How is the investment in Graphene going to pay off?

Introduction by Professor Peter Dobson

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The outputs of research on graphene and related materials continue to fill pages of the science literature. There is an impatience amongst politicians and some investors to see financial returns from this in the near future. Is this realistic? This gathering of experts might point to the answer.

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Graphene is a form of carbon!

- Pre 1985 forms were diamond, graphite and amorphous carbon
- The basis of the whole of organic chemistry
- Carbon fibre reinforced composites (from 1963)
- C60 (1985): any applications yet?
- Carbon nanotubes (1991-3) a few niche applications
- Graphene (2004) scores of ideas, but....?

Carbon fibre composites

Invented at RAE Farnborough in 1963, In 1969 a House of Commons select committee inquiry into carbon fibre asked: "How then is the nation to reap the maximum benefit without it becoming yet another British invention to be exploited more successfully overseas?" By then Rolls Royce had abandoned these for the fan blades of the RB211.

Carbon Nanotube Applications

Most of these structural examples are blends of carbon fibre and CNTs

- Beware of Hype!
- Does the processing complexity warrant their use?
- Costs will be higher than ordinary high quality carbon fibre

CNT and Graphene

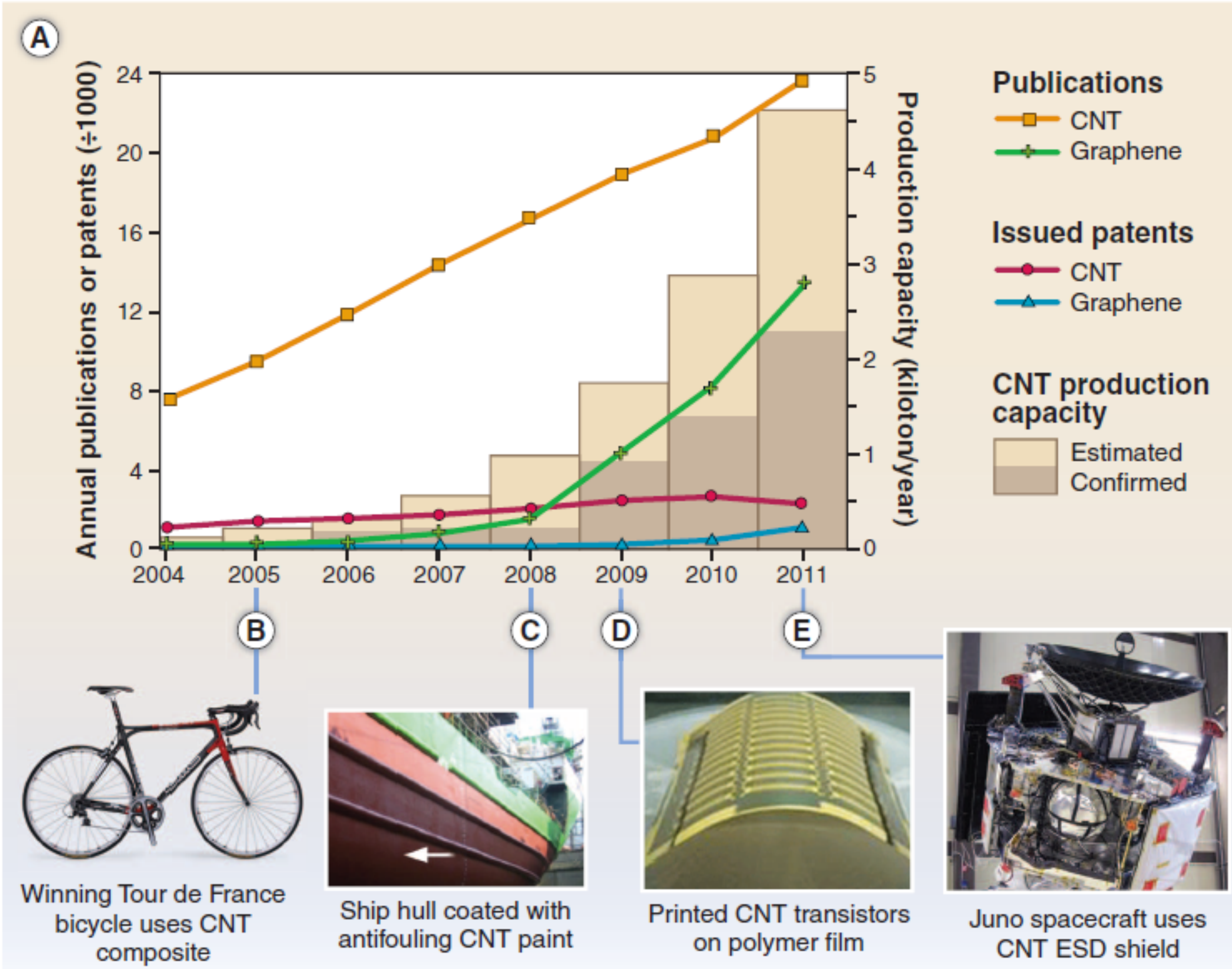


Fig. 1. Trends in CNT research and commercialization. (**A**) Journal publications and issued worldwide patents per year, along with estimated annual production capacity (see supplementary materials). (**B** to **E**) Selected CNT-related products: composite bicycle frame [Photo courtesy of BMC Switzerland AG], antifouling coatings [Courtesy of NanoCyl], printed electronics [Photo courtesy of NEC Corporation; unauthorized use not permitted]; and electrostatic discharge shielding [Photo courtesy of NanoComp Technologies, Incorporated].

