The Future of Transistors: An Overview on Graphene Nanoribbon Synthesis and Applications

Felix Fischer Lab

By Julian Magdalenski

Professor Felix R. Fischer is an esteemed scientist in the field of graphene nanoribbons (GNRs) and related nanoscale materials. Acquiring his bachelors first in Germany, his PhD in Switzerland, then a postdoctoral fellowship in New York before becoming an associate professor here at Berkeley, Professor Fischer has traveled all around the world chasing his love of chemistry. His work is centered around post-silicon materials, specifically the bottom up synthesis of bandgap-tunable GNRs and their incorporation into functional electronic devices such as field-effect transistors, molecular circuits, and solar cells. Due to the steady decline in transistor density on integrated circuits, many are looking towards GNRs as a potential replacement for silicon-based transistors, which could launch us into a new age of computational power and efficiency.

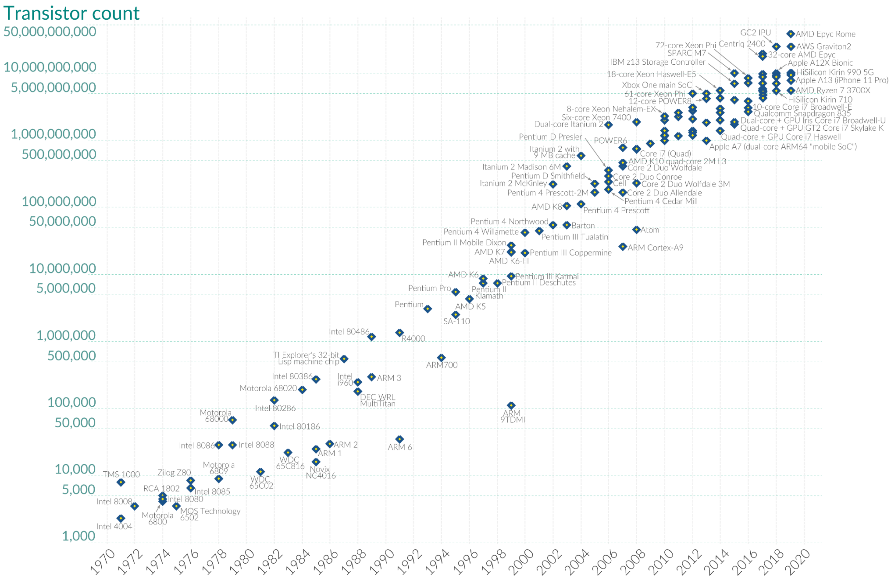
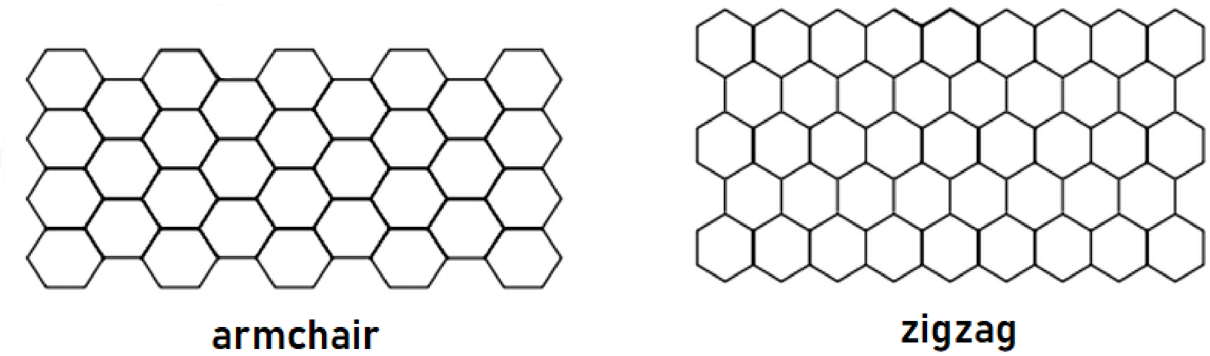


Figure 1: A semi-log plot of transistor counts per microprocessor over time.

In 1975, Intel co-founder Gordon Moore posited that the number of transistors in a dense integrated circuit would double approximately every two years. As his prediction was so incredibly precise, this observation has since been deemed “Moore’s Law,” and has accurately predicted transistor count for microprocessors ever since. However, many feel that the end is in sight for Moore’s Law, as the physical limitations of silicon based electronics are close to being reached. This is where the potential of GNRs lies, in breaking the physical barrier of silicon and using carbon based transistors instead to shrink the size of transistors and ultimately allow more transistors to be fit in a given integrated circuit. A silicon atom is around 0.2 nm in size, but its behavior in a circuit becomes unstable and difficult to control before this scale may be reached.

