Smart Sensors in Homes and Mobile Phones for Environmental Monitoring

Professor Julian Gardner

Microsensors and Bioelectronics Laboratory

University of Warwick, UK

http://www2.warwick.ac.uk/fac/sci/eng/research/grouplist/sensorsanddevices/mbl/

ISOCS & MiNaB-ICT

Joint Event on Sensing for Smart Anything Everywhere: Materials, Technologies, Applications

Tutorial Course 25-26 June 2016 - Otranto (Lecce), Italy

Contents of Tutorial

- Introduction to Warwick University
- Gas Sensors for New Devices – WHY?
- Potential Applications/Market for Gas sensors
- Smart Homes
- Smart Phones and Gas Sensors Today
- Conclusions and Future Needs

Introduction to Warwick University

Warwick University, UK

- Research-led University
- 20,000 students
- 1300 academic and research staff
- 40% of student population are postgraduate
- Research in all 30 Departments and 43 Research Centres
- Outstanding RAE performance in 2008

The University of Warwick is a *top 10* university

- Consistently in the **top 10** of UK universities
- Ranked **7th** in UK Research Assessment Exercise (RAE)
- According to a 2013 High Fliers Research Ltd. survey, reported in the Daily Telegraph January 17th 2013, Warwick is the **"top target for graduate employers"**

2013 Guardian University League Table	
1	Cambridge
2	Oxford
3	London School of Economics
4	St Andrews
5	**Warwick**
6	UCL
7=	Durham
7=	Lancaster

University Research Centres

Central Facilities (library etc)

School of Engineering

Electrical/Electronic Engineering

Mechanical/Civil Engineering

Manufacturing Systems

Research Groups and Laboratories

Microsensors and Bioelectronics Laboratory

Julian Gardner

- Professor of Electronic Engineering
  - BSc PhD DSc Ceng FIEE SMIEEE FREng
- Head of MBL
- 25 years experience in microsensors
- 500 publications (200 refereed journal)
- 12 books (4 series editor)
- 5 spin-out companies

http://www2.warwick.ac.uk/fac/sci/eng/research/grouplist/sensorsanddevices/mbl/

Microsensors and Bioelectronics Laboratory

- Dr Marina Cole
- Dr James Covington
- Dr Evor Hines
- Dr Mike Chappell

- Dr Zoltan Racz
- Dr Foysol Chowdhury
- Dr Prasanta Guha
- Shrey Pathak
- Marina Talib
- Phil King
- Arash Ghadar
- Max Joseph
- Chris Purssell
- James Taylor
- Reza Tamadoni
- 2 Technicians

- **Prof Derek Chetwynd - Mechanical**

- **Prof Nick Dale - Biology**
- **Prof Chris Dowson - Biology**
- **Dr Crawford Dow - Biology**

- **Prof Pat Unwin - Chemistry**

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Some Collaborations

Prof. Florin Udrea	Cambridge University
Dr. Tim Pearce	Leicester University
Prof. Phil Bartlett	Southampton University
Prof. Christofer Hierold	ETH, Zurich
Prof. Peter Hesketh	Georgia Tech, USA
Prof. Vijay Varadan	PennState University, USA
Dr. Su Tan	Nangyang Tech, Singapore

- **Agilent/Hewlett Packard**
- **Alpha MOS, France**
- **AlphaSense Ltd**
- **Applied Sensor, Sweden**
- **Cyrano Sciences, USA**
- **Denso**
- **Honeywell, USA**
- **Osmetech plc**
- **Philips**
- **Thales**
- **Sony, Germany**
- **Welch-Allyn, USA**

My research areas

- Electronic Noses
- Microsensors and Nanomaterials
- CMOS Chemical Sensors
- Artificial Olfactory Mucosa
- Neuromorphic aVLSI Micronose
- Electronic Tongue
- Cell-based SAW microsensors
- Summary

Gas Sensors for New Devices – WHY?

New Devices and the 2015 Market

- Consumer electronics is full of ASICS & also sensors/MEMS

400 million computers sold

800 million phones sold

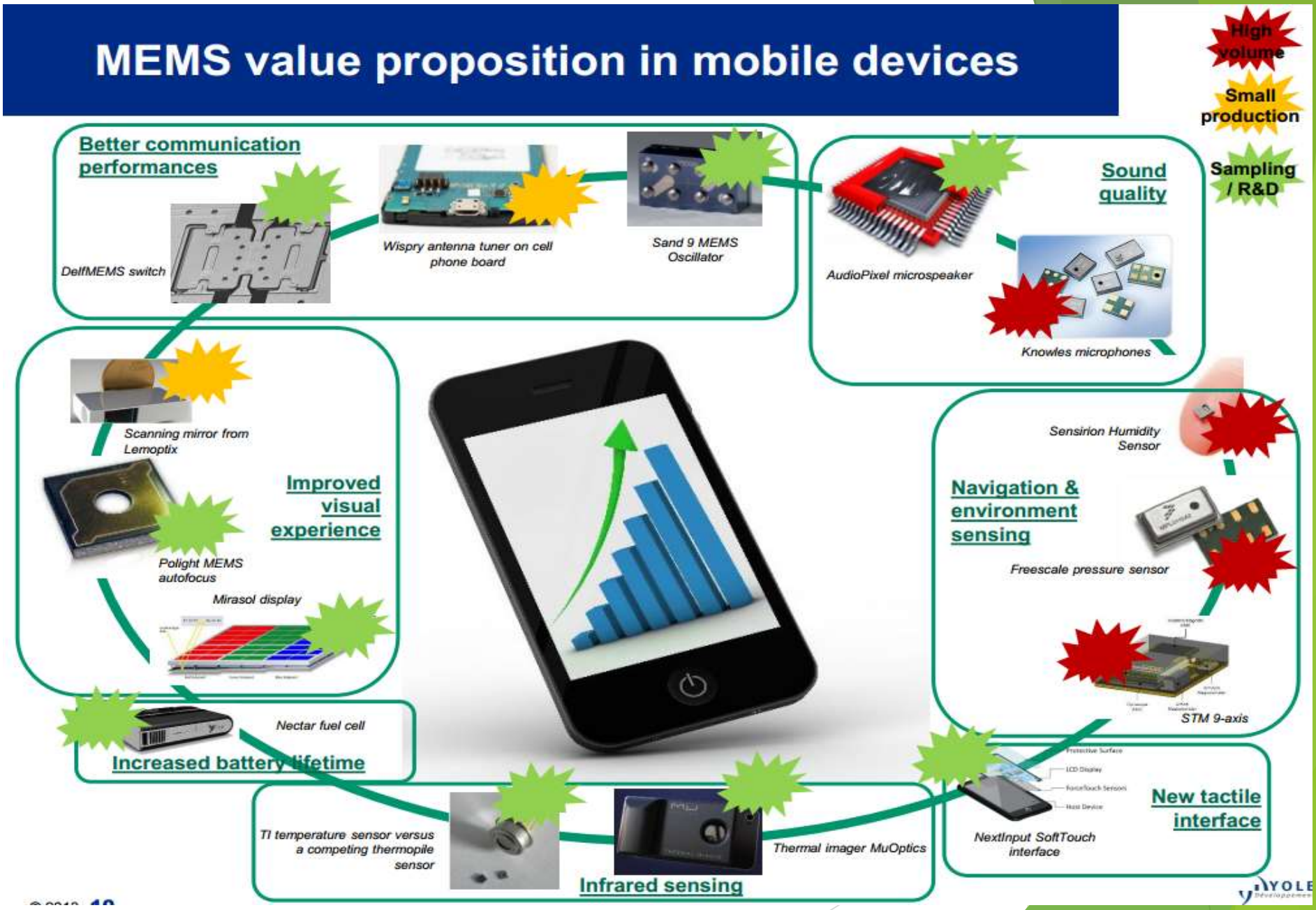
200 million tablets sold

Billions sensors sold

Samsung Gear

Nike Band

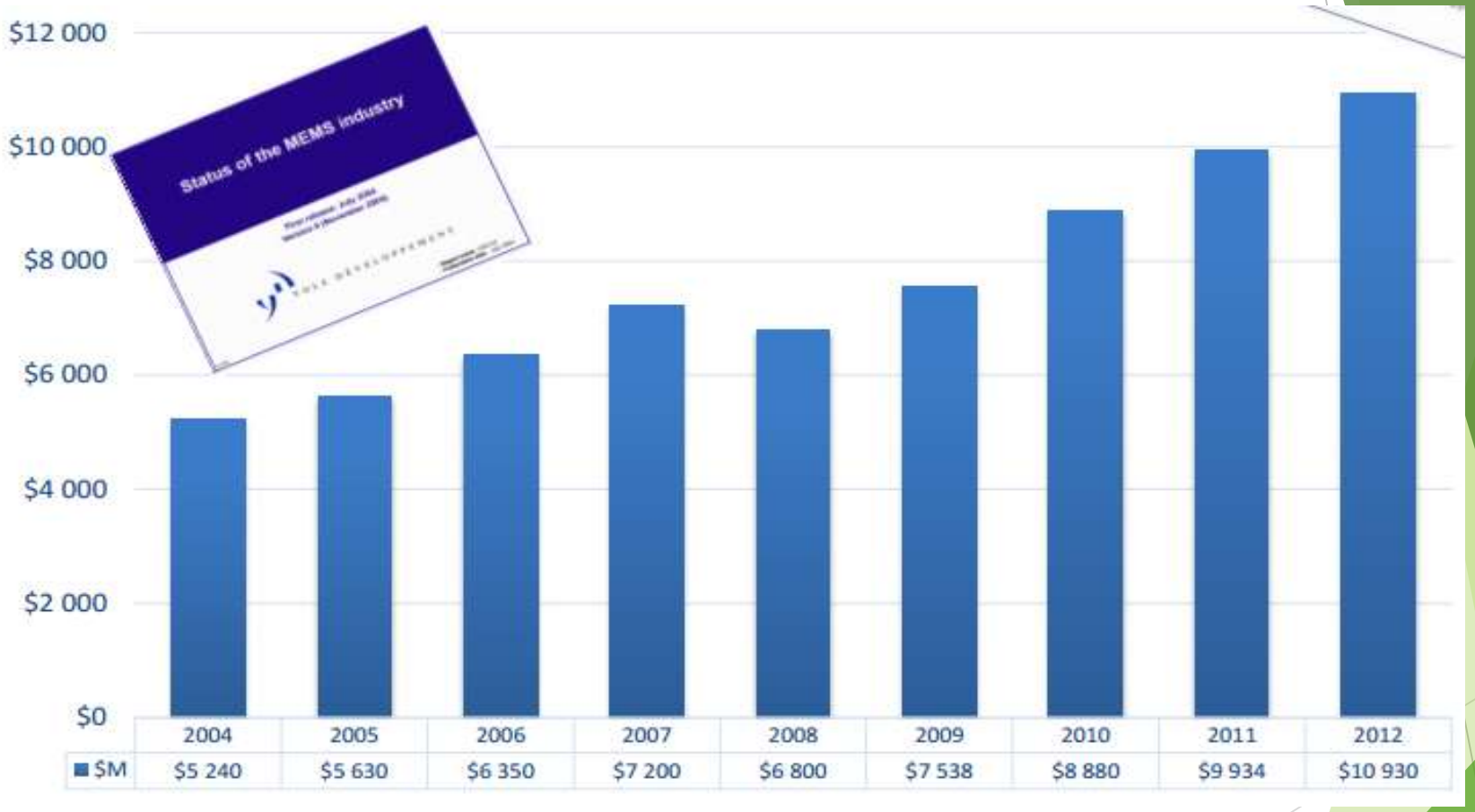
MEMS value proposition in mobile devices