This comparison might be a useful guide to investment?

De Volder et al.
Science **339**, 535 (2013)

Physical properties of Graphene at room temperature

Fracture Strength	125 GPa
Young's Modulus	1100 GPa
Thermal Conductivity	5000 W m^{-1} K^{-1}
Mobility	200,000 cm^{-2} V^{-1} s^{-1}
Surface area	2630 m^2 g^{-1}

There are additionally many other properties that may widen its appeal:

- optical transparency (in layers or composites)
- electric field dependent conductivity (for transistors and sensors)
- controllable band-gap (yet to be established in exploitable form)
- quantum Hall effect

Methods of making Graphene

Table 1 – Advantages and disadvantages for techniques currently used to produce graphene.		
	Advantages	Disadvantages
Mechanical exfoliation	Low-cost and easy No special equipment needed, SiO_2 thickness is tuned for better contrast	Serendipitous Uneven films Labor intensive (not suitable for large-scale production)
Epitaxial growth	Most even films (of any method) Large scale area	Difficult control of morphology and adsorption energy High-temperature process
Graphene oxide	Straightforward up-scaling Versatile handling of the suspension Rapid process	Fragile stability of the colloidal dispersion Reduction to graphene is only partial

Soldano et al. Carbon 48, 2127 (2010) (for more detail)
Several additions to the above include:

- Chemical exfoliation
- Different precursors/ catalysts for film growth…..

The Graphene oxide routes that yield a suspension of graphene that can be processed into layers looks like being the most promising early method for many applications.

