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How we made the carbon nanotube transistor

Cees Dekker recounts how his team built the first room-temperature transistor based on a single carbon nanotube.

Cees Dekker

What if, instead of using conventional top-down silicon electronics, transistors could be built from the bottom up using single organic molecules as the switching elements? This idea, which became the basis of today's field of molecular electronics, first emerged in the 1970s. It was only in the 1990s, though, when nanotechnology had advanced to a level where single molecules could be manipulated, that the first experimental devices began to appear.

In 1993, as a young and eager associate professor at Delft University of Technology, I had initially focused the research efforts of my group on measuring the electrical conductance of a single conducting polymer molecule. Within two years, we had created a device in which a single wire of a phthalocyaninepolysiloxane polymer was connected between two closely spaced metal nanoelectrodes. There was one problem though – we did not observe any measurable electrical conduction from the single polymer molecules. We concluded that at the single-molecule level, conducting polymers were not actually such great conductors, which was quite disappointing. We thus broadened our view to try to find more promising molecules.

Back in 1991, Sumio Iijima of the NEC Corporation had reported the synthesis of carbon nanotubes – micrometre-long structures made from graphitic sheets that are seamlessly rolled up into tubes with diameters of around one nanometre. Excitingly, bandstructure calculations suggested that these nanotubes could exhibit metallic band conduction. This would be a significant advantage over the conducting polymers that we had explored, which were, in fact, disordered semiconductors offering merely some variable-range hopping conductivity. Unfortunately, for years after Iijima's report, the production of clean nanotubes was cumbersome. In 1996, however, the group of Richard Smalley at Rice University managed to produce single-walled carbon nanotubes at high yield. Shortly after learning of this, I contacted Smalley, and we decided to join forces in order to measure the transport through a single carbon nanotube molecule.

This yielded a breakthrough. Within only a few months, we were able to measure transport through an individual single-walled carbon nanotube. Based on low-temperature experiments by a brilliant PhD student in my group, Sander Tans (now a valued colleague professor at Delft University of Technology with an active research lab at AMOLF in Amsterdam), we showed that carbon nanotubes were genuine quantum wires with very long (micrometres) electronic coherence lengths – confirming theoretical predictions of metallic behaviour. Around the same time, the group of Paul McEuen, who was then based at the University of California, Berkeley, showed similar results on ropes of bundled nanotubes. And this was only the start. Intriguingly, depending on the wrapping angle, nanotubes can come in metallic or semiconducting variants, a prediction that we and Charles Lieber's group at Harvard University independently confirmed using scanning tunnelling spectroscopy experiments.

At this time, we also realized that it should be possible to use a single semiconducting carbon nanotube to make a transistor – and we set out to make it. We stretched individual semiconducting nanotubes across metallic electrodes and used the underlying silicon substrate as a gate electrode – establishing the basic three-terminal layout of a field-effect transistor (Fig.1). Gratifyingly, the current–voltage curves showed very significant modulations with gate voltage, even at room temperature, which was consistent with band bending in a ~0.6 eV bandgap semiconducting nanotube. Impressively, this first data showed that the conductance could be modulated by six orders of magnitude by changing the gate voltage. The results of this work – a room-temperature transistor made from a single carbon nanotube molecule – were published in *Nature* in May 1998. In the final sentence of the paper we also remarked that it was quite striking that it seemed possible to qualitatively describe the ultra-small nanotube device by the same semiclassical models that are used for devices in today's computer industry.

Our work was quickly followed up by others, most notably by Phaedon Avouris and colleagues at IBM's T. J. Watson Research Center in New York, who in October 1998 published their findings on transistors made from single- and multi-walled carbon nanotubes in *Applied Physics Letters*. Many related developments followed, where my group established different transistor variants such as single-electron transistors at room temperature, intramolecular nanotube junctions that acted as rectifying diodes, and coupling multiple transistors into small proof-of-principle electronic circuits for digital logic operations with logic gates, AC ring oscillators, and the like. In 2001, the latter work was included in the flurry of new results on nanoelectronics that was selected as the 'Breakthrough of the year' by the journal Science.

In the years following these discoveries, my research interests shifted to biophysics and nanobiology, and I became less involved in the continuing development of carbon nanotube electronics. The focus of many researchers in the field also shifted to graphene (where, funnily enough, the first graphene ribbons were described as 'nanotubes that are cut open along their length') after the discovery of the two-dimensional material in 2004. But carbon nanotubes have remained a research topic of considerable interest to many. Indeed, the outlook on using carbon nanotubes to build practical devices, in areas such as RF electronics, digital electronics, and flexible electronics, remains bright.

