The physics and uses of graphene

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September 27, 2015

How was graphene discovered?

Graphene was first isolated in 2004 by Geim and Novoselov [1]. The two scientists would hold what have been called "Friday night experiments" [1] in which they would perform experiments not necessarily involved with their usual field of work. It was during one of these Friday night experiments that they first managed to isolate graphene. The two scientists realised an inconsistency in the appearance of graphite flakes as they used tape to peel away layers from a lump of graphite [1]. In this way, they continued until graphite was peeled to fewer and fewer layers eventually reaching some very rare flakes of graphene. The method they employed is a very simplistic approach to what is known as mechanical exfoliation. This approach has been developed further and is still used to make samples in the lab for testing which produces the "highest quality material" with respect to "overall mobility and absence of structural defects"[2].

What is graphene?

Graphene is a one-atom thick hexagonal lattice composed solely of carbon atoms covalently bonded to each other. Each carbon atom forms a bond with three other carbon atoms, thus leaving the remaining electron delocalised and free to roam throughout the lattice. A. K. Geim defined graphene in the following way: "Graphene is a single atomic plane of graphite, which – and this is essential – is sufficiently isolated from its environment to be considered free-standing."[3]

Where was graphene conceived of?

The existence of graphene was first theorised by P.R Wallace [4] in 1946 in order to further understand the properties of graphite. It was believed by many theorists that graphene could not exist in the free-state [5] because it would be thermodynamically unstable. At absolute zero a 2D lattice of any size could exist [6], however as the temperature increases, so does the vibrational energy. Some of this vibrational energy will face in a direction that is out of the plane [7]. If the restraining force is overcome this could result in the surface buckling or breaking apart [7].

How can the quality of the graphene be tested?

Although graphene is not truly transparent, at just one atom thick it is essentially invisible to the naked eye. In order for its quality to be assessed under an optical microscope it must first be made visible. One method involves placing graphene on a silicon wafer with a carefully chosen thickness of silicon dioxide [5]. With this carefully selected substrate, a clear enough contrast is provided so that graphene can be seen. The thickness of the layers can be determined by the colour of the sample with the substrate itself being light purple, graphene a deep purple and multiple layers of graphite appearing blue [8]. However the thickness of silicon dioxide has to be very precisely determined as even a difference as little as 15nm can render single-layer graphene totally invisible [5]. However many other techniques for analysing the quality of graphene produced have been devised which often utilise the unique properties of graphene, for example the observation of the quantum hall effect [9]. Another notable method includes Raman spectroscopy [9] which measures low-frequency modes such as rotational and vibrational modes [10]. Raman spectroscopy relies on inelastic scattering of monochromatic light [10].

Applications of graphene

Graphene has many superlative qualities such as thermal and electrical conductivity, mechanical strength and optical properties. This leads to a wide variety of possible applications. However the true power of graphene is unlocked when it is combined with itself or other 2D materials. One potential application might be the replacement of silicon based transistors and diodes.

