

Graphene industry

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How many academic scientist?

Do you think “graphene” is getting boring?

Well.. maybe not entirely, but basic properties are well understood. I think it is ready for real application development!

Graphene is unique material yet alchemist is not required

Periodic Table of the Elements

1 1IA 11A																	18 VIIIA 8A
1 H Hydrogen 1.0079	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 He Helium 4.00260
3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.989769	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.981	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.06	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon 222.01758
87 Fr Francium 223.0197	88 Ra Radium 226.0254	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [265]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Uuq Ununquadium [289]	115 Uup Ununpentium unknown	116 Uuh Ununhexium [288]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
Lanthanide Series		57 La Lanthanum 138.905	58 Ce Cerium 140.115	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.965	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967	
Actinide Series		89 Ac Actinium 227.0277	90 Th Thorium 232.0381	91 Pa Protactinium 231.03688	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium 244.0642	95 Am Americium 243.0614	96 Cm Curium 247.0703	97 Bk Berkelium 247.0703	98 Cf Californium 251.0796	99 Es Einsteinium [254]	100 Fm Fermium 257.0951	101 Md Mendelevium 258.1	102 No Nobelium 259.1059	103 Lr Lawrencium [262]	
	Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetals	Nonmetals	Halogens	Noble Gas	Lanthanides	Actinides							