Source: Yole Status Report, July 2013

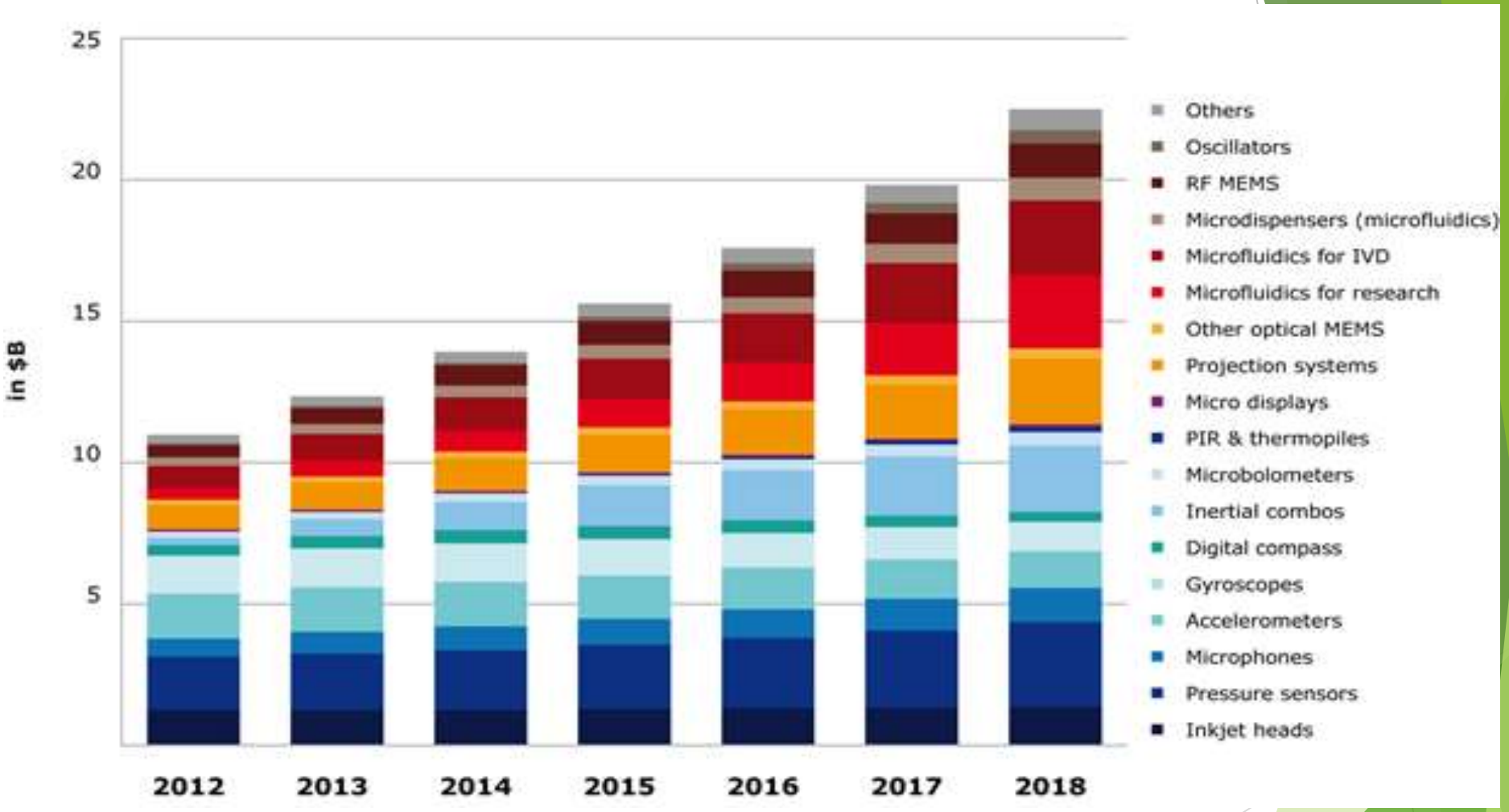
Potential Applications/ Market for Gas sensors

