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Graphene: research now, reap next decade

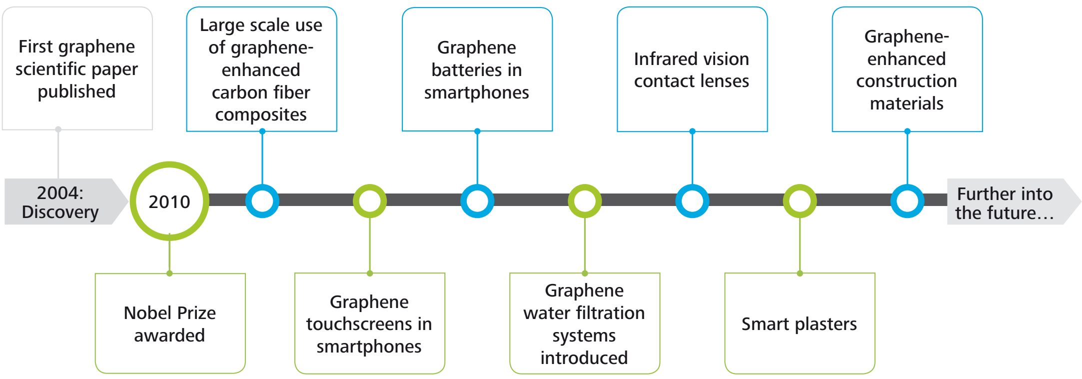
Deloitte Global predicts the total value of the graphene materials market in 2016 is likely to be in the low tens of millions of dollars, equivalent to less than an hour's projected revenues from smartphone sales this year. Research and development spending on graphene is likely to be in the hundreds of millions of dollars in 2016; in the medium term, graphene may be incorporated into products worth many billions of dollars per year, but it may be decades before this material's potential is fully realized.

In 2016, while there are expected to be a few dozen commercially available products that include graphene, the material is likely to be a composite. For example, graphene could be incorporated to improve the strength and weight of the carbon fibers used to manufacture sports equipment[80].

Graphene has been called a 'wonder material'[81], as it offers an unrivalled combination of tensile, electrical, thermal and optical properties. Significant investments have been made in recent years which could hasten the pace at which we start to see more practical applications of graphene and new technologies. For example, the European Union has invested $1.3 billion in 'The Graphene Flagship', a consortium of academic and commercial researchers[82]. The UK Government has provided £235 million ($353 million) to fund a graphene research center[83]. Tech companies are investing in developing their understanding of the material. Samsung for example has already applied for hundreds of graphene-related patents[84].

Graphene is a single atom thick two-dimensional structure, which is a million times thinner than a human hair or a sheet of paper. It is based on graphite, which in turn is a crystallized form of carbon, one of the most abundant elements in the world. A team of scientists from Manchester won the 2010 Nobel Prize for Physics for isolating small amounts of graphene, by applying sticky tape to chunks of graphite and then peeling the layers off one by one[85], leaving a layer of graphene on the tape[86].

Figure 6: Graphene predictions timeline



Source: Deloitte Global, 2015

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Graphene is flexible and very strong, and (in one aspect) is tougher than a diamond and stronger than steel. It is currently used as an element within a resin to manufacture solid structures, as is the case with carbon fiber sports equipment[87]. For example, carbon fiber tennis rackets are made using a small amount of graphene[88]. At the 2015 Geneva Motor Show, Spania unveiled the world's first supercar to incorporate graphene into the structure of a car[89]. Going forward, graphene could be increasingly incorporated in manufactured products. For example, it could reduce the weight of vehicles, cutting down both fuel consumption and resulting emissions.

It is transparent: 97 percent of light passes through it. It also an excellent conductor, and can carry heat and electricity more efficiently than gold or copper. This could make it very useful for developing the next generation of electronics such as solar panels and batteries.

Incorporating graphene into batteries could increase their performance enormously. Energy density could be increased up to tenfold, enabling smartphones to last days without recharging, and an electric car's range to equal or surpass that of gasoline vehicles[90].

Memory chips based on graphene have the potential to increase smartphone storage capacities tenfold, and also reduce power consumption and increase memory access speed[91]. Graphene could lead the way in flexible smartphones by providing an alternative to silicon, which is brittle and could break when bent.

It could also be applied to any surface to convert it into a screen; it would be equivalent to applying a layer of high-tech plastic wrap[92].

Graphene is impermeable to gases and liquids, while graphene oxide is permeable to water only. This means that graphene oxide could be used for desalination[93], or the removal of harmful radioactive isotopes[94].

Graphene also has the capability to change the way in which we interact with the world: it could be used to create contact lenses that enable infrared vision[95], and to develop 'smart plasters' that reduce the risk of anti-bacterial infection[96]. However, the toxicity of graphene to humans has yet to be confirmed through scientific studies.

The potential of graphene is phenomenal, but patience is vital: there are several challenges to be addressed before a graphene era can be realized.