Only carbon and carbon only

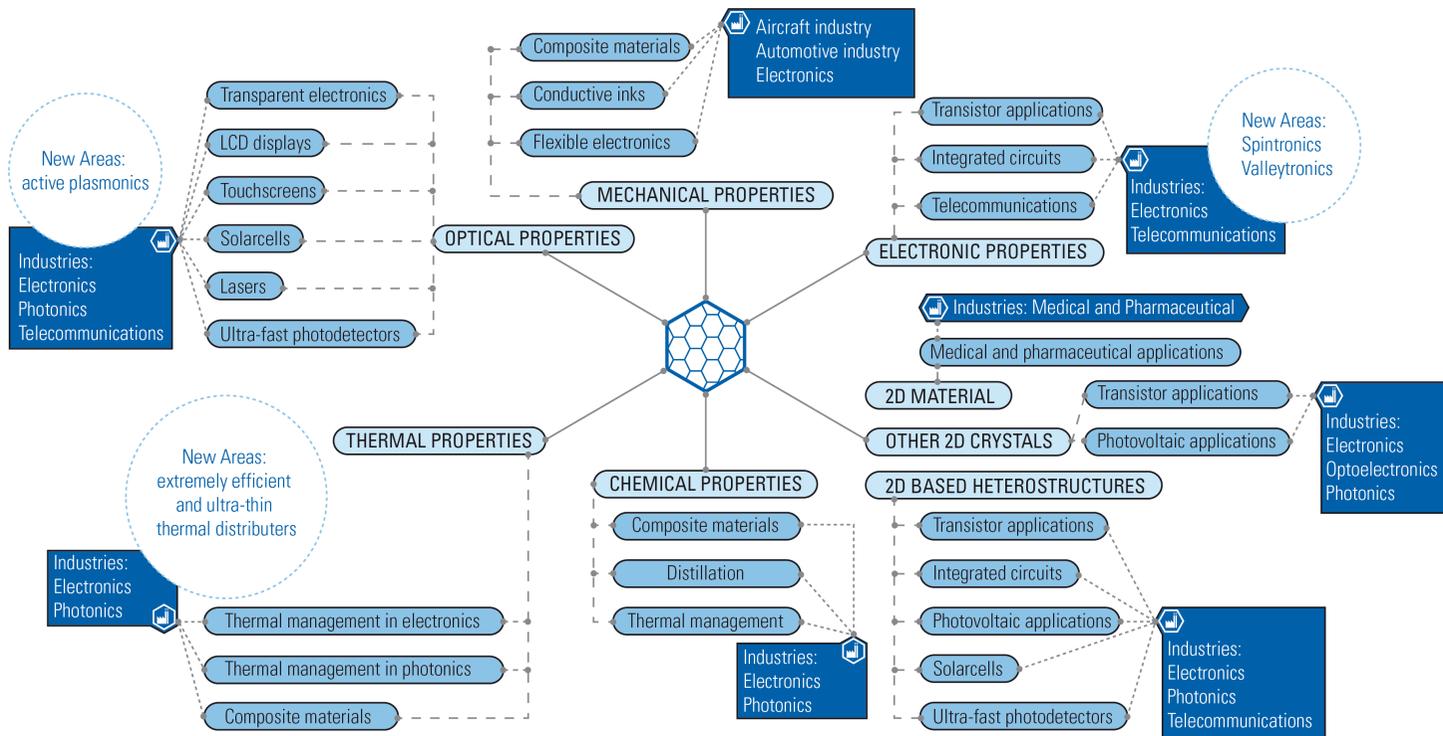
“Only” silicon

Hype? Maybe, but graphene
serves unprecedented
opportunities!

Graphene technology is a Promising Platform for a Wide Variation of Different Applications

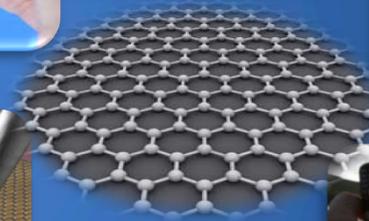
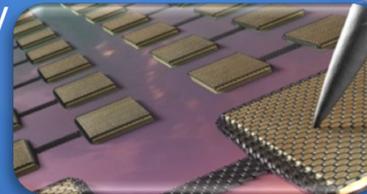
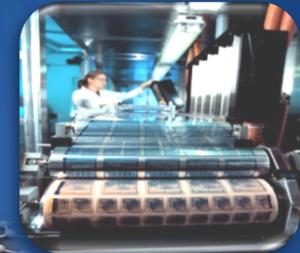
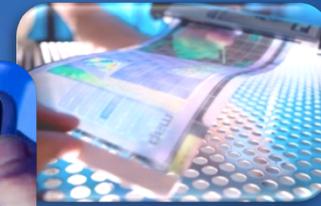
Graphene Flagship

PROPERTIES & APPLICATIONS OF GRAPHENE



Many Technologies Have Been Trying to Make a Big Impact, But Unsuccessfully: Why Would Graphene Be Different?

- **Radical technology:** Significantly increased performance
- **Thin film technology:** Relatively easy adaptation
- **Generic technology:** Wide range of potential applications. Platform.
- **Disruptive technology:** It offers new value propositions



Graphene technology is getting more matured and there is a promise. So why we haven't seen yet any real killer applications?

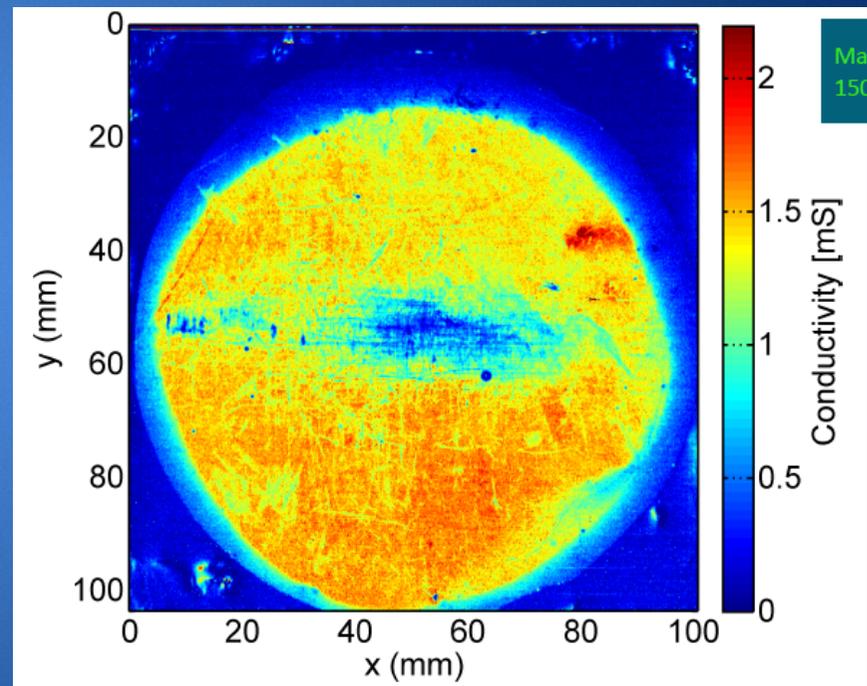
Why we haven't seen yet any real killer applications?