MEMS Past Market in $M 2004-20012



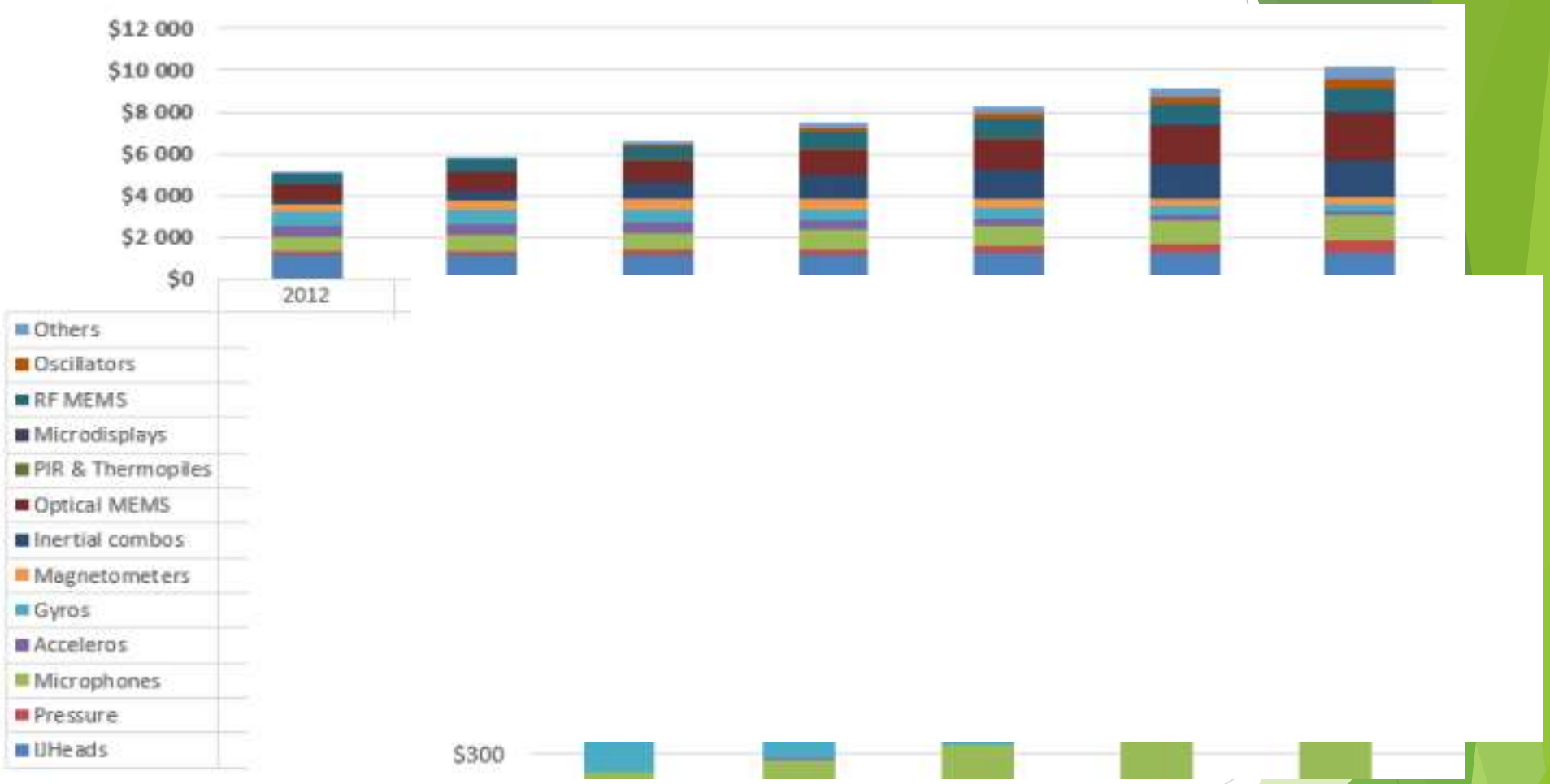
Source: Yole Status Report, July 2013

MEMS Market – Forecast by Device



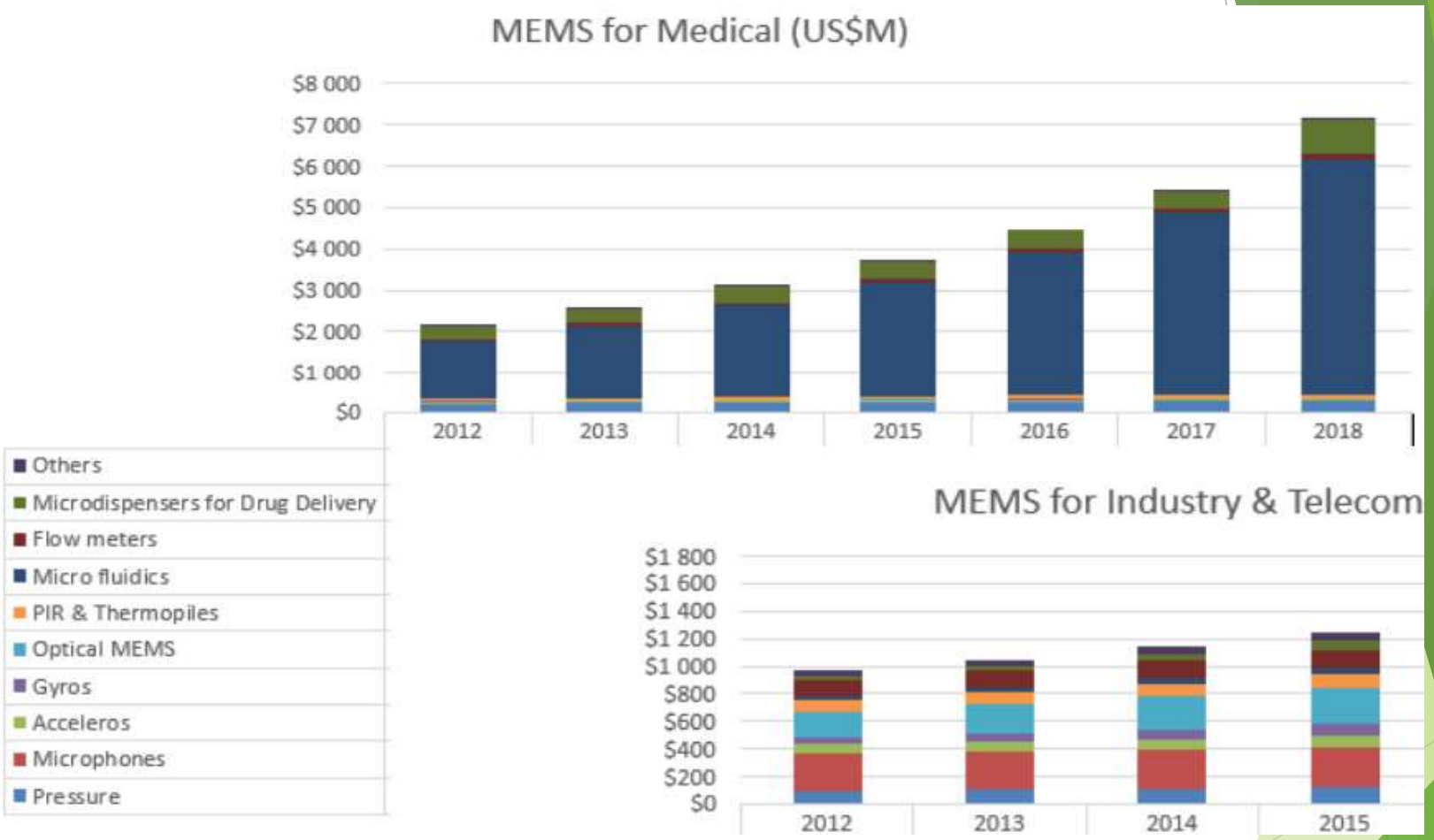
Source: Yole Status Report, July 2013

MEMS for Consumer in $M – Future Outlook



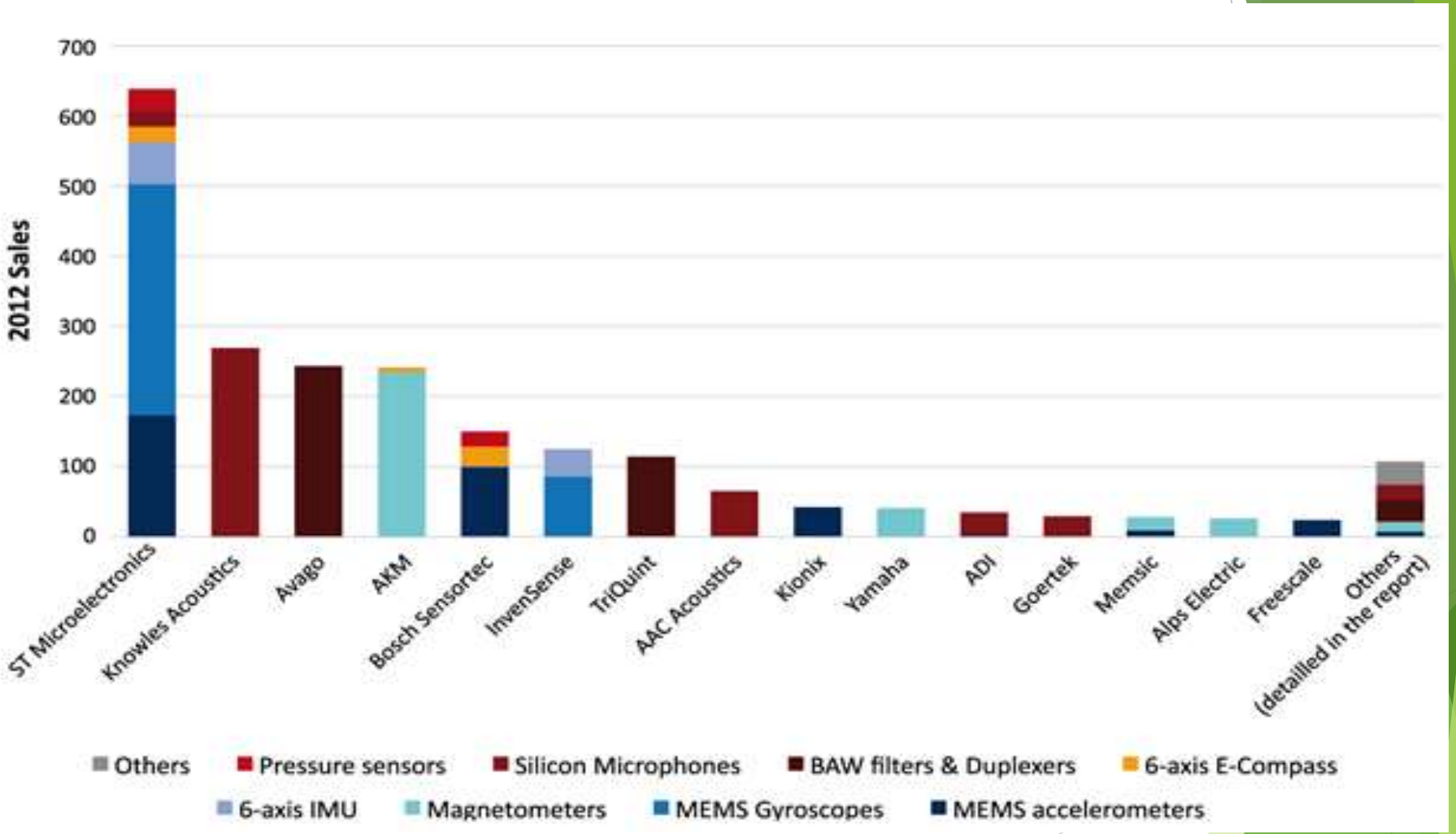
Source: Yole Status Report, July 2013

MEMS Market for Medical and Industry – Future Outlook



Source: Yole Status Report, July 2013

Top MEMS Suppliers in 2012 by Revenue ($M) for Mobile Phones and Tablets



Source: Yole Status Report, July 2013

Challenges for Smart Sensors in Homes and Phones

- Low power for battery operation
- Low cost for homes (<€15-20) and phones (<€2-5)
- High volumes need millions manufactured per month
- High reliability
- Sensors to be stable (3-10 yrs) and accurate to a few percent

- Ultimately IoT wants 1T sensors for 10c each or less

Smart Sensors in Homes for Environmental Monitoring

Environmental sources and gases

Contamination Source	Emission Source	VOCs
Building Materials	Adhesives, Carpets, Cement, Flooring, Solvents,	Formaldehyde, Alkanes, Alcohols, Aldehydes, Ketones
Combustion	Engines, Appliances, Smoke	Hydrocarbons, CO, CO2
Consumer Products	Household cleaning supplies	Acetone, alcohol, spirits
Furniture	Wood, Poly Vinyl Chloride (PVC), Glues	Toluene, Xylene, Decane
Human Being	Breath	Acetone, Ethanol, Isoprene, CO2
	Flatulence	Methane, Hydrogen
	Cosmetics	Limonence, Eucalyptol, Alcohols
Office Equipment	Printers, Copies, PCs	Benzene, Styrene, Phonole

From Cambridge CMOS Sensors Ltd

Indoor Air Quality

- VOCs have been recognized as one of the principal trace constituents of poor Indoor air quality (IAQ) which can lead to a range of chronic adverse health effects such as throat / eye irritation, dizziness, headaches and tiredness (fatigue)
- Long term exposure to certain VOCs (like Formaldehyde) can harm the nervous system, aid development of cancers, and liver and kidney toxic effects

Home

In-Car

Office

- Potential Sources of VOCs at home, in-car or office

Smart Homes Devices

- **Smart sensors are already in homes**
  - **Temp., humidity & pressure**
  - **Air quality CO_2 sensors too available**

Future: Particles/dust, Toxic gases & VOCs

Short Break?

Smart Phones and Gas Sensors Today

Environmental Gases & Smartphones

- Humidity and Temperature sensing
- Oxygen level
- CO_2 level for air quality
- VOCs - Ethanol, Formaldehyde
- Others: NO, Isoprene, NH_3

- CHALLENGES FOR SMARTPHONE IMPLEMENTATION
  - Manufacture in high volume with low CoV
  - Small size and ultra low power requirement
  - Low cost sensors (less than €5 per module)
  - Lifetime/selectivity/sensitivity

PHONE PLUG-INS HERE NOW

- Ethanol level
- Low power and digital
- iPhone plug in

TRAVEL EASY

Elite Alcohol Breath Tester

TRAVEL EXCLUSIVE

A small device compatible with an iPhone 30-pin docking connector in order to check alcohol levels in the body. Operated by blowing into the device, where a reading of your blood alcohol level will then be shown.

The reading is not legally binding and cannot be used in a court of law. *iPhone not included.