The main challenge lies in manufacturing large quantities of graphene, in various formats, and at an affordable price, with effective yields and a purity sufficient so as not to impair graphene's desired chemical properties. Production volumes also need to be scaled up to factory level.

Despite many academic and commercial research groups investigating methods of production, making large quantities of graphene remains a profound challenge. Graphene is currently produced by a variety of methods, which can be summarized as either 'bottom up' or 'top down'. 'Bottom up' methods use chemistry to synthesize layers of graphene, while 'top down' approaches utilize graphite. The Nobel prize-winning 'sticky tape approach' and the 'how to make graphene in your kitchen' approach (described below) are examples of 'top down' production methods that yield high-quality tiny graphene fragments. However, they are micrometers in size, and these methods are not suitable for large scale manufacture[97].

How to make graphene in your kitchen (if you have lab equipment)

As with many emerging technologies, theories abound but practice is a little harder. It is possible to create graphene using a kitchen blender to combine graphite powder with water and dishwashing liquid[98]. A precise quantity of dishwashing liquid is required to make this work, with the volume dependent on the properties of the graphite powder used. Determining this requires advanced and expensive lab equipment[99]. But as of end-2015 this approach, like many others, remained theoretically viable, but not yet proven in a large production run.

The principal example of a 'bottom up' production method is chemical vapor deposition (CVD) which involves creating a graphene layer on another layer (for example copper foil)[100], 'unzipping' carbon nanotubes and the reduction of graphene oxide[101]. While some of these these methods can produce square meters[102] of graphene, they may produce highly defective graphene, or require the use of hazardous materials. As such, there is still some way to go in optimizing the production processes.

As of end-2015, the market price of graphene was about $100 per gram[103]. Once the method of production is optimized and scaled up, the cost of graphene is expected to come down to the cost of the raw materials, which will likely be centered on the existing suppliers for graphite: China and India[104].

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While graphene is a 'wonder material', there is another major hurdle to overcome before its use can become widespread in electronics. Semi-conductors, like silicon, are characterized by their ability to turn on and off as their electrons can only move freely within the material in the presence of energy due to the existence of a small band gap. A band gap is the energy range between the valence band (where an electron cannot conduct electricity) and the conduction band (where it can). If material is an insulator, this band is large, and the electrons cannot move from one band into the other and the material has no electrical conductivity. One of the reasons why graphene has such high conductivity is due to the fact that it has no band gap and electrons are free to move between these two bands with no resistence. At the present time, scientists are still developing methods by which to insert a band gap while still maintaining graphene's highly attractive properties [105].

Other barriers to the development of graphene are the established processes and supply chains for existing materials used in electronics; for example silicon, which is the industry standard in microelectronics, and indium tin oxide which is widely used as transparent electrodes used in touch screens[106]. Until graphene can be produced and supplied at a competitive price to these existing technologies, it is unlikely to become ubiquitous in the market. This means that it will most likely be about a decade before graphene can be used commercially as an alternative to silicon, but this should provide ample time to understand the material and to evaluate its potential performance[107].

While products marketed as 'graphene' may be on the market in 2016, many, if not all, will likely be constructed principally from more traditional materials and incorporate a limited quantity of graphene.

We would expect graphene to continue to be used as a supplementary material in the short term (and through to 2020 at least), until the manufacturing process for graphene is mature enough for it to be used as a key material in products.

Bottom line

It is important to be cognizant both of graphene's potential, as well as the many challenges that need to be overcome before its fantastic properties can be exploited. In 2016, and most likely in the decade to come, graphene will be in a research and prototyping phase. The potential benefits are significant; the challenges are commensurately high.

We predict that sales of materials will likely remain the principal source of revenues in 2016. We expect to see some of the first real graphene-based products entering the market. The number of 'graphene' products on sale in 2016 will likely number in the tens. We anticipate that the graphene market, including material sales, will likely not surpass $30 million in 2016. By the end of the decade material sales may still be a little more than $100 million – which represents growth, but also a continuation of the research phase[108].

We should put graphene's life cycle trajectory in perspective: many of the most impactful materials have taken decades before attaining mainstream adoption. Aluminium was used as a luxury metal in 19th century France. Even when manufacturing costs fell it remained a niche material until the invention of the airplane, which uniquely required aluminium's specific combination of strength and weight to make commercial flight viable. Indeed, it is only now that aluminium is becoming incorporated increasingly into premium passenger cars.

Carbon fiber has similarly had a long gestation: it was first used commercially in the late 1800s as a component in light bulbs[109]. Today it is used only selectively in vehicles, even though its benefits are very well understood.

In 2016, graphene-enhanced products are only going to offer a glimpse of the material's full potential, but a key point to consider is that new materials disrupt existing products and lead to new technologies. So some of the future technologies and benefits of graphene, which could embody the 'graphene era' and change our world, only currently exist within the realms of our imagination.

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