- The field is only 10 years old!
- Outstanding microscopic properties are challenging to transfer to macro-world
- Lack of standardized processes and control over properties
- The price (monolayer)
- TBI (to be invented)

Mass manufacturing for graphene exists, but device manufacturing is a lot more than just growth

- A large throughput processes for monolayer and platelet graphene are well established.
- Postprocesses for graphene are also important, but somewhat missing.
 - 1) Growth
 - 2) Transferring
 - 3) Patterning
 - 4) Functionalisation or doping
 - 5) Contacting
 - 6) Integration with other components
 - 7) Encapsulation
 - 8)

Conductivity map of graphene on PEN . Measurement done by AMO GmbH



Why Short Term Applications Are So Important?

- Famous Kromer's lemma of new technology

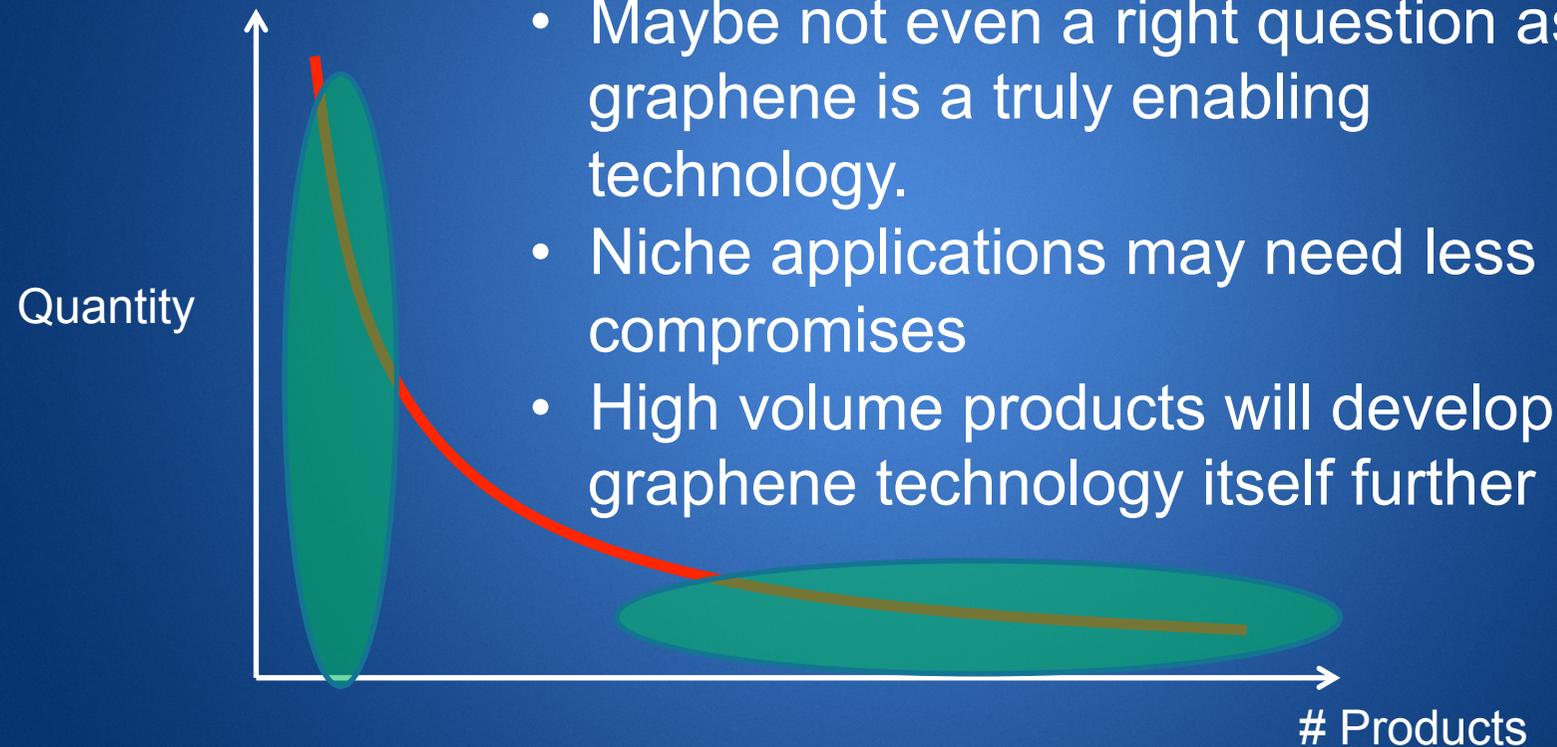
The principal applications of any sufficiently new and innovative technology always have been – and will continue to be – applications *created* by that technology.