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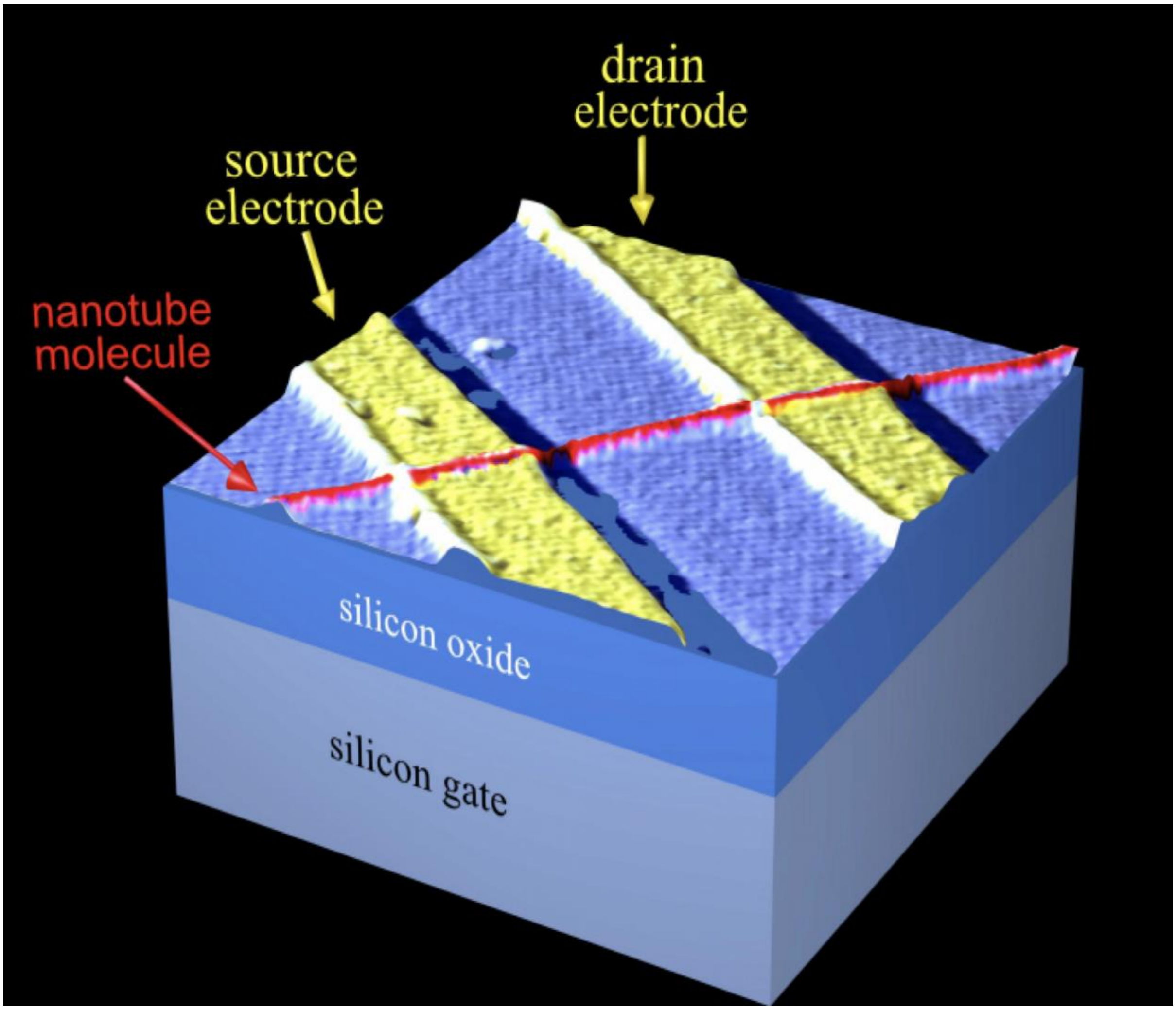
Figure 1. The first carbon nanotube transistor. A three-dimensional rendering of an atomic force microscopy image of the device. The conductance of an individual semiconducting carbon nanotube (red) that is connected to source and drain nanoelectrodes (yellow) can be modulated by a voltage on the silicon back gate (light-blue bottom) – creating a single-molecule field-effect transistor that operates at room temperature.


drain
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