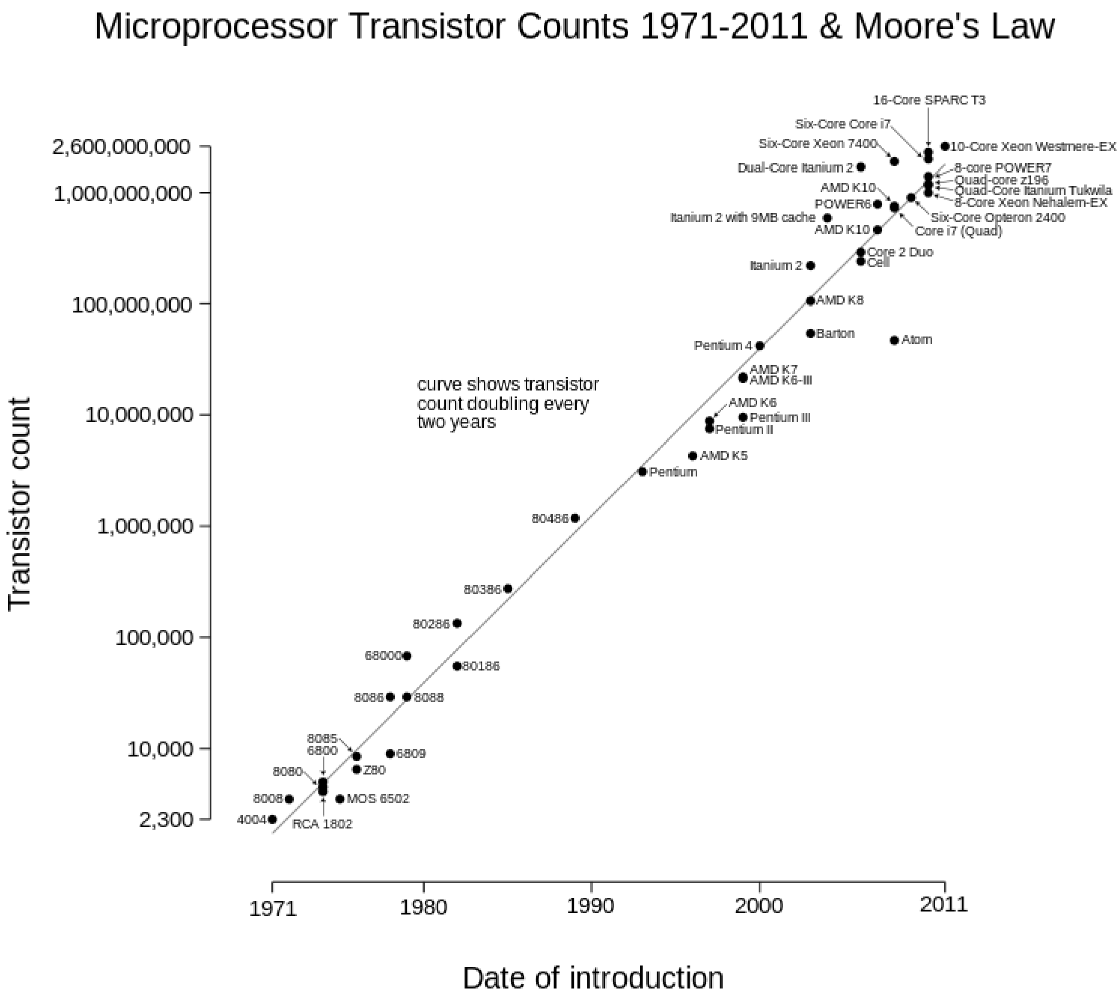

Figure 1: Logarithmic scale of Transistor count versus Date of introduction. [21]

In 1965 Gordon E. Moore projected that the number of components per integrated circuit would double every year, which he then revised to doubling every two years in 1975 [11] as we can see in Figure 1 above. This prediction has proved to be quite reliable for the past four decades and was instrumental to setting targets for the progression of semiconductor electronics. However after the fifth decade since its birth Moore’s law is beginning to show signs of slowing down. Intel, a leading manufacturer of electronics chips, has already had to delay product releases due to difficulties in the manufacturing process as they reach chip sizes of around 10nm [12].