- Short term applications will pave the way towards the principal applications!
- However, even short term applications must bring something new – either a price advantage, increase in performance or new attributes.

What kind of applications we will see in the near future?

- Applications with a clear “graphene benefit”. No one is willing to replace something with graphene just for the sake of replacing!
- Applications which are based on the unique graphene properties or the on the unique combination of properties.
- Applications with manufacturing which is compatible with present processes.
- Applications in which the final cost structure of the final product is sufficient.
- Applications what you can produce and sell.

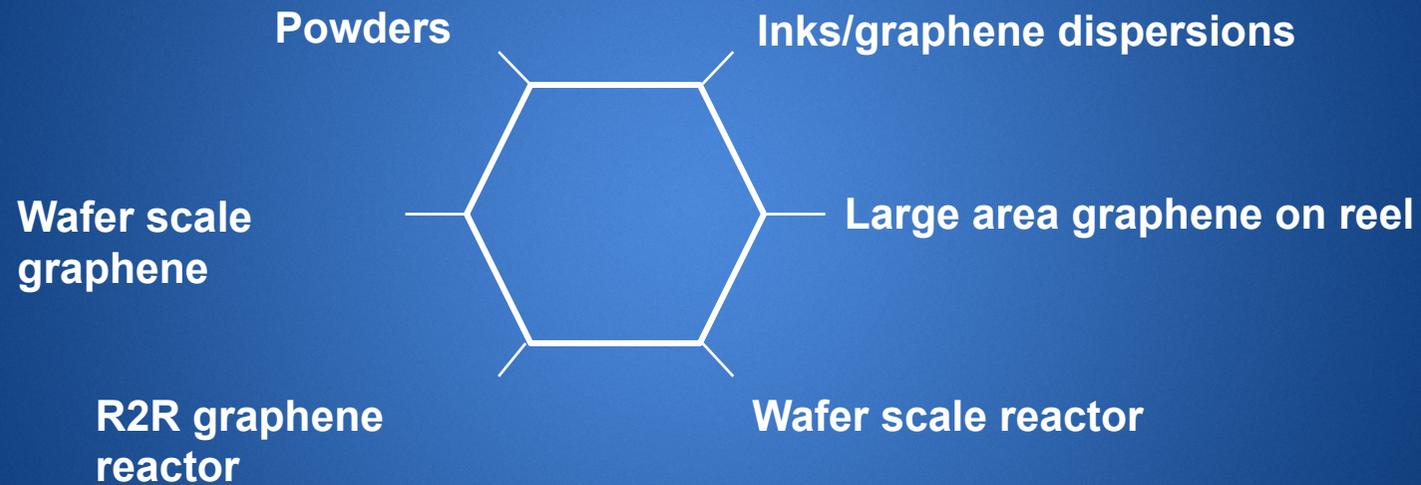
Should the focus be in head or in long-tail products?



What would be THE killer product?

What is "graphene" ? Can you purchase that from internet and just use it?

Sources of graphene for industry – one solution does not fit all!



Sources of graphene for industry

Powders

Inks/graphene

Reduced graphene oxide powder
(Graphene)



PROS:

- Really low costs
- Large volumes
- In house ink formulation
- Composite formulation

CONS:

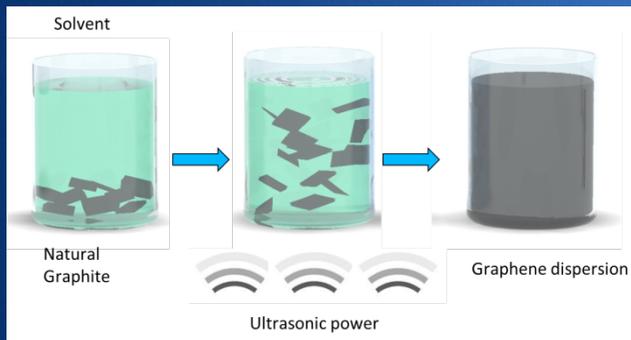
- From electronics perspective only the starting material
- A lot of chemical and process expertise are needed

