# Zakaria Moktadir

**Researchers at the University of Southampton, UK, have found a way to effectively shut down the current flow in graphene nanowires to produce a graphene channel transistor. Lead author Dr. Zakaria Moktadir tells us how.**

**FURTHER READING**
http://www.nano.ecs.soton.ac.uk/

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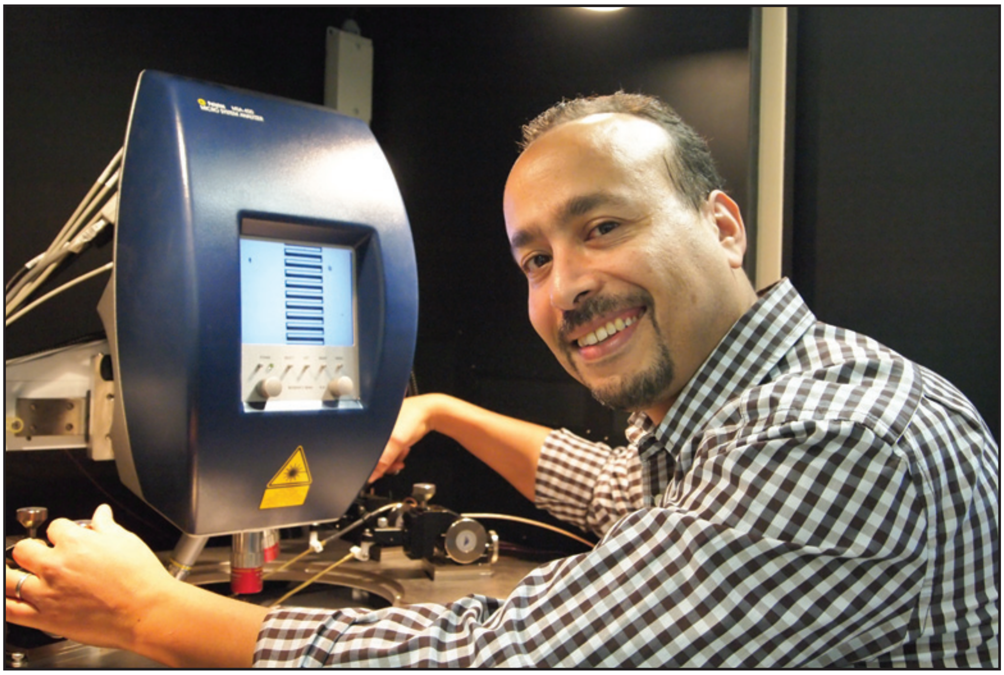
'U-shaped bilayer graphene channel transistor with very high $I_{on}/I_{off}$ ratio', Z. Moktadir, S.A. Boden, A. Ghiass, H. Rutt and H. Mizuta



## Channel transistors

**In channel transistors** electric current flows through an isolated channel-like structure. Every transistor has a physical channel, a corridor where carriers of electrical current (electrons or holes) reside. When a bias is applied at one end, the carriers start to move, allowing the electricity to flow in the channel. The flow can be controlled using another voltage source called the gate voltage. To realise high-performance transistors, two fundamental requirements have to be met: high current through the channel at 'on' state and very low current when 'off'. The control of 'on' and 'off' currents constitutes the basic operation of logic circuits. In conventional silicon transistors, high 'on' current is achieved by scaling down the channel length while very low 'off' current is achieved via good electrostatic control of carriers, thanks to the inherent energy bandgap of silicon. However, the intrinsic physical properties of graphene make this current flow difficult to turn off.

## Graphene?

Composed of a single atomic layer of carbon arranged in a two-dimensional honeycomb structure, graphene has the highest known electrical mobility – a measure of how fast carriers of electrical current move in a material in response to an applied electric field. This leads to very high 'on' current. Electrons in graphene travel almost ballistically making it potentially suitable for future ultra-fast electronic devices. Researchers have also discovered that bilayer graphene transistors have low electrical noise compared to silicon FETs. However, the difficulty in turning the current off, owing to the inherent gapless nature of graphene, hampers its possible use in integrated circuits. This prompted the research reported in our Letter – to find a way to shut down the current in the transistor channel.

## Clarified states

The key result reported in our Letter is that the current in the transistor channel can be turned off with a current on/off ratio about three orders of magnitude higher than previous graphene transistors. In general, researchers use two methods to improve the ratio of the current in the 'on' state to the 'off' state, which characterises the switchability of the transistor. One method is to apply a strong electric field across the transistor channel; the other is to cut graphene into very small ribbons of a few nanometres in width to form the channel. Both methods have practical drawbacks: applying a strong electric field requires large voltages and modern lithographic methods cannot achieve the necessary accuracy to easily make graphene nanoribbons less than 5 nm in width.

We devised a third way – geometrically manipulating graphene nanowires. We discovered that introducing geometrical singularities (such as sharp bends and corners), has the effect of shutting down the current completely – very significant if one wants to build logic circuits in graphene.

## Squaring off

The main challenge to our approach was that graphene transistors are generally fabricated using electron beam lithography, and making a sharp corner with this method is challenging as it suffers from proximity effects that render any sharp corners rounded. We were therefore aware that the only possible solution would be to use a maskless focused ion beam milling technology. Our facility has state of the art equipment to do this kind of work: a helium ion microscope which uses a helium ion beam, and a focused gallium ion beam system. The tightly focused beams can carve extremely fine geometries on graphene making it possible for us to implement our idea.

**ABOVE:** Dr. Zakaria Moktadir and his colleagues at the University of Southampton have produced a graphene field effect transistor with a current on/off ratio three orders of magnitude greater than other state of the art graphene devices
**BOTTOM:** A SEM image of the U-shaped graphene device. The researchers found that sharp bends and corners shut down the current in graphene nanowires

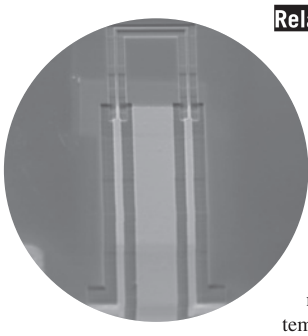
## Moving forward

We are working hard on improving these transistors. We still need to fully understand the mechanism at atomic scale which causes the current to stop flowing in the channel. Also, there are reliability issues to address and the range of gate voltage over which good gain is observed, which is an important parameter in logic circuits, needs improvement. We need to address the transistor behaviour as a function of temperature and the noise levels in the transistor. We are planning to develop building blocks of logic circuits and are engaged in the fabrication of a simple inverter.

## The road to application

As with any new technology, widespread use will probably require a few more years of development. Beside the issues mentioned earlier there are many others that need to be tackled such as design optimisation to reduce transistor area, large scale manufacturing, variability and yield, and fabrication process optimisation. In particular, wafer-scale graphene growth technology needs to be established in order to realise low-cost manufacturing of graphene integrated circuits.

## Related projects



We are actively involved in developing a variety of graphene devices, including single electron devices which allow electrons to flow one by one, quantum information technologies, and graphene photonics. Another promising direction is graphene nanoelectromechanical systems; the goal is to develop sensor systems with extreme charge and mass sensitivities combining graphene resonators with graphene transistors. We are also conducting research into the fundamental properties of graphene-semiconductor and graphene-metal interfaces as this is of crucial importance to build reliable graphene circuits.