£19

Nanobreak Plug-in Sensor from Nasa

The Product

The Nanobeak Sensor

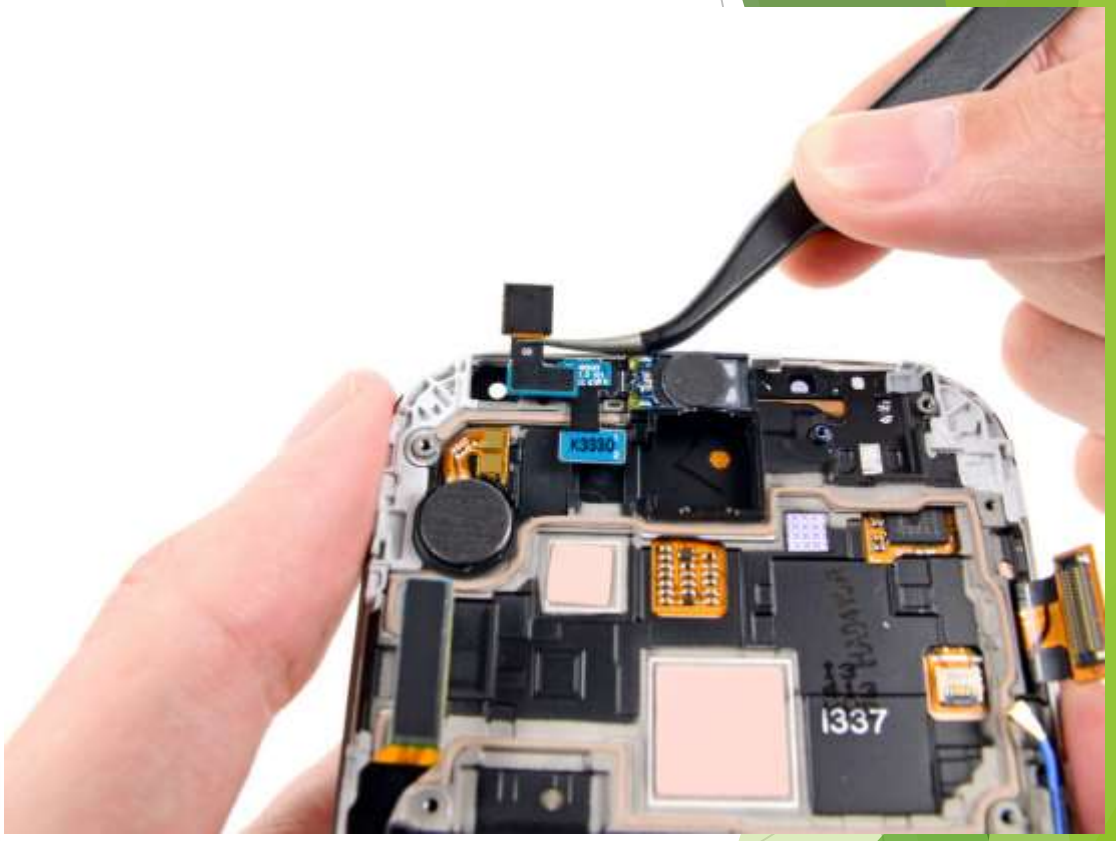
- Plugs directly into an iPhone
- Collects and analyze chemical data in real time
- Senses chemicals in the air
  - using a “sample jet”
  - multi-channel silicon-based sensing chip

NASA

Nanobeak Inc.

FIRST IN PHONE – HUMIDITY SENSOR

- Sensirion chips for T and RH
- SHT21 & Later SHTC1
- Capacitive type
- +/- 2% RH +/- 0.3C
- Low power and digital I2C
- In Samsung Galaxy S4



The Smart Gas Sensor

CCMOSS technology enables Air Quality monitoring through miniature multi-sensing devices!

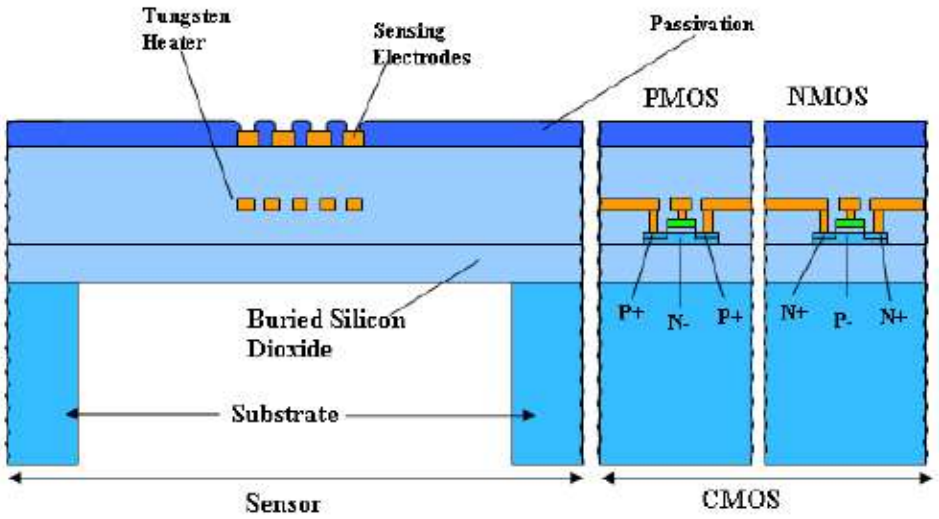
- **Indoor Air Quality (IAQ) monitor to detect a wide range of indoor air pollutants**
- **Toxic Gas Detector to alarm the user to dangerous levels of Carbon Monoxide (CO)**
- **Alcohol Breathalyser to provide ethanol levels on breath as indicator of Blood Alcohol Content (BAC)**

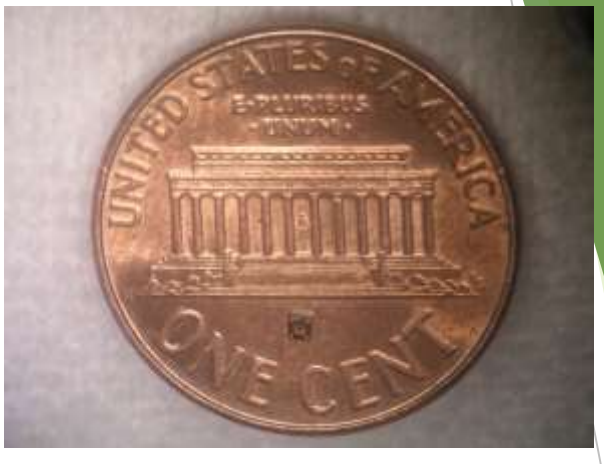
From Cambridge CMOS Sensors Ltd – founded 2008

Cambridge CMOS Sensors Ltd founded in 2008 with UWAR IPR

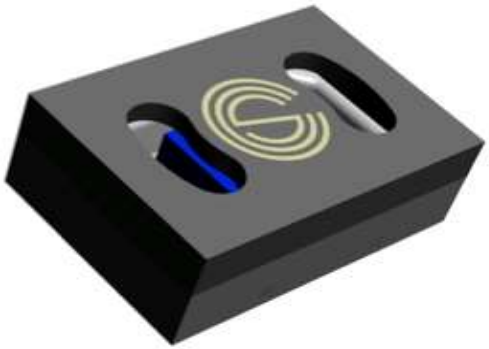
- **33 staff**
- **3 awards for innovation**
- **>12 patents**
- **Office in China/US**
- **MOX and IR technology**

Small Low-Power Smart CMOS Gas Sensor (CCS800)

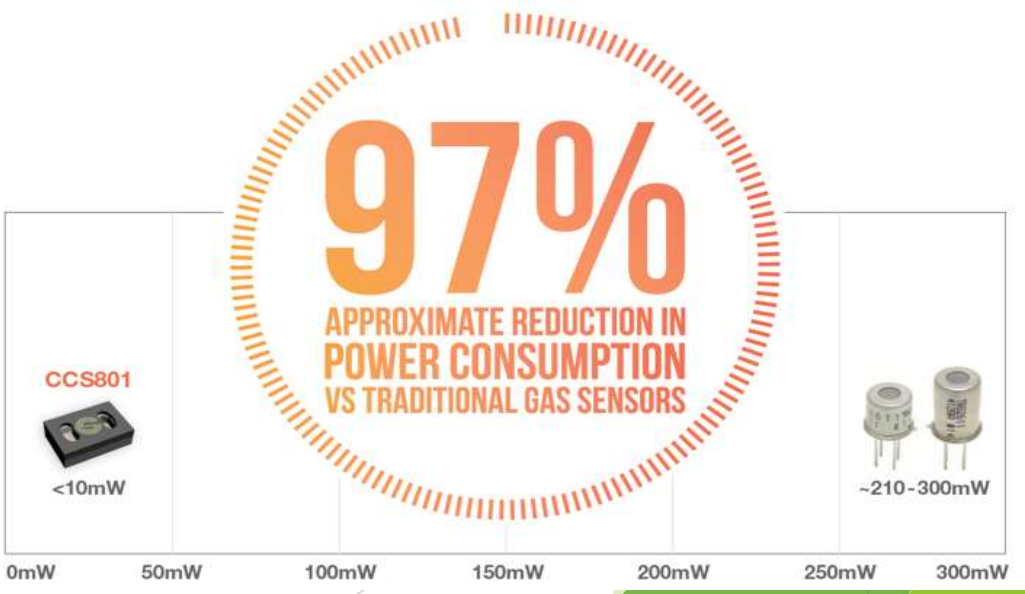




Sensor 1 mm by 1mm



Package 2 mm by 3mm



From Cambridge CMOS Sensors Ltd

Alcohol Breathalyser

- **CCS801 responds to Ethanol (ppm in Breath) is down to 10ppm within ±25% accuracy over temperature and humidity range ~4 s required for breath analysis**
- **Phone apps could be user activated or enabled while on call**
- **Smartphone apps monitors ppm level in breath. Rather than giving the user a PPM / BAC reading the app provides Low / Medium / High warning indication**
- **It is an alcohol indicator and not a certified sensor**

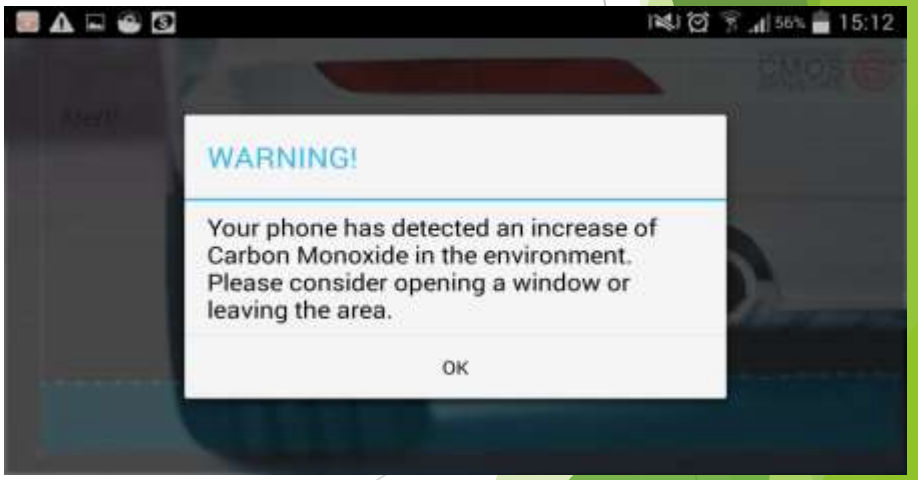
ppm in Breath	BAC	Note
52	0.02%	China legal driving limit
104	0.04%	Concentration impairment
208	0.08%	UK legal driving limit
520	0.20%	Severe motor impairment Loss of consciousness