Sources of graphene for industry

Graphene Ink
(Vorbeck Materials)



Common method for fabricating inks
(University of Cambridge)



Powders

Inks/graphene dispersions

PROS:

- Sustainable cost structure is possible already today - Potentially lower costs than with Ag inks, also better mechanical and chemical stability
- Large area electronics is possible
- Appealing for flexible electronics

CONS:

- Final performance does not meet all application requirements at present (e.g. conductivity vs. transparency)

Sources of graphene for industry

Graphene on SiO₂/Si
(Graphenea)



Graphene on PET
(Graphenea)

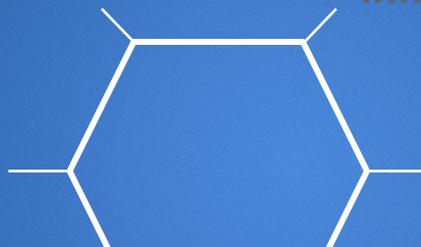


Powders

Inks/graph

ns

Wafer scale
graphene



Large area graphene on



PROS:

- Compatibility with wafer scale silicon processes – in principle easy adaptation with IC industry
- Relatively high quality

CONS:

- Limited size and throughput
- Pre-patterned substrates are tricky

IN ADDITION TO PREVIOUS

PROS:

- Possibility for more complicated process flows than with sourced graphene
- Tailored growth processes – different graphene for different applications

CONS:

- Investment costs
- "Graphene expertise" must be in house

Water scale
graphene

R2R graphene
reactor

Large area

Wafer scale reactor

stry

Graphene CVD reactor for 300 mm wafers
(Aixtron)



Sources of graphene

PROS:

- Large throughput – lower costs
- Compatible with other R2R processes
- Standardized quality

CONS:

- Quality at present?

100 m long graphene film on PET
(SONY)



Kobayashi *et al.*

APPLIED PHYSICS LETTERS **102**, 023112 (2013)

Large area graphene on reel

Wafer scale reactor

Sources of graphene for industry

IN ADDITION TO PREVIOUS

PROS:

- Tailored graphene materials are possible
- Graphene reactor could be part of a more complex R2R system

CONS:

- Large investment costs
- Graphene related material and process expertise are needed in house

