Research trends in nanoparticle sensors

Soot sensor based on Thermophoresis







Thermophoresis:

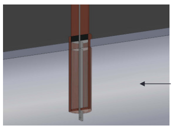
A force acting on particles in a temperature gradient →

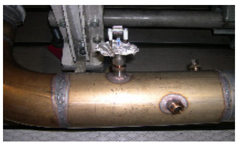
Soot is deposited on the coldest surface

Thermos packaging to decrease temperature on the sensor surface!

3. Research trends in nanoparticle sensors

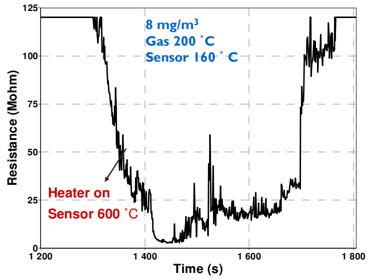
MD13 Heavy duty truck engine





3. Research trends in nanoparticle sensors

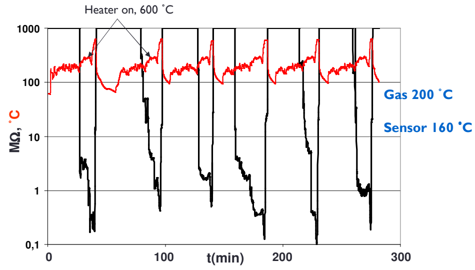
Soot Collection and Burn Off Cycle



Robert Bjorklund, Ann Grant

3. Research trends in nanoparticle sensors

6 World Harmonized Transient Cycles



(30 min/cycle, 18 min response time, 1370 mg/cycle, 40 mg/kWh)

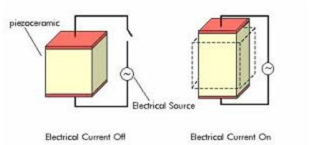
Robert Bjorklund and Ann Grant

3. Research trends in nanoparticle sensors

Piezoelectric effect and resonating sensors and array

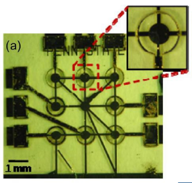
- Piezoelectric QCM array sensor with a resonance frequency of ~66 MHz and aerial sensitivity of **10^{-9} g**
- Sensor with 8 separate quartz resonators in one array, for example
- Δf increased on sensors coated with selective substance compared to non-coated resonators → good selectivity

Piezoelectric effect:



www.piezomaterials.com

QCM sensor array:



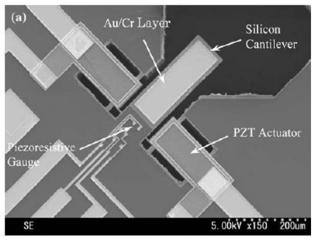
Ping Kao, Doerner S., Schneider T., Allara D., Hauptmann P. & Tadigadapa S. (2009) A Micromachined Quartz Resonator Array for Biosensing Applications. Journal of Microelectromechanical Systems, 18(3), p. 522-530.

3. Research trends in nanoparticle sensors

Piezoelectric cantilever beams

- A silicon cantilever beam structure with separate PZT actuators has been developed to increase the Q-factor of the sensor
- High Q-factors of 1113 and 7279 was measured in atmospheric pressure and in 35 Pa pressure, respectively. Sensitivity in scale of **10^{-9} g**

High-Q silicon cantilever structure with separate PZT actuators



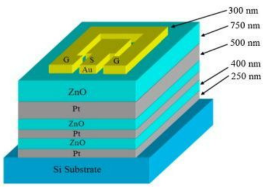
Lu J., Ikehara T., Zhang Y., Mihara T., Itoh T. & Maeda R. (2009) High quality factor silicon cantilever driven by piezoelectric thin film actuator for resonant based mass detection. Microsystem Technologies 15(8), p. 1163-1169.

3. Research trends in nanoparticle sensors

Film bulk acoustic resonators

- Film bulk acoustic resonators (FBAR) have become a notable choice in high sensitive mass sensors beacuse of their high resonance frequency
- An acoustic mirror is used to reflect most of the mechanical energy back to the piezoelectric resonator, instead of being dissipated in the substrate
- FBAR sensors with selective coatings can be used as biosensors also
- Typical FBAR application which uses ZnO and Pt layers and has a resonance frequency of ~4 GHz and mass sensitivity of **10^{-12} g** scale.

A typical FBAR application



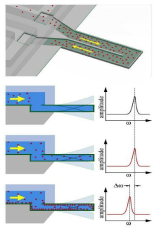
Yan Z., Song Z., Liu W., Ren H., Gu N., Zhou X., Zhang L., Wang Y., Feng S., Lai L. & Chen J. (2007) Material and device properties of ZnO-based film bulk acoustic resonator for mass sensing applications. Appl. Surf. Sci. 253(24), p. 9372-9380.