Movie

CO – Toxic gas detection

- **Carbon Monoxide (CO) is an odourless, tasteless and colourless gas, and exposure can be fatal!**
- **CCS801 responds to carbon monoxide down to 20ppm within ±25% accuracy over temperature and humidity range**
  - **-15°C -> +55°C Ambient temperature**
  - **Up to 95% relative Humidity**
- **Background apps on smartphone monitors CO levels every 30s (programmable) and provides Safe / Warning / Alert indication to the user about possible dangerous changes in their environment**
- **The phone should not be marketed as a life critical safety device to avoid legal/litigation issues.**

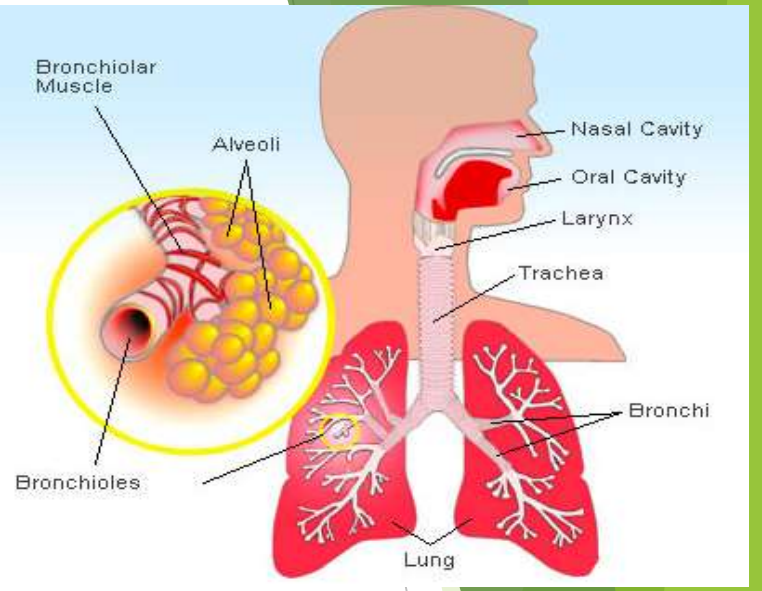
Concentration	Symptoms
35ppm (0.0035%)	Headache & dizziness within 6-8 hrs of constant exposure
100ppm (0.01%)	Slight headache in 2-3 hrs
200ppm (0.02%)	Slight headache within 2-3 hrs; loss of judgement
800ppm (0.08%)	Dizziness, nausea and convulsions within 45 mins; insensible within 2 hours



PHONE SENSORS

- Resistive type MOX
- CCS 2 mm by 3 mm package
- Low power and digital

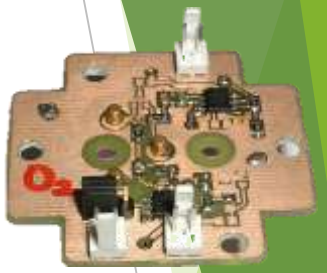
Breath Analysis



- Concentrations of gases O_2 and CO_2 present in a sample of exhaled breath can provide a non-invasive insight into a person's health. VOCs are at PPB to Low PPM Levels
  - Acetone – Metabolism and Diabetes
  - Isoprene – Cholesterol
  - Ammonia – Liver condition
- End Exhaled gas, expired from the alveolar, presents a reflection of the gas exchanges occurring inside the lungs.
- Excellent (but expensive) breath monitors exist today and are in our hospital lab and used routinely.
- **Indirect Calorimetry** – considered the gold standard for energy expenditure (EE) assessment in clinical care, where volumes of oxygen consumed and carbon dioxide produced are measured.

PORTABLE Breath analysis: NEED FOR LOW COST Gas Sensors

- Sensors used for environmental gas monitoring often unsuitable for breath analysis
- Fast response time required for breath-by-breath measurements, when adult exhales 12x per minute.
- Nearly completely saturated, approximately body temperature (~36 °C)
- Flow sensor required for exhalation identification and volume calculation.
- O_2 required to a tolerance of 0.5%
- CO_2 to 1.2%



Alphasense: Eectrochemical O_2 sensor

GSS SPRINTIR: NDIR CO_2 sensor

Gases and breath analysis

Table 1. List of gases found in exhaled breath and their diagnostic purpose.

Gas	Inhaled	Normal Exhaled	Abnormal Exhaled	Healthcare Application/Diagnosis	Reference/s
Carbon dioxide	0.04%	3%–4%	-	Respiration monitoring, control of mechanical ventilator, capnography	[34–36]
Carbon Monoxide	0.25 ppm	0.5–2.1 ppm	16.7–29.3 ppm	Identification as smoker, chronic obstructive pulmonary disease (COPD)	[37–39]
			1.13 ppm	Severe sepsis	[40]
			5.6 ppm	Asthmatic patients	[41]
			4.4 ppm	Haemolysis	[42]
Nitric Oxide	<2 ppb	5.3–7.4 ppb	19.2–30 ppb	Asthma diagnosis	[43–46]
			16.3 ppb	Seasonal rhinitis	[47]
			12.9 ppb	Experimental influenza	[48]
			2.3–4.7 ppb	Cystic fibrosis	[49,50]
Hydrogen	0.5 ppm	<5 ppm	>16–20 ppm increase	Gastrointestinal diseases (small intestinal bacteria overgrowth, carbohydrate malabsorption), diarrhoea	[51–55]
Methane	1.7 ppm	<1 ppm increase	>16 ppm increase	Diverticulitis, constipation, irritable bowel syndrome	[56–58]

From: Sensors Journal 2016, Gardner and Vincent

Hydrogen breath analysis

Table 2. Types of hydrogen breath tests and their diagnostic potential [52,54].

Test Substance	Indications from the Test
Fructose	• Fructose malabsorption • Irritable bowel syndrome • Intolerance of sweets, honey or fruits • Chronic inflammatory bowel diseases
Lactose	• Estimation of oro-cecal transit time • Small intestinal bacterial overgrowth • Investigation of bloating • Intolerance of milk, dairy products, pastries or chocolate • Primary or secondary lactose intolerance
Glucose	• Small intestinal bacterial overgrowth • Exocrine pancreatic insufficiency • Cirrhosis of the liver • Secondary lactose intolerance • Intolerance of sugar and sweets

From: Sensors Journal 2016, Gardner and Vincent

VOCs & Breath analysis

From: Sensors Journal 2016, Gardner and Vincent

Table 3. List of diseases and the VOCs found in relation to each.

Disease	VOCs	Reference
COPD	Isoprene, C 16 hydrocarbon, 4,7-dimethyl-undecane, 2,6-dimethyl-heptane, 4-methyl-octane, hexadecane	[67]
	Isoprene, acetic acid, benzaldehyde, benzene, nonadecane, toluene	[68]
	Benzaldehyde, limonene, 2-ethyl-1-hexanol, nonanal, menthone, menthol, decanal	[69]
	Decane, 6-ethyl-2-methyl-decane, benzene, butylated hydroxytoluene, limonene, 2-propanol	[70]
Lung Cancer	Acetone, acetonitrile, 2-3-dimethylbutane, hexane, limonene, pentane	[71]
	Ethyl benzene, hexane, trans-2-nonenal, pentane, 2-methyl pentane, heptanal	[72]
	Isobutane, methanol, ethanol, acetone, pentane, isoprene, benzene, toluene	[73]
	Toluene, o-xylene, styrene, 1-methyl-3-benzene, 2,3-dimethyl-hexane, 3-ethyl-3-methyl-2-pentanone	[74]
	Styrene, decane, isoprene, benzene, undecane, hexanol, heptanal	[75]
Breast Cancer	4-Methyl-2-heptanone, 2-nonanone, 2-dodecanone, 2,4-dimethyl-1-heptene, 2-xylene	[76]
	Cyclopropane, ethylidene, 1,4-pentadiene, 1,3-butadiene, 2-methyl	[77]
	3-methylhexane, decene, caryophyllene, naphthalene, trichloroethylene	[78]
	Heptanal, acetophenone, isopropyl myristate, 2-propanol	[79]
Chronic Liver Disease	Ammonia	[80]
	1-Decene, 1-octene, €-2-nonene	[81]
	Isoprene, carbon disulphide, dimethyl sulphide, pentane, ethane, acetone	[82]
Liver Cirrhosis	Methanol, 2-butanone, 2-pentanone, C8-kentone, sulfoxide-compound	[83]
	3-methylbutanal, propionic acid, octane, terpene, 3-carene, 1-hexadecanol	[84]
	Acetone, styrene, dimethyl sulphide, dimethylsilane, phenol, tetradecane	[85]
	Limonene, methanol, 2-pentanone	[86]
Colorectal Cancer	Ethanol, acetone, ethyl acetate, 4-methyl octane	[87]
	Nonanal, 4-methyl-2-pentanone, decanal, cyclohexane, 1,3-dimethylbenzene	[88]
	Cyclohexanone, 2,21-dimethyldecane, ethylaniline, cyclooctylmethanol	[89]
Ovarian Cancer	Styrene, nonanal, 2-ethylhexanol, 3-heptanone, decanal, hexadecane	[90]
	Decanal, nonanal, styrene, 2-butanone, hexadecane	[91]

HOME BASED Breath ANALYSIS using SMARTPHONES

- Smartphones can wirelessly connector to gas sensor systems and provide intuitive monitoring interface.
- Potentially sensors to help monitor lifestyle can be included inside mobile devices.
- Bluetooth enabled microcontroller considered for remote breath sampling of patient's in UHCW respiratory chamber.
- Portable metabolic rate analyser could be used to log data, show metabolic rate variation over period of 1 day (e.g. after eating) and perhaps track progress over period of several weeks.

HTC One M8 phone, contains step counter fitness monitor, providing daily activity level.

Plug-in modules or wireless monitors available (<$50) for smartphones display alcohol content from breath sample

Apple iPhone 6 with Barometer

- First phone with pressure sensor in
- MEMS type

Sensors: Barometer, three-axis gyro, Accelerometer, Proximity sensor, ambient light sensor.