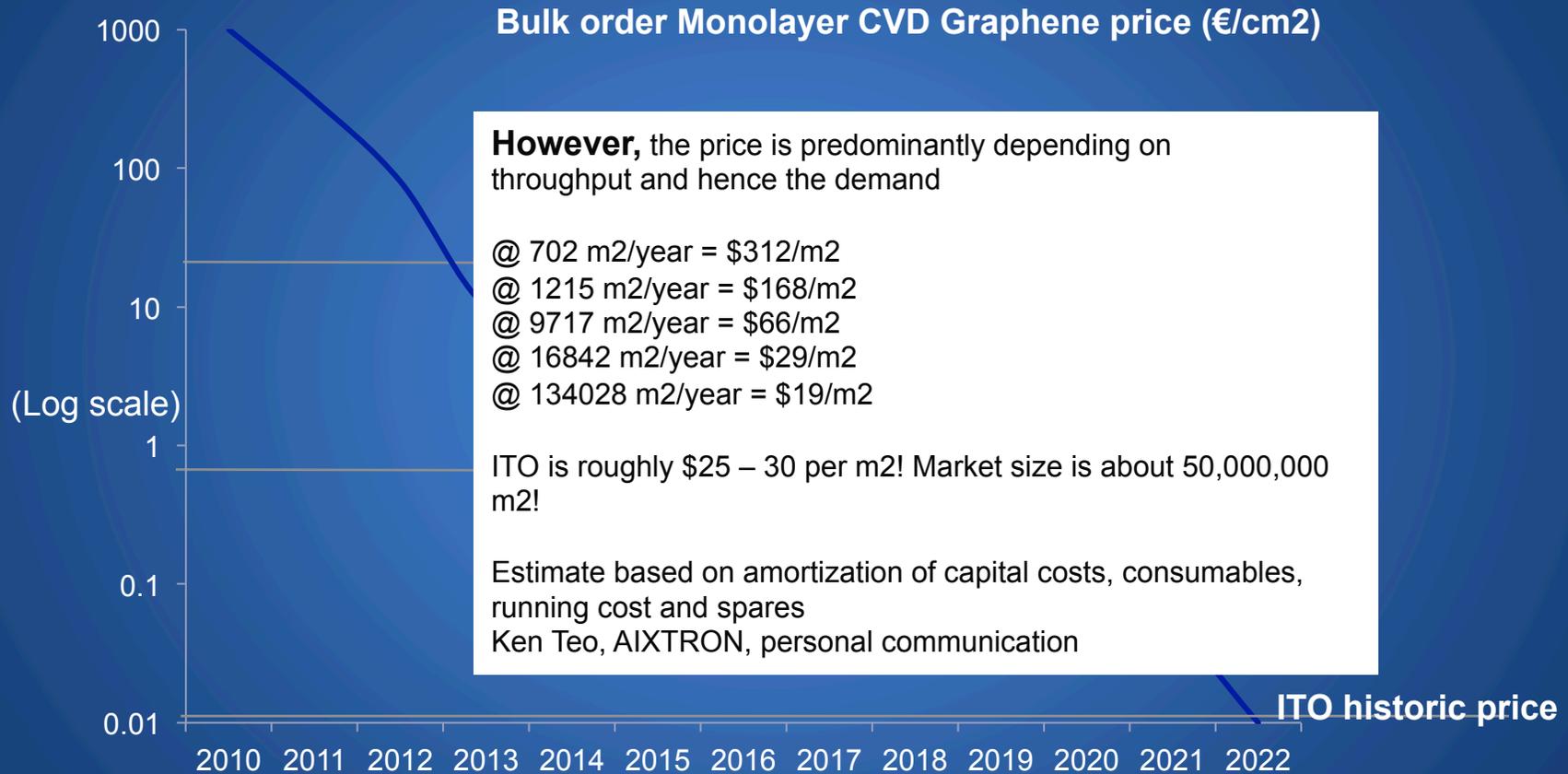
Wafer scale
graphene

**R2R graphene
reactor**

Wafer scale reactor

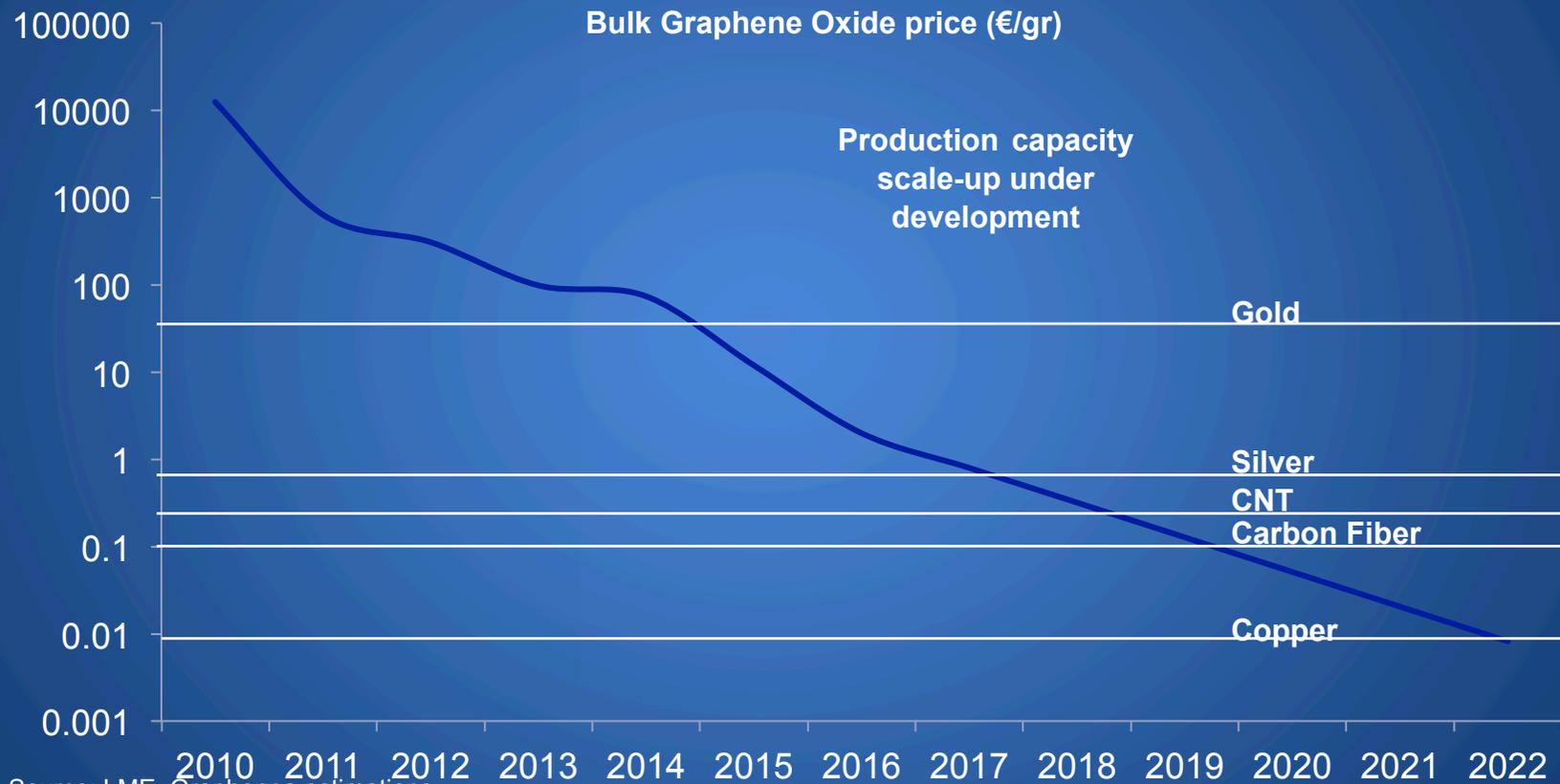
Graphene is expensive, isn't it?

Graphene Is Intrinsically Cheap – Source Material Costs Are Negligible



Source: Graphenea estimations

Graphene Oxide prices are also declining sharply due to production efficiency and economy of scale



Source: LME, Graphenea estimations

The Need for Increased Graphene Throughput Can Rise From Multiple Different Applications

Smart device as an example

Touch
-ITO replacement

Flexible display
-ITO replacement

Antenna
-Flexible antennas



Battery
-Flexible battery electrodes
-other G-benefits

Inter-connects
-Graphene based
flexible solutions

Cover
-Heat distribution
-Graphene composites

Towards graphene systems



- Quality – Quantity – Reliability – Price
- Standardisation – materials, process libraries and simulation tools
- Well established regulation – no surprises due to changing legislation or due to changing regulation

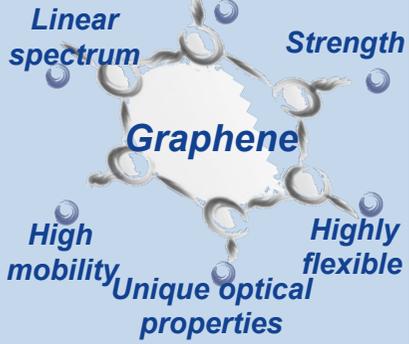
Key Takeaways

- Many properties of graphene are universal – they are arising from the fundamental nature of graphene itself. Often it is challenging to utilize fully all strange properties of graphene due to practical or present technical limitations. However, real present day applications do exist and a lot more of promising applications are just round the corner.
- Short term applications are beneficial or even essential to get the "ecosystem" flourish, before the key commercial applications are possible.
- The manufacturing processes should be compatible with existing processes
- The price of the suitable graphene is very much depending on the demand and the throughput
- Quantity, quality, reliability and price and Standardisation-regulation-legislation.

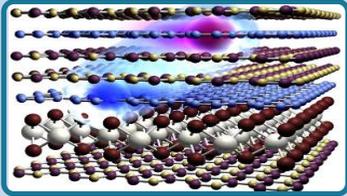
Roadmap

Platform

One Atom Thin



Hybrid 2d structures



Industrial
Academic

2013

Industrial workshare
Academic workshare



Components

- Transistors
- Spin valves
- Flexible displays
- RF tags
- Ultra-light batteries
- Solar cells
- Ultrafast lasers
- Composite materials
- Prostheses
- Sensors
- ...