Graphene has the potential to be important for new composites

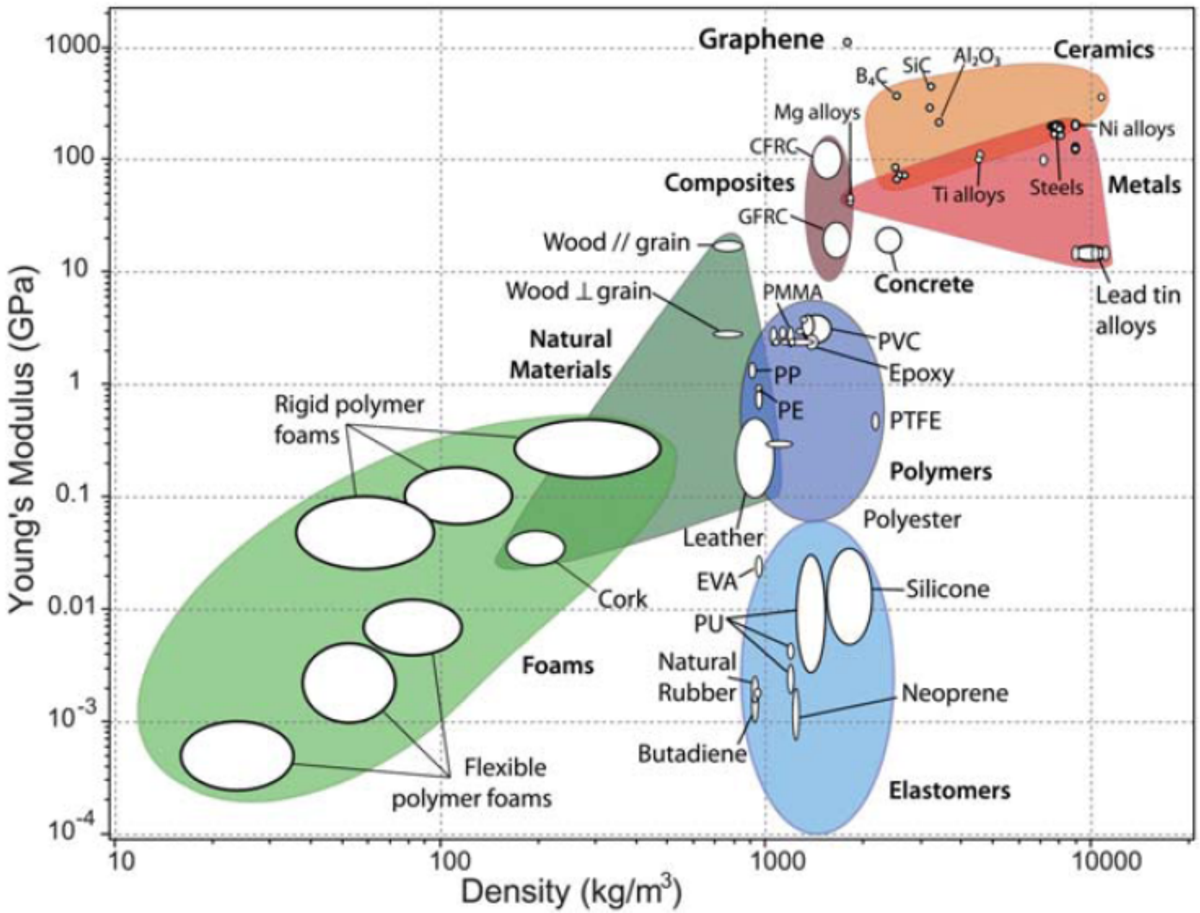
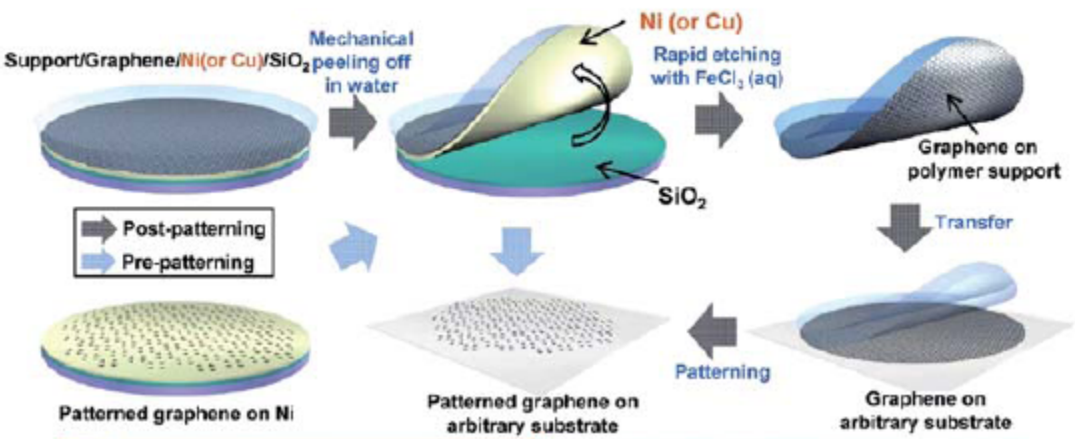
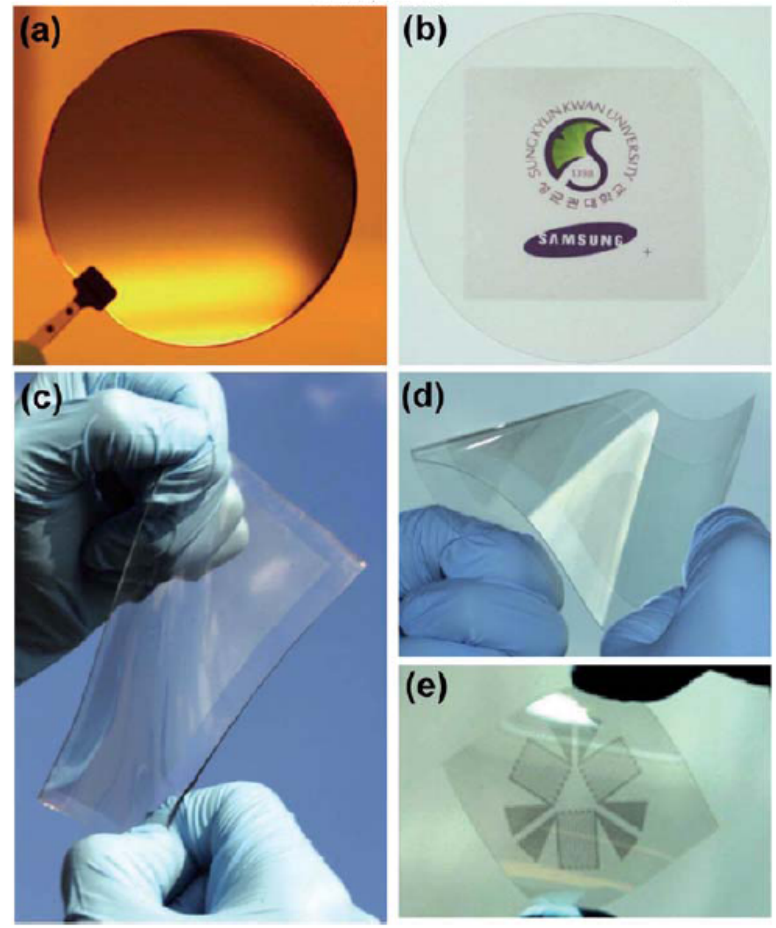


Fig. 3 Chart of Young's modulus as a function of density comparing graphene properties to more traditional materials. Note the axes are in logarithmic scale. Graphene density was taken as 2200 kg m^{-3}.

Verdejo et al. J Material Chem. **21**, 3301 (2011)

Large Area Graphene Films





Verdejo et al. J Material Chem. **21**, 3301 (2011)

Adapted from:

Y. Lee, S. Bae, H. Jang, S. Jang, S.-E. Zhu, S. H. Sim, Y. I. Song, B. H. Hong and J.-H. Ahn, *Nano Lett.*, 2010, **10**, 490–493.

So, where are the real applications?

- Replacement for other carbon forms in sensors, especially biosensors; batteries and capacitors, solar cells (almost immediate)….but is there a significant improvement?
- A filler for composites to give improved strength and thermal and electrical conductivity whilst maintaining transparency (near to medium term)
- New active transistor-like devices (long term)

What are the Challenges?

- Industry needs to identify the customers
- Scale-up and processing will take longer than we think!
- Disruptive technologies always carry a risk that existing technologies will rise to the challenge!

This meeting might help to identify some the answers and other challenges for Graphene.

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