MULTI-GAS SENSORS – THE HOLY GRAIL

- Figaro MOX based (Japan) – Q4 2014?
- Sensirion MOX based (Switzerland) – Q1 2015?
- Cambridge CMOS Sensors – 2015?
- AMS/AppliedSensor MOXs?
- Others …

- Technologies also coming:
  - RT MOX on Plastic
  - IR for CO_2
  - FBAR/Polymer VOCs
  - Nanowires/CNTs??

Sensirion preps multi-gas sensor 'nose' for smartphones

November 21, 2013 // Peter Clarke

Sensirion AG, a vendor of temperature and humidity sensors, has developed a multi-gas sensor that it is planning to sell to smartphone makers.

Page 1 of 3

The sensor platform will allow phones to act as alcohol breathalysers and monitor air quality, amongst other applications, as part of the next stage of smartphone evolution, the company reckons.

Moritz Lechner, co-CEO of Sensirion (Staefa Zurich), said that the company has working examples of multi-gas sensors and plans to ship samples to potential customers in the spring of 2014 with the aim of ramping production in 2015.

CONCLUSIONS

- Few sensors can satisfy the demanding specification
  - For homes: Size not issue, <€15, <100 mW
  - For phones/wearables: Size is issue, <€5, < 5 mW, < 3.0 V, 2 year life etc
- Low-cost silicon platforms possible (also plastic ones)
- Life/stability issues of MOX films still an issue
- Further cost/size/power reduction needed for smart watch market

New iWatch

Samsung

Addidas

Nike

Future Low-cost Smart Sensors

- VOCs like formaldehyde – major solvent problem in China
- CO/NOx from combustion engines
- Diseases from environment (Star Trek Tricorder?)

- Particulate matter (PM10, PM2.5 and UFPs) in air
  - Acoustic sensors **SAWR** and SMR

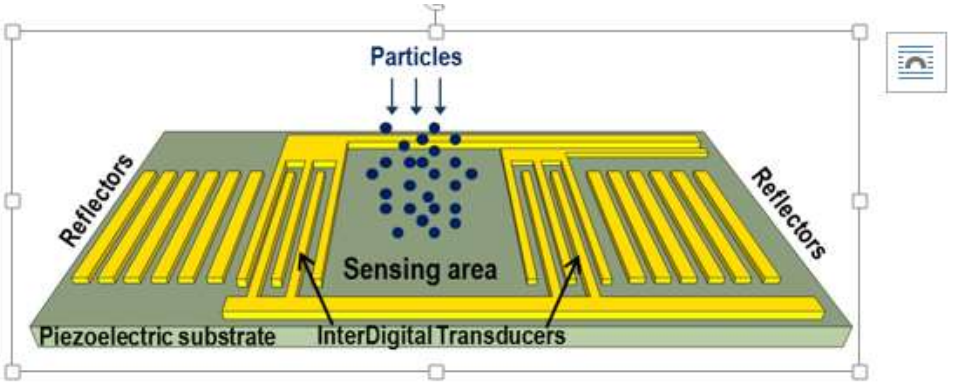


Figure 1. Basic principle of SAWR particle detection: Schematic of a surface acoustic wave resonator based sensor with sub-micron sized particles deposited on the active sensing area.

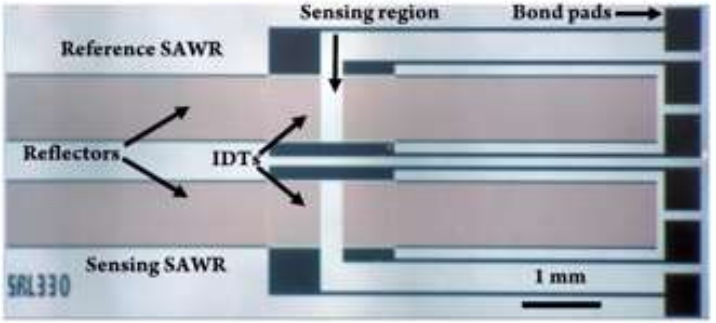


***Figure 3. Dual SAWR Sensor Photograph:** Optical micrograph of a 262 MHz Dual Rayleigh SAWR (free) sensor fabricated on X-propagating ST-cut quartz with aluminium electrodes for particle measurements*

From: Sens. Act. A 244 (2016)
Thomas et al.

SAWR based Particle Sensor

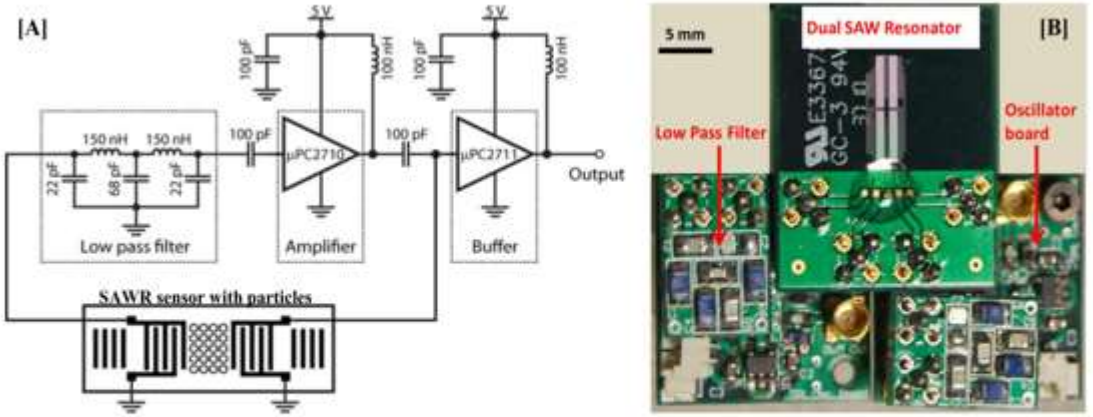


Figure 5: Particle sensor circuitry and photograph: *[A] Schematic of SAWR oscillator including the filter, amplifier and buffer stages [B] Photograph of a dual 262 MHz (free) SAWR oscillator based sensor with surface mount amplifier, filter and buffer circuitry.*

- $LiTaO_3$ piezoelectric
- Not CMOS compatible

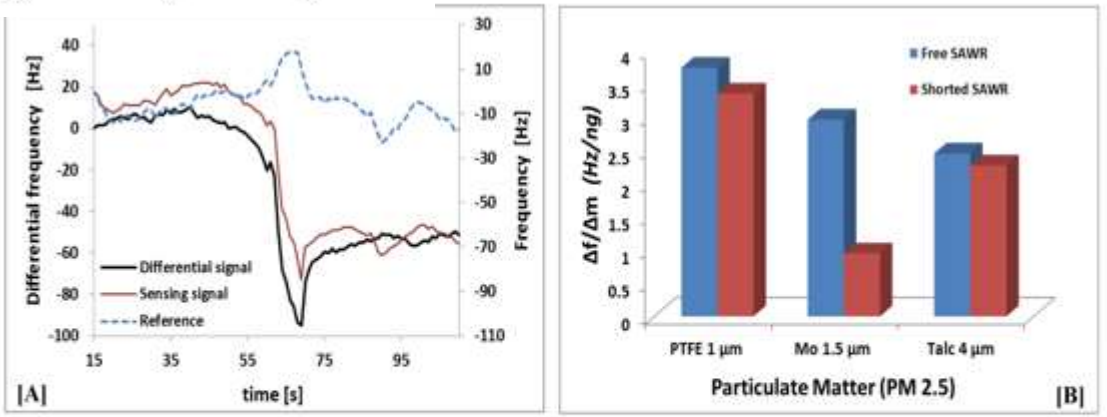
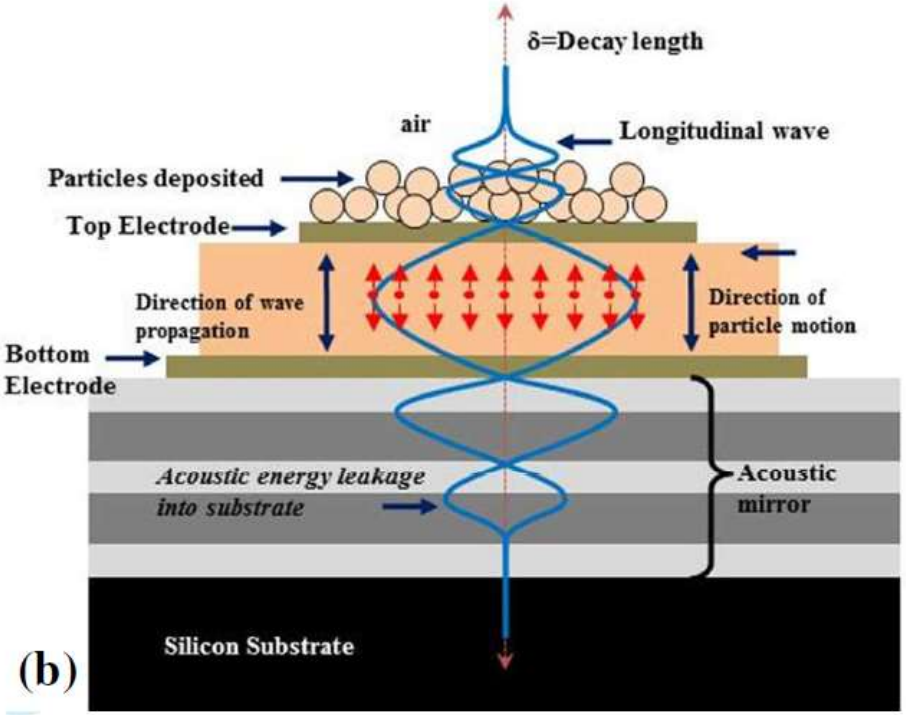