Production techniques

- Large scale synthesis
- On demand growth
- Nanoribbons
- Growth on flexible substrates
- Inks
- Interfaces
- Doping
- Superstructures
- Toxicology
- ...



2016

System Integration

- Flexible electronic
- Superfast optical communication
- Ultrafast low-power electronics
- Self-powered devices



Industrial workshare
Academic workshare

2023

Vision beyond 2023

- ICT**
- Faster
 - Cheaper
 - Flexible

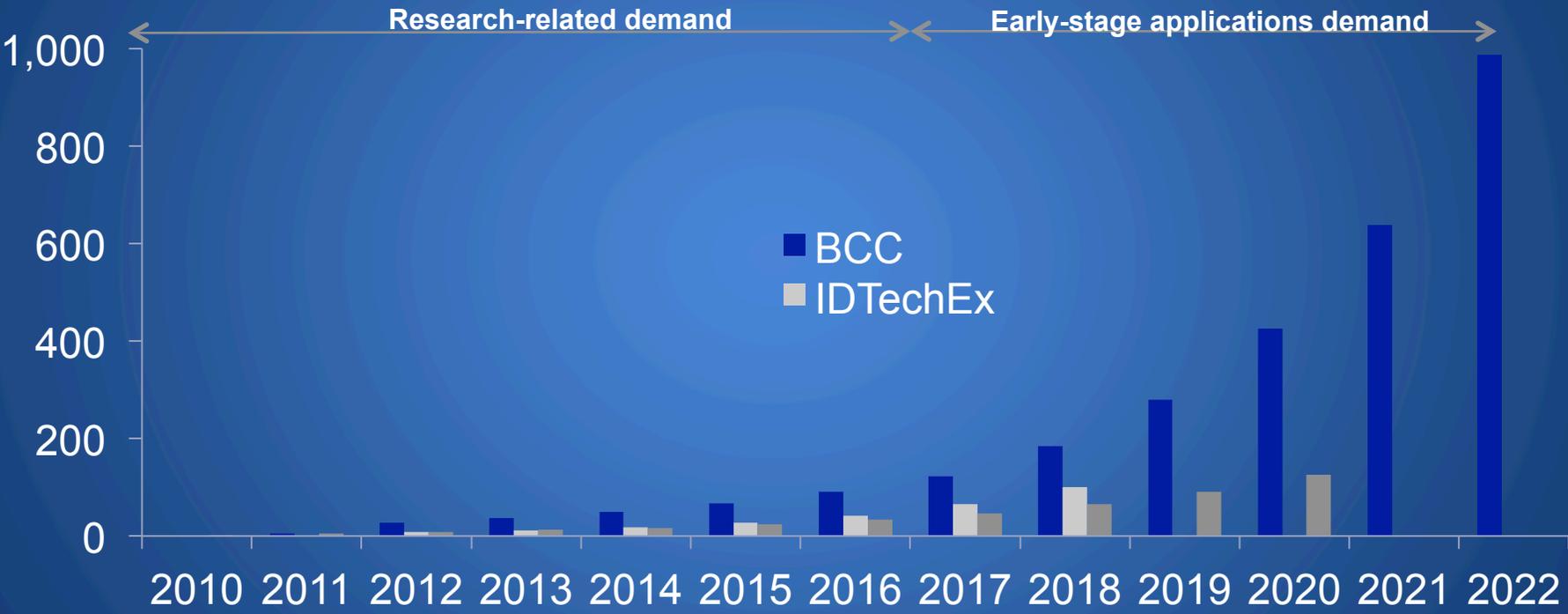
- Energy storage and conversion**
- Efficient
 - Cost effective
 - Renewable
 - Sustainable

- Health**
- Cost effective
 - Bio compatible

- Societal benefits
- Jobs
- Education

Graphene Market Is Still Very Small and Driven by Research-related Demand

Global Graphene market forecast (\$M)



GRAPHENEA, Source: BCC, IDTechEx, Lux Research, Graphenea elaboration