**Fall**

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Emerging Technology Business Concept

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**Business Implications of Emerging Technologies RPI : Lally School of Management & Technology
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An in depth analysis of Kayvan Rafiee’s

graphene production process and its

implications for 4 distinct industries.

Introduction to Graphene
 The term graphene was coined in 1962, however basic research and the in-lab production of graphene took place in the mid 1990’s with the first graphene lattice being produced in 2004. Graphene is essentially a 1 atom thick hexagonal lattice of bonded carbon atoms, which takes the shape of nano-scale chicken wire. Andre Geim, the discovering scientist, had originally produced graphene by sandwiching a piece of readily available graphite in between two pieces of tape and then peeling away the tape over and over until he realized under the microscope he had a 1 atom thick layer of carbon atoms. Graphene has several properties that make it unique. Graphene is at present said to be the strongest material ever tested. “Measurements have shown that graphene has a breaking strength 200 times greater than [steel](http://en.wikipedia.org/wiki/Steel)” - wiki. Another important property of graphene is that it has extremely high electron mobility, which makes it suitable for applications in several new types of electronics (notably touch-screen displays).
Kayvan Rafiee
 Kayvan was born and raised in Tehran Iran and got his bachelors and masters in mechanical engineering at the University of Tabriz. He obtained a second masters degree at RPI in industrial management and engineering. He is currently working on his PhD at RPI in mechanical engineering as well. Kayvan sees himself as practically focused and his research in graphene reflects this. In discussing his technology, Kayvan seems genuinely happy to be part of a larger graphene research community; however it is not his main motivation in pursuing this technology. The research of his second masters degree is focused on practical manufacturing technologies, which he views as very appealing to companies looking to commercialize new technologies. Kayvan, unlike most scientists in his discipline, is highly motivated by commercialization and even remarked in our interview that in 5 years he would like to have a house in Spain and Hawaii and be living easy. Kayvan also discussed details of the path he sees his technology following in order to be commercialized, remarking that he would like to sell the process to a large materials or manufacturing firm who would also employ him and his brother (the researchers), as is typical when obtaining a new process technology. Kayvan is well versed in technology commercialization and his motives are certainly in line with it as well.
Kayvan’s Graphene Production Method
 Kayvan has developed a manufacturing process in order to significantly reduce the cost to produce graphene. As described above, the process of making graphene (even in an imperfect form) was expensive and extremely time consuming. Kayvan’s innovation makes the production of graphene easier, cost effective and scalable for bulk production. The new process does not produce perfect single atom layers of graphene; it yields somewhat imperfect multi-layer (3-5 layers) graphene which is still extremely useful in a number of applications.
 The process which Kayvan invented uses graphite oxide as an input to produce multi-layer graphene. Graphite oxide has small gaps between the layers of carbon caused by the oxygen atoms. Kayvan’s process forces the gaps to be larger and eventually fade away in order to get graphene. The graphite oxide is put through a thermal shock up to 2000 degrees C per minute which exfoliates thin layers of the existing compound into the final multi-layer graphene. The graphene produced is stronger and lighter than carbon nano-tube materials and can be produced at a much cheaper cost.
Current Applications
 For a variety of reasons, graphene is one of the most promising discoveries in recent years. Graphene is stronger than diamonds, extremely light, mostly transparent and is the most conductive material currently known.  The main hurdle to the widespread use of graphene and the reason we don’t hear about it everyday, is because it’s so difficult and expensive to produce, at least in near flawless form.  Graphene’s potential uses vary widely depending on how expensive, flawless and large the piece is. Near perfect Graphene sheets have a wide variety of uses in sensing applications. Less perfect graphene pieces/powders have immediate uses in strengthening composite materials used in endless everyday applications.
Future of Graphene
2 potential business models: service provider, or graphene producer

 This technology innovation is a process breakthrough rather than a new product breakthrough. Because of Kayvan’s new method of producing graphene, a vast array of possibilities for improving existing composites is now achievable. We find two likely possibilities for business models utilizing this new process. The first would be a complete composite service provider that would not only create graphene from bulk graphite, but also offer composite part prototyping and manufacturing of composite parts and materials. This model would mimic existing firms in this area such as Zyvex and directly compete with them.  Another model would be to simply produce bulk graphene to sell to existing composite manufacturing firms.  This model would require a smaller initial investment but would comprise a smaller portion of the value chain and could face significant risk if a cheaper or better way of producing graphene is discovered.  Because our breakthrough innovation corresponds to a process, we chose to focus on 4 areas where low cost graphene such as Kayvan’s is likely to make a large impact on existing industries.
Prosthetics (Medical)

 According to studies, composites infused with graphene are stronger, stiffer, and less prone to failure than composites infused with carbon nanotubes or other nanoparticles. These properties are extremely helpful in prosthetics industry. Prosthetics involves the development and production of replacements for missing body parts, such as teeth and limbs. Referring to our last report about 3D pringting technology, graphene composites can be used as the materials in 3D printing to produce customized replacements. The combination of these two technologies will bring disruptive changes to prosthetics industry regarding the properties, production process and value chain of the products.
Body Armor
 Another potential application for Graphene we identified was body armor. Body armor is a rather large industry with the largest buyer clearly being the US Government and possibly foreign governments. Between 2004-2006 $5.2 billion was awarded in body armor contracts to a variety of firms in the US. A few large players in the industry are Ceradyne, Armor Works, and Simula Inc., winning a majority of US body armor contracts in the same time period. Currently the US armed forces use a body armor system made of the latest release of Kevlar fibers (Protera: 1996). There is a new fiber in development called M5 which is scheduled for possible release in 2010-11 but is still being tested.