In contrast, a carbon atom’s size is around 0.0914 nm, which allows for smaller transistors to be designed without the instability silicon devices are currently facing at this scale. GNRs have a very high current conducting capacity (1000 times larger than copper), and when graphene is confined to an essentially one dimensional ribbon, a band gap large enough to expose semiconductor properties can be generated. Yet, limitations in the yield and the inhomogeneity of traditionally synthesized GNRs has been a prohibitive obstacle in the way of commercial applications so far. Fischer’s bottom-up synthesis approach to generating GNR based field-effect transistors aims to solve this problem.

There are two main types of graphene nanoribbons: armchair and zigzag. As the name implies, these two vary based on the geometry at their edges; while zigzag GNRs have edges where each successive edge segment is at the opposite angle to the previous, in armchair GNRs, each pair of segments is a 120/-120 degree rotation of the prior pair, producing an “armchair” pattern. While these two forms of graphene look similar, they have slightly different electron properties that affect their ability to function in a semiconducting way. While zigzag GNRs have been shown to always be metallic, armchair type GNRs can be either metallic or semiconducting depending on the width. Both types can be utilized in the construction of electronics, either for field effect transistors, sensing devices, or advanced electronic devices involving topological quantum dots. The potential utility of GNRs is expansive, but how exactly are these exciting little strips of carbon synthesized?


armchair

zigzag

Figure 2. GNR structures with armchair edge geometry (right) and zigzag edge geometry (left).

In Fischer’s lab, these GNRs are constructed from a bottom-up synthesis approach, where starting materials are first turned into polycyclic aromatic compounds, then functionalized with a halide (typically bromine or iodine). These monomer precursors are then heated in the presence of a metal surface, leading to biradical intermediate formation through dehalogenation. These intermediates can couple to each other, leading to linear polymers. These linear polymers can then be turned into GNRs through a process called cyclodehydrogenation. Once deposited on a metal surface such as gold, passivating layers such as aluminum oxide can be added, and then the GNR fabrication process is mostly complete.

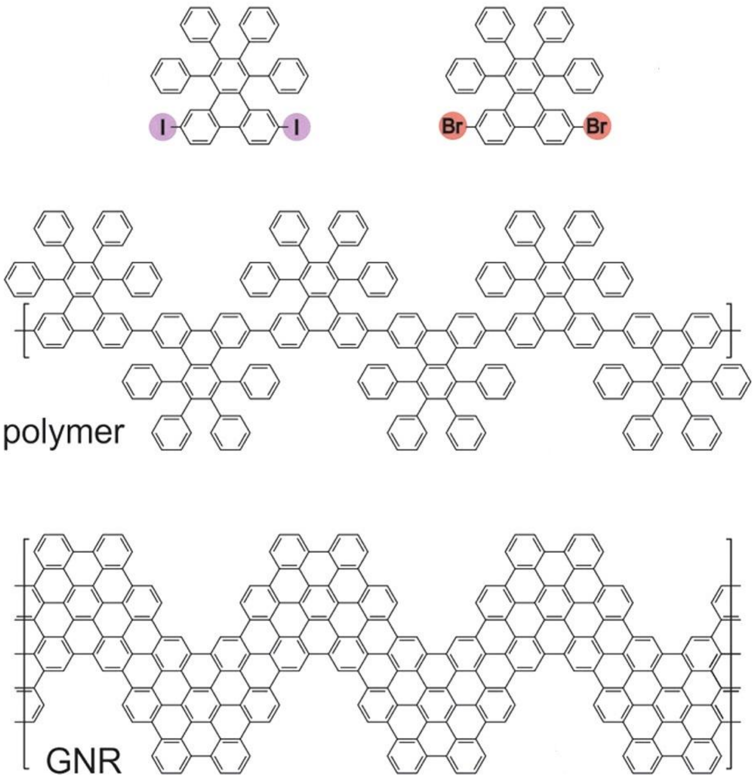


Figure 3. Monomer precursors dehalogenated to form linear polymers, then cyclodehydrogenated to yield an armchair GNR.

The potential applications of GNR based field-effect transistors and other related electronic devices is largely untapped, but incredible headway is being made by brilliant researchers which is paving the way for future innovations and breakthroughs in the field of modern electronics. While Moore’s law may be coming to an end for silicon-based systems, a revitalization of the transistor fabrication process by the way of novel GNR developments could see Moore’s law be brought back to life or even exceeded in the years to come. Professor Fischer is sitting on the cutting edge of the development of this technology, and although his lab group is still in its early stages, he has already seen remarkable results. There is no doubt that in time the chemical revelations his group unearths will influence the commercial applications of GNRs in a major way, potentially revolutionizing modern technology and processing power.

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