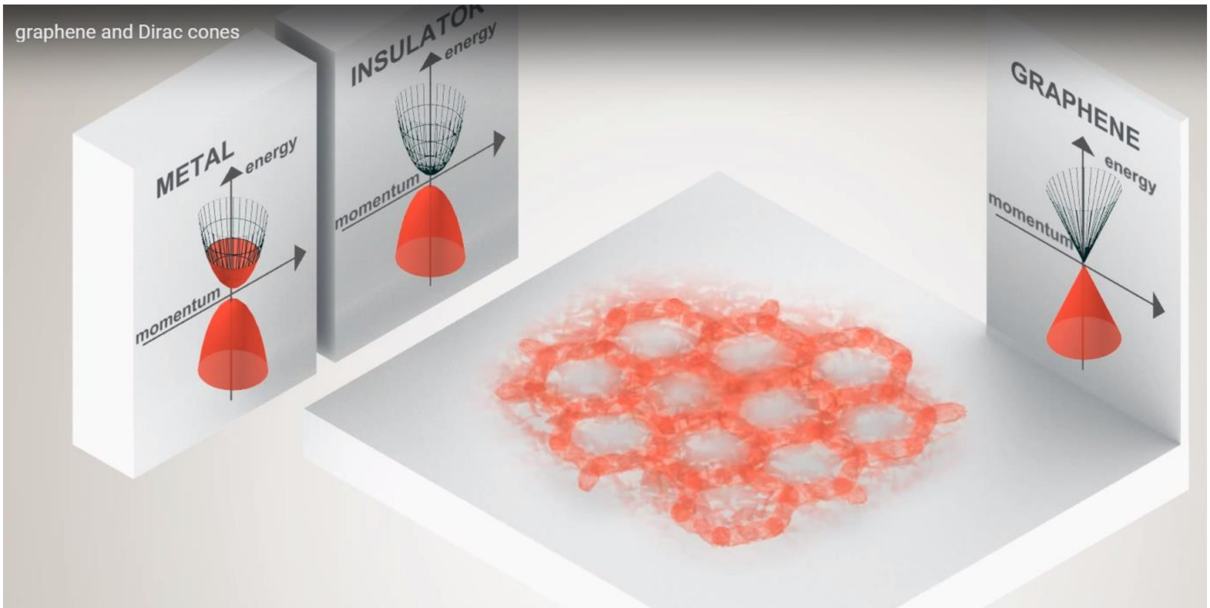

Figure 2: Here we can see both the lack of a bandgap in graphene as well as the linear relationship between energy and momentum. [22]

In its pure form, graphene is not a suitable material to produce transistors and diodes from. Transistors and diodes, which form the basis of essentially all modern electronics, work by being able to effectively switch on and off. This ability to switch between the on and off state is what allows for Boolean logic in digital logic gates such as XOR gates. In conventional silicon based electronics, this is achieved by utilising a band gap; an energy range where no electron states can exist. When energy (z-axis) is plotted as a function of momentum (in two dimensions hence the x and y axes) the bands become paraboloids and there is a visible band gap between the two paraboloids as shown in Figure 2. This is due to energy having a quadratic dependence on momentum. However in graphene, we observe something called a Dirac cone which shows that the energy has a linear dependence upon momentum. However we can also see from the diagram that graphene has no band gap, which means there is no energy level at which current cannot flow in graphene.

One technique that is being explored utilises a phenomenon known as negative differential resistance to try achieve behaviour similar to that of conventional transistors. This could potentially lead to “non-Boolean computational architectures” [13]. Negative differential resistance occurs when current decreases as potential increases [14]. The idea proposed by Liu et al is that as the current flows through the material this will correspond to a drop in potential difference which can be detected and used to perform logic [15]. Using their proposed system an XOR gate can be made using 3 transistors instead of the minimum of 8 which would be needed in complementary metal-oxide semiconductors (CMOS) [13]. In addition the operation frequency of the transistor could be as high as 427 GHz [13], due to the high carrier mobility(essentially a measure of how quickly a charge carrier is pulled along by a given electric field) of graphene, making it an ideal material for applications such as radio-frequency identification.

Another application being explored is the use of graphene in lighting. Graphene has the potential to revolutionise lighting not only on the streets and in the home, but also with the potential of on-chip lighting.

In order to emit significant light in the visible spectrum on a chip, the graphene must reach high temperatures by using a current to heat the material similar to conventional filament bulbs. However due to graphene being an exceptional thermal conductor, heating graphene to these temperatures proves very difficult as the heat is dissipated too quickly [16]. The solution to this problem lies in Umklapp scattering. Umklapp scattering is a process whereby phonon momentum is almost opposite to that of the initial state [17] at shorter wavelengths. This results in thermal resistivity at high temperatures in crystals with little defects [18] such as graphene. This phenomenon allows graphene to reach temperatures as high as 2800K resulting in visible light [16]. However in order for these conditions to be reached the graphene must be freely-suspended instead of mounted on a substrate which it typically is, as the substrate would act as a heat sink to prevent it from reaching the temperatures described [16].

Once the challenges required to manufacture graphene this way are overcome, the doors are opened for a whole variety of new electronics. The ability to create on-chip lighting paves the way for near-transparent flexible lighting displays which could have applications in contact lenses, television screens and potentially products such as wearable-displays. Another possibility would be interfacing the optical circuits with electronic circuits which could have a significant impact on data transfer [16].

On the other hand graphene is also having an impact on increasing the efficiency of everyday light bulbs. The first commercial application of graphene to come from the National Graphene Institute was graphene light bulbs [19]. Although very little information has been released, the bulbs are claimed to have “lower energy emissions, longer lifetime and lower manufacturing costs” [19]. If these claims are to be believed then it shows that graphene is already making its way to the marketplace just over a decade after discovery, a similar timescale to that of the transistor [20].

What’s next?

Clearly graphene is a revolutionary material capable of doing much more than what is described here, however it is still apparent that the strength in graphene is when it is combined with other materials to produce a desired effect. We have seen how graphene alone cannot be used as transistors and special conditions must be met in order for light to be produced for on-chip lighting. For this reason I think that the future of graphene will not only be in the modification of its structure to produce new materials such as graphane, but to combine it with other 2D crystals that are being developed to make nano-scale composite materials.

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Word count (excluding references): 1590