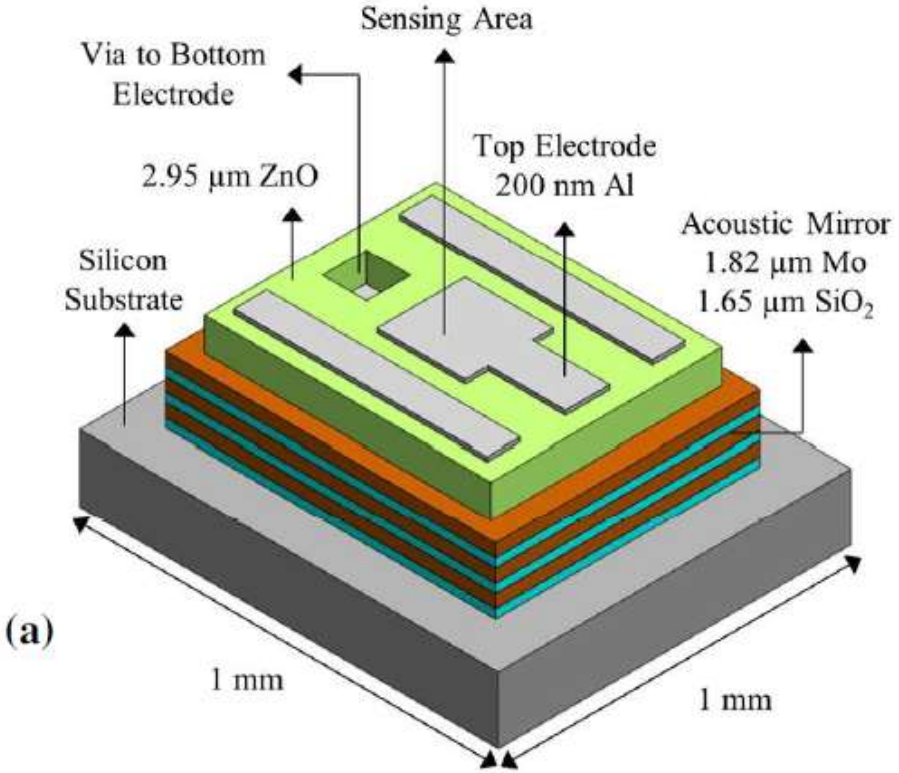
Figure 7. SAWR response to PM deposition: *[A] Typical frequency output of a dual free SAWR sensors in response to a deposition of ca. 0.21ng of 0.75 µm-sized gold particles (ca. ~50 particles), on to the central active area. [B] Sensitivity analysis obtained using free SAWR devices and shorted SAWR devices for a variety of particles.*

From: Sens. Act. A 244 (2016) Thomas et al.

SMR based Particle Sensor

- CMOS compatible
- ZnO piezo
- Small footprint





From: IEEE Sensors Journal (2016)
Thomas et al.

SMR Sensor Circuitry

- Reference channel
- Simple RF oscillator for 1-port device
- Low cost micro-controller

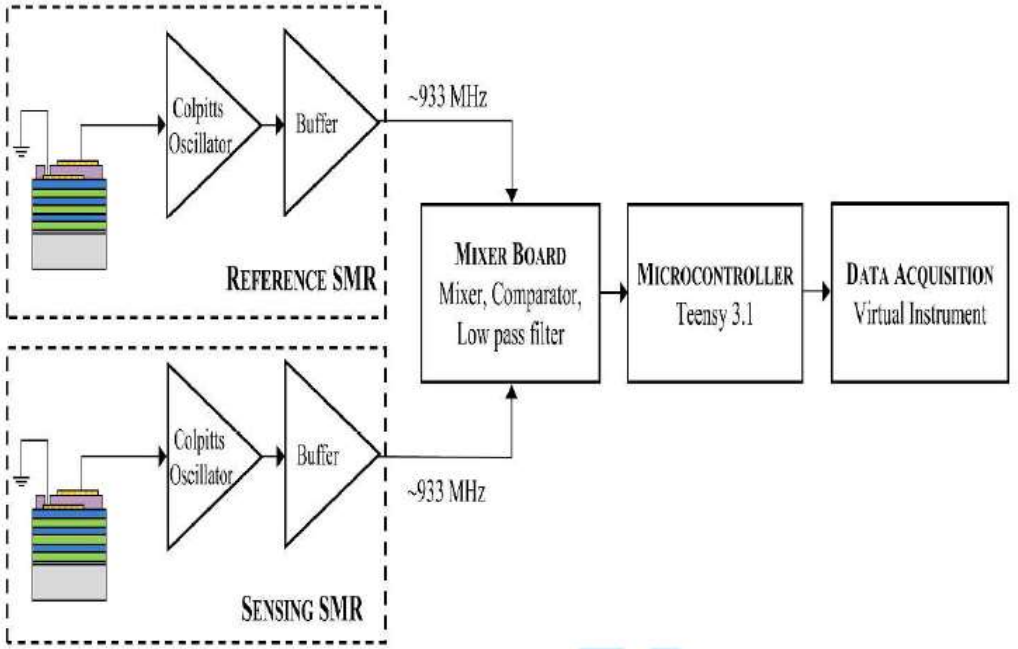
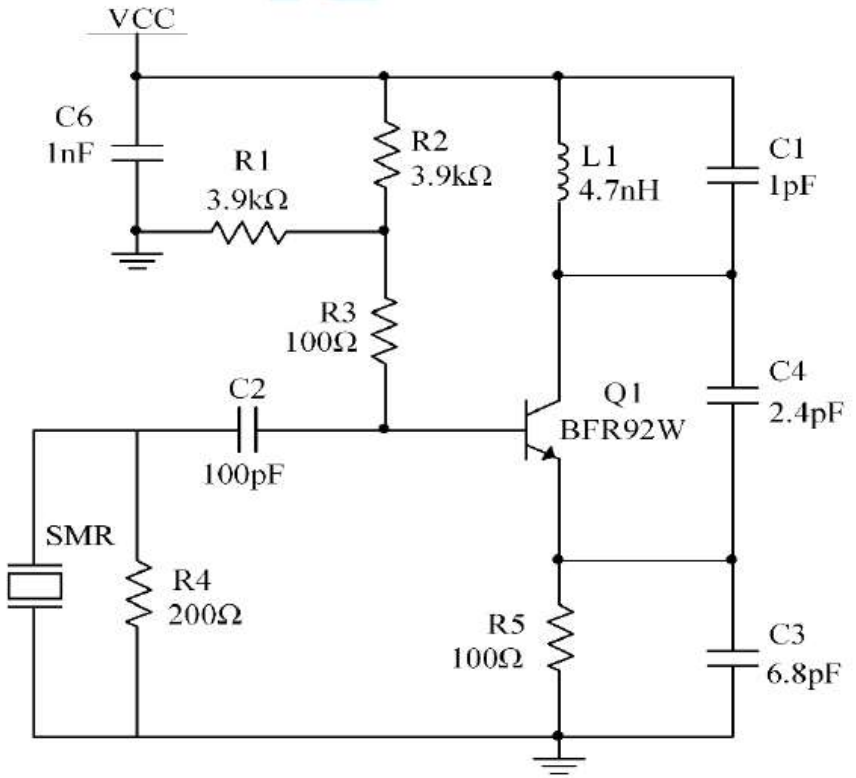


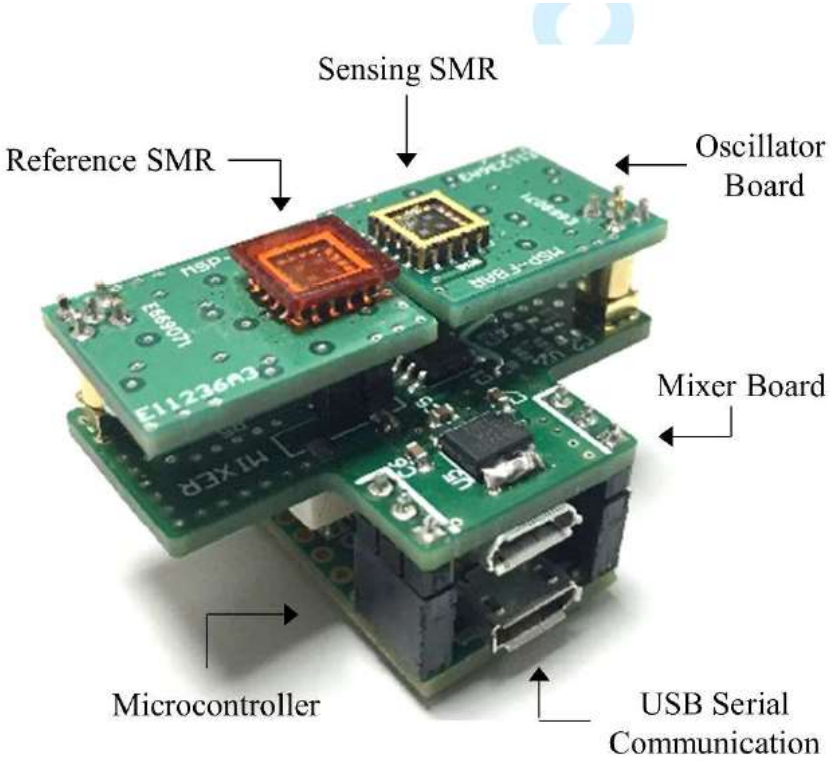
Fig. 1. Overall structure of the developed differential mode particle sensing system based on Solidly Mounted Resonators.



From: IEEE Sensors Journal (2016) Thomas et al.

