The Charm of Magic-Angle Twisted Multi-layer Graphene

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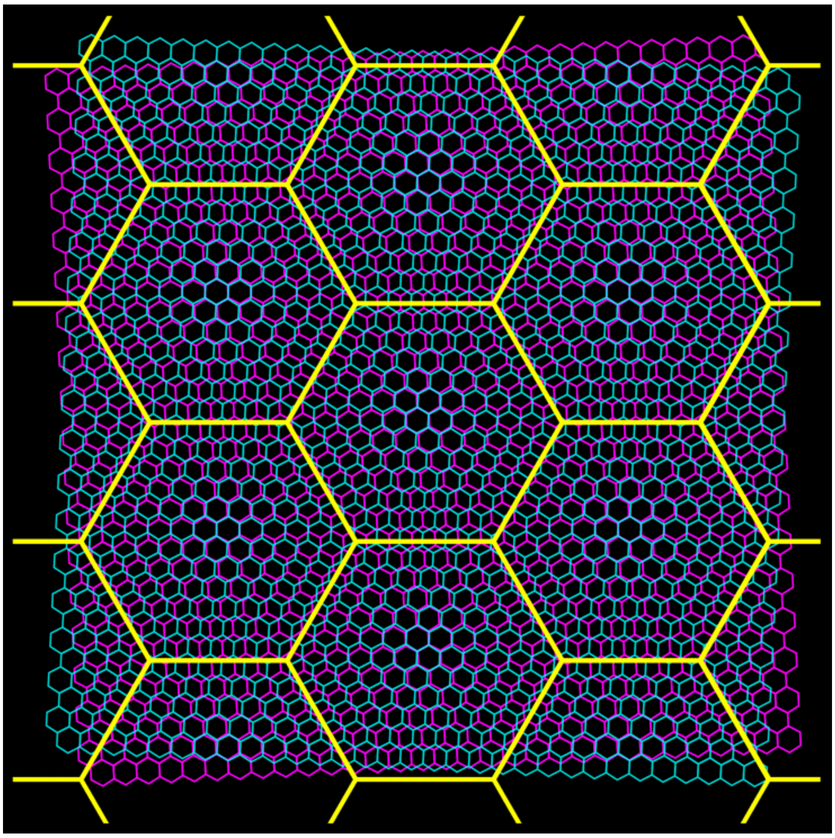

In the history, transportation of electricity is a greatly important problem to people. Due to the resistance of the transport circuit, it will emit heat to the atmosphere and there always exists lots of energy loss on the process of transportation, which brings tremendous confuse to us. The energy loss in this process may occupy 50%-70% of the total energy in the transport of electricity. You can also understand this process even in your home. By opening the light, you will find it not only emit light but also heat into the room. This additional heat will increase energy cost. Centuries of people have been struggling with how to solve the problem of dissipation. In the 1911, the physicist Heike Kamerlingh Onnes discovered the superconductivity in the liquefy helium, which brought surprise to the whole human beings because superconductivity directly means there is no resistance at all in the transport process. In other words, if we replaced the circuits in our life with the material presenting superconductivity, there would be no loss at all in transport of electricity. However, such kind of material still exists an extremely troublesome problem: harsh restrictions on temperature condition. In fact, the temperature of superconductivity discovered by Onnes is just only $-269℃$. If the temperature of the material is high, the superconductor will return back to a normal metal again. For nearly a century, scientists are dedicated to discovering high-temperature superconductors, which will lead to high-temperature superconductivity even in the room temperature condition. In the following years, plenty of scientists dedicate to developing all kinds of high-temperature superconductors named conventional superconductors. However, the shortcomings of them are also obvious: the material they use is rare in the nature. It is always difficult to look for the elements or the compound they required, leaving a harsh problem to us.

Recently, a new approach was proposed to find new high-temperature superconductors. In 2018, Professor Pablo's group published a paper on unconventional superconductor to realize high-temperature superconductivity[1]. In the experiment two layers of graphene were utilized as the material to discover the zero-resistance phenomenon. They stack the graphene layers together to form a bilayer structure. Further, by rotating one layer of them by approximately $1.1°$, which is called magic angle, relative to the other layer, we get the twisted bilayer structure of graphene. In this case, the experimental results tell us that the system presents zero resistance in the $-271℃$ temperature, which indicates the occurrence of superconductivity. The reason why this experiment is important to us is the first try to use one of the most common material in the industry: graphene, to realize the superconductor. As we know, graphene is only made of the carbon atoms, nearly everywhere in the nature. This is unlike the conventional superconductors demanding specific elements or compound rare on the Earth. Hence, we call it unconventional superconductors.

Another reason we call it unconventional superconductor is it shows us the Moiré structure. This experiment is also the first try to connect superconductors with Moiré structure indeed. The Moiré structure means if we rotate the one layer in the bilayer structure relative to the other one, then it the bilayer object will shower larger periodicity. This can be shown if you stack two honeycomb-like nets together and rotate one layer of them. In solid state physics, we say the Moiré structure enlarge the minimal distance on the lattice which is called lattice constant. For monolayer graphene, the lattice constant is always given by: $a = 0.246nm = 2.46 \times 10^{-10}m$, which is quite small compared with the objects in our life. This is shown by the side length of green or purple hexagon in the diagram. However, if we prepare such a magic-angle twisted bilayer graphene, we can see the periodicity can be enlarged due to the twisted angle. Taking the experiment I listed above, the lattice constant of the Moiré structure is $a = 13nm$, nearly 100 times of that in the normal monolayer graphene. Magically, the experiment I introduced here bridges the Moiré structure and superconductivity which seems to be irrelevant to each other. This is also important for us since it opens the gate to research the material with Moiré structure. After that, they also tried other materials like twisted trilayer graphene[3] and also achieved great success.

The techniques behind this experiment will also benefit us in the future possibly. In the context above, I explained that the material will provide great help for us to transport electricity in the future without any energy loss. Another benefit of twisted bilayer structure to us is optical communication. The ongoing challenges is the interconnects bottleneck in high-speed computing systems. In the traditional research, researchers always focus on the silicon photonics since many components in the computing system can be directly integrated on the silicon-based processors. However, light sources and photodetectors are always difficult to be integrated. It is exciting that twisted bilayer structure provides more opportunities for development of optical communication. The photodetectors on a p-n junction of bilayer $\mathrm{MoTe_2}$ can be integrated more easily[3].

From above discussion, we can see the uses of superconductors can cover plenty of scopes in our life. Even though the industrial production of twisted bilayer graphene is still not well developed yet, we believe that it will gain its ground in the future. And that’s why I think it can be considered as a hidden gem in basic science.

References:

[1] : Cao, Y. et al. Unconventional superconductivity in magic-angle graphene superlattices. Nature 556, 43–50 (2018).

[2] : Cao, Y. et al. Tunable strongly coupled superconductivity in magic-angle twisted trilayer graphene. Nature 590, 249-255(2021).

[3] : Bie, Y. et al. A $MoTe_2$-based light-emitting diode and photodetector for silicon photonic integrated circuits. Nature Nanotechnology 12, 1124-1129(2017).