3. Research trends in nanoparticle sensors

Suspended microchannel cantilever beam

- A cantilever beam with microchannel has been presented for biomolecular detection in fluid
- The small molecules in fluid flow through a microchannel and the walls of the channel is coated with receptor molecules to trap the target particles
- The resonance frequency is shifted with the mass change of the beam
- The Q-value of 700 is achieved and mass resolution in **10^{-15} g** scale

A schematic of suspended microchannel cantilever beam

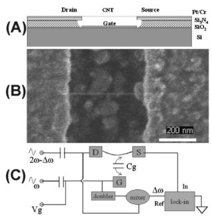


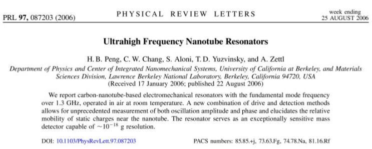
Burg T.P., Mirza A.R., Milovic N., Tsau C.H., Popescu G.A., Foster J.S. & Manalis S.R. (2006) Vacuum-Packaged Suspended Microchannel Resonant Mass Sensor for Biomolecular Detection. Journal of Microelectromechanical Systems15(6), p. 1466-1476.

3. Research trends in nanoparticle sensors

Carbon Nanotube Resonator

- Silicon technology based FET structure with a single carbon nanotube "channel" vibrating at the frequency of 1.3 GHz due to Coulombic attracttion stimulation. NEMS device.
- Sensitive also for the charged particles and ions around the CNT, mass detection sensitivity in the scale of **10^{-18} g**





PRL **97,** 087203 (2006) PHYSICAL REVIEW LETTERS week ending 25 AUGUST 2006

Ultrahigh Frequency Nanotube Resonators

H. B. Peng, C. W. Chang, S. Aloni, T. D. Yuzvinsky, and A. Zettl

Department of Physics and Center of Integrated Nanomechanical Systems, University of California at Berkeley, and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 17 January 2006; published 22 August 2006)

We report carbon-nanotube-based electromechanical resonators with the fundamental mode frequency over 1.3 GHz, operated in air at room temperature. A new combination of drive and detection methods allows for unprecedented measurement of both oscillation amplitude and phase and elucidates the relative mobility of static charges near the nanotube. The resonator serves as an exceptionally sensitive mass detector capable of $\sim 10^{-18}$ g resolution.

DOI: 10.1103/PhysRevLett.97.087203 PACS numbers: 85.85.+j, 73.63.Fg, 74.78.Na, 81.16.Rf

4. Chempack project

Combination of chemical sensors and packaging for new innovative sensor concepts (Chempack)

- TEKES funded 4 years FiDiPro project with Prof. Anita Lloyd Spetz, Linköping University, Sweden
- The goal of the project: to develop a sensors which detect nanoparticles according to their size, density, and content
- Nanoparticle detectors utilize widely different high sensitivity mass sensors using the shift of resonance frequency
- Using piezoelectric thin films in high sensitivity mass sensors, different organic molecules and even DNA can be detected
- *Single solid state sensor* which can be used in detecting for example size distribution of nanoparticles, have not yet been realized

4. Chempack project

Nanoparticle sensor – ideas:

Detection of particle size

Integration in packaging:

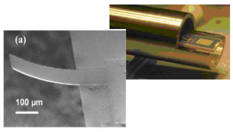
- Resonator structures (membranes, cantilevers)
  - Thermophoresis
  - Applied voltage (particles often charged)
  - Magnetism
- Dielectrophoresis
- Filters
- Adhesive layer, one time use sensor
- Structured sensing layers (NP shape)

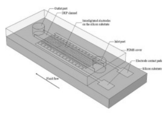
Detection of particle content:

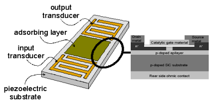
- Trapping particles (thermophoresis, magnetism, electric field)
- Combustion
- Multifunctional sensor arrays (FET, MOS, Optical, Calorimetric…)
- Smart operation and data evaluation

Detection of toxic effect on cells:

- The cell clinic



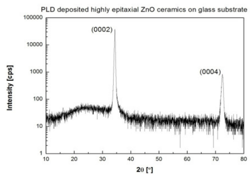




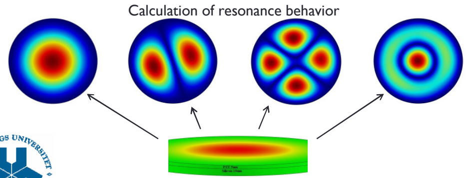
4. Chempack project

Nanoparticle sensor development

- COMSOL Multi-Physics modeling of various piezoelectric resonance based sensors desings
- Pulsed Laser Deposition (PLD) experiments of high quality ZnO thin films for sensor structures

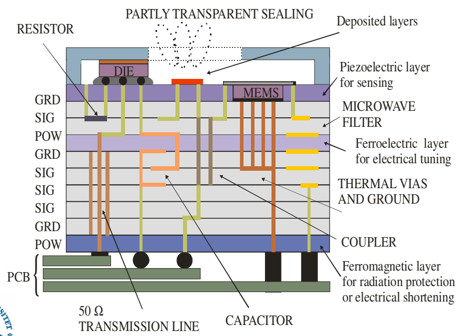


Calculation of resonance behavior



5. Smart sensors

Autonomous atmosphere sensor package – Smart sensor



Thank you for your attention!

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