SMR Sensor System & Set-up

- Discrete components
- Small size



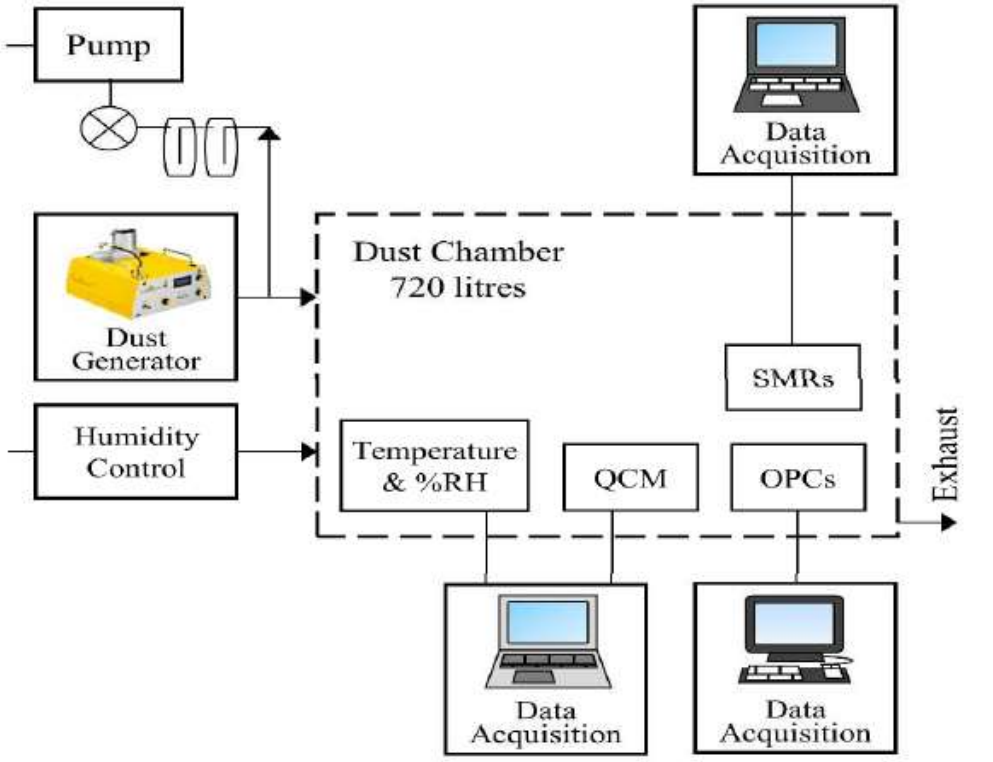
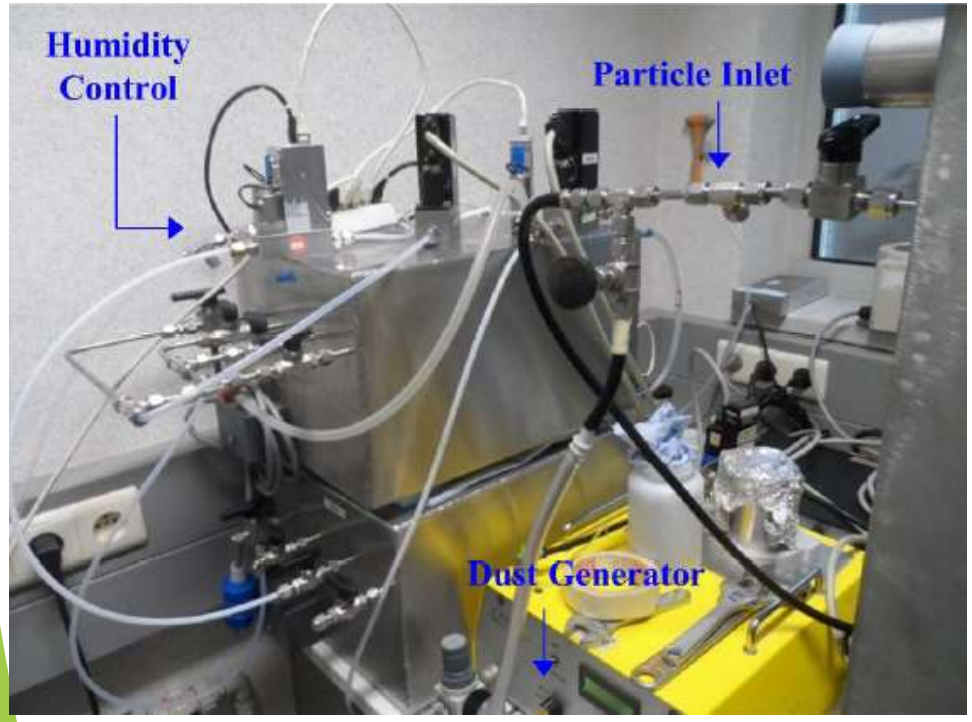


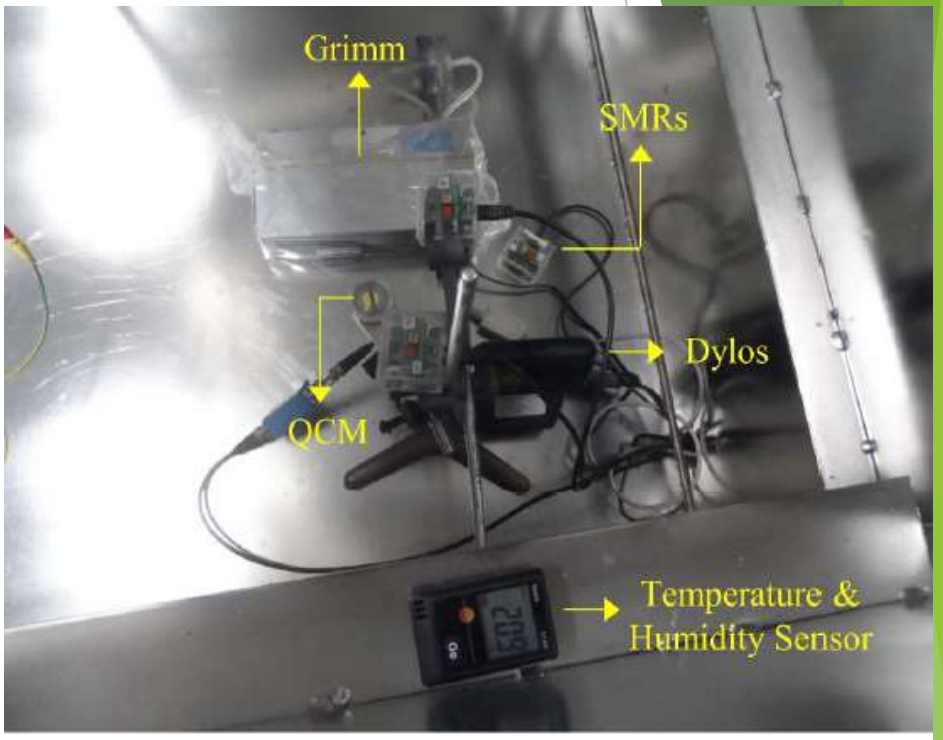
Fig. 6. Block diagram of the setup used to perform particle testing with the developed SMR-based unit.

From: IEEE Sensors Journal (2016) Thomas et al.

Test Chamber

- Standard dust generator
- Controlled system





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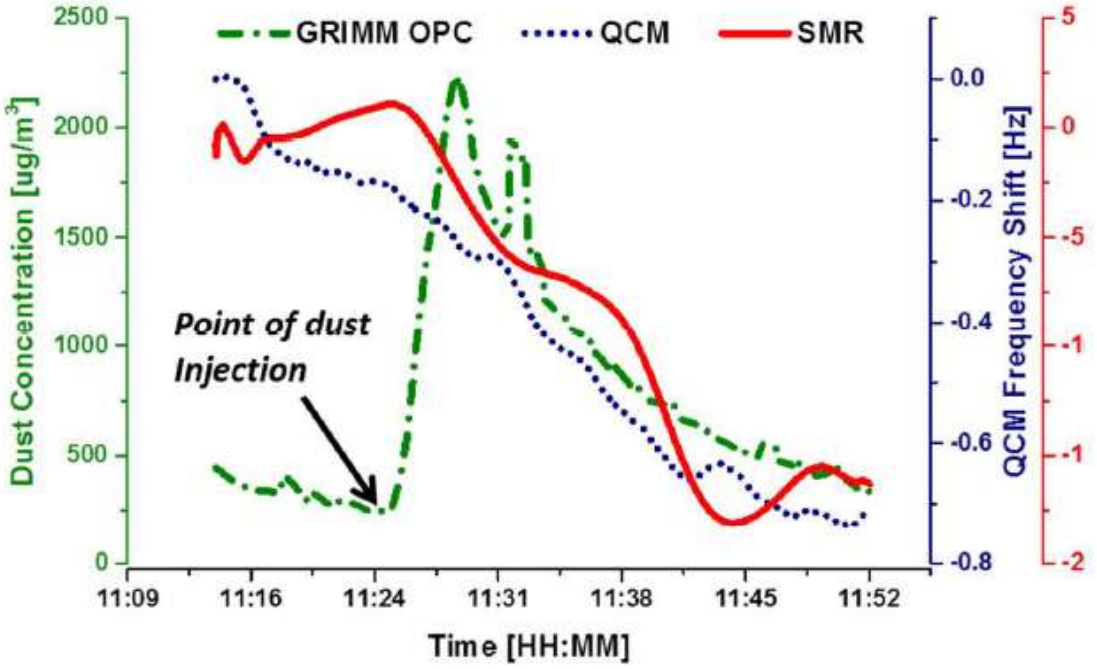
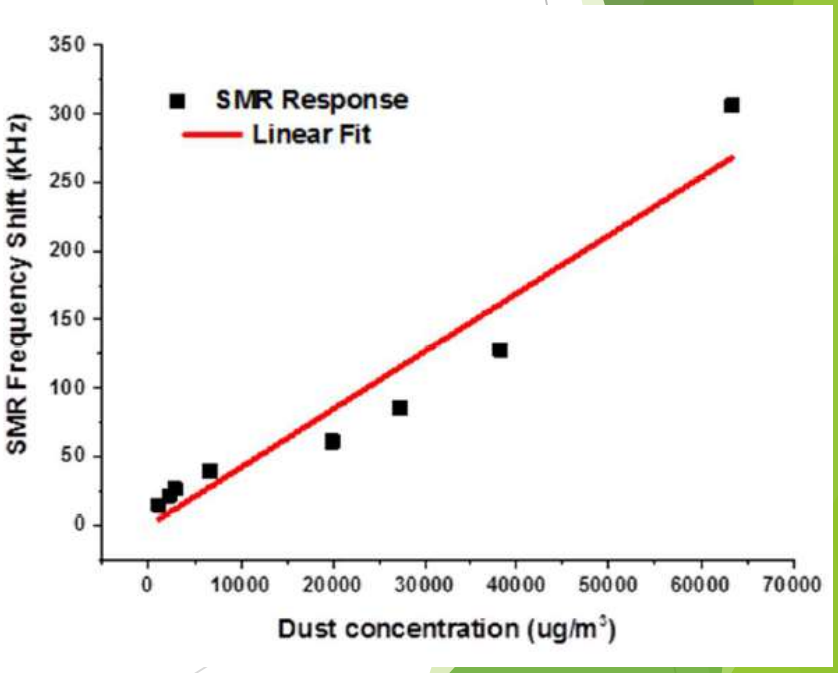
SMR Performance

- CMOS compatible
- ZnO piezo
- Small footprint





From: IEEE Sensors Journal (2016) Thomas et al.

Conclusions on Particle Sensing

- Environmental issue often overlooked
- Need for low-cost, low power small device
- SMR based particle sensor looks promising
  - ASIC interface under development
- Cheaper simpler than optical methods

Acknowledgements

- MBL students and research fellows
  - http://www2.warwick.ac.uk/fac/sci/eng/research/grouplist/sensorsanddevices/mbl/
- Cambridge CMOS Sensors Ltd for some slides/pictures and video clip
  - www.ccmoss.com

Late News

News release: 16th June 2016 (Business Weekly)

CAMBRIDGE CMOS SENSORS → ams

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