Other nano-technologies are currently being used in conjunction with fibers to significantly increase impact strength of vests. BAE systems licensed nano-infused fiber technology from University of Delaware in 2008 but no products have been developed as of yet. The University of Cambridge has also been using nano-tech to strengthen fibers mostly with graphene’s cousin carbon nano-tubes. The US and British government have already shown keen interest in the carbon nano-tube fiber technology and it began being produced in large scale at Nanocomp in 2008. Graphene would be a logical next step from carbon nano-tubes as it is much stronger and through Kayvan’s process is able to be produced in large volumes at a relatively low cost. Graphene could be introduced into the production and ultimate composition of the fibers used to weave the final vest. Graphene could also be used in a polymer composite as a base plate backing armor vests; this would be particularly advantageous as it could reduce the weight while increasing the strength of the vest.
Sporting goods
 Graphene can also be used in sporting goods, a $12 billion dollar industry in the U.S. Sporting goods include rackets, golf clubs, skis, snowboards, athletic footwear, padding, protective equipment, and other types of sports-related equipment. Sporting goods may be designed to provide a user with a competitive advantage, improve durability, enhance the user's comfort, or protect the user from being injured. While adding material to sporting goods may improve their ability to resist wear, absorb impacts, dampen vibrations, or perform other advantageous functions, it may also add bulk and weight to the sporting goods. Currently, carbon nanotube fibers are used in sporting equipment, but graphene can allow improved designs with optimized flexibility, responsiveness, and strength. Zyvex currently uses this technology in a partnership with Easton to produce baseball bats, but the next immediate opportunity we see for this technology is in golf clubs.
Energy
 Graphene has enormous potential as an ingredient in composite materials and high-strength, light-weight parts are especially important in the energy industry.  This industry is full of components that would benefit tremendously by what graphene brings to the table.  As we look for new ways to harness our natural resources with increased focus on renewable resources, this industry will continue to grow.  Emphasis will be placed on any way to increase efficiency.  When trying to capture the energy from things such as wind, the lighter the weight of the turbine, the less wasteful and more efficient it can be.  Graphene composites will allow us to harness more of our resources and produce less waste.  According to BCC Research, the domestic market for wind energy turbine components will reach nearly $70 billion in 2013.  And this is just the tip of the iceberg.  Turbines are used in almost all energy capture including nuclear, gas, oil and hydro.  In all of these scenarios having lighter-weight and stronger components will allow them to operate in more efficient manor, stretching our resources and opening new doors.
Hurdles/resources needed going forward with our applications:
 Graphene is much more promising than its predecessor, carbon nanotubes. To turn graphene applications into reality, the material must first be synthesized in large quantities. Graphene has several problems, notably a lack of an obvious 'band gap', a break in electron energy levels that would allow it to be easily used as a transistor. The most obvious solution is to cut the material into ribbons, which have discrete energy levels. But cutting the sheets creates a jagged edge of dangling chemical bonds that can pick up unwanted contaminants. Because graphene is so thin, even the slightest brush from neighboring atoms can alter its mechanical and electrical properties.
 Until now, graphene has often been grown on substrates of silicon carbide, a costly material that is available in only limited quantities from suppliers. Kayvan mentioned that producing a single layer of graphene was almost three times more expensive than the cost of producing multiple layers, such as what he currently produced in the lab. Producing a single layer of graphene inexpensively is the next step in graphene, because a single layer with no defects has the greatest potential for alternative uses.
Major competitor:

The greatest competitor of graphene is carbon nanotubes. Graphene has three distinct advantages over carbon nanotubes. The first advantage is the rough and wrinkled surface texture of graphene, caused by a very high density of surface defects. These defects are a result of the thermal exfoliation process that the Rensselaer research team used to manufacture bulk quantities of graphene from graphite. These wrinkly surfaces interlock extremely well with the surrounding polymer material, helping to boost the interfacial load transfer between graphene and the host material.

The second advantage is surface area. As a planer sheet, graphene benefits from considerably more contact with the polymer material than the tube-shaped carbon nanotubes. This is because the polymer chains are unable to enter the interior of the nanotubes, but both the top and bottom surfaces of the graphene sheet can be in close contact with the polymer matrix.

The third benefit is thinness. Graphene is the thinnest of all possible materials in the universe. It shares many of the properties that excited physicists about nanotubes a decade ago, but it is easier to make and manipulate, giving greater hope that it will make the move from laboratory to practical application. Physicists have made transistors out of graphene and have used it to explore odd quantum phenomena at room temperatures.

Conclusion:
 Graphene just by its nature offers a variety of applications across a wide array of industries. Kayvan’s process innovation however produces a somewhat imperfect graphene, which is most suitable for use in composite materials. Through our analysis we have identified 4 industries: body armor, sporting goods, medical and energy that we believe will likely be impacted by this process and graphene technology. An important point to keep in mind is that using this technology could manifest two different business models. Firstly one could provide end-to-end graphene composite part production, or one could simply produce graphene in bulk and sell it to composite part manufacturers. Going forward a major hurdle is ensuring that the manufacturing process will scale. The next step for graphene production as Kayvan mentioned was finding a way to cheaply produce single layer continuous sheets. In the coming years however we believe that the graphene produced by Kayvan’s method will lead to a variety of innovative composite products (in a range of industries) increasing functionality across a number of parameters.

Appendix

Call report:
**When:** Friday, December 3, 2010
**Who:** Kayvan Rafiee and our group
**What was discussed:** Graphene technology

## Graphene Lattice:



# References

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