CARBON-BASED ELECTRONICS

Better radio-frequency transistors with nanotubes

Arrays of carbon nanotubes can be used to build radio-frequency transistors with a higher operating frequency and better linearity than silicon technology.

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Radio-frequency (RF) transistors are used to amplify and switch high-frequency electronic signals and are a key component in wireless communication systems. They have historically been dominated by III–V semiconductor technologies: primarily InP and GaAs high-electron-mobility transistors (HEMTs). However, the market for silicon metal–oxide–semiconductor field-effect transistors (MOSFETs) has increased drastically since around 2000, when improved performance due to decades of device scaling finally qualified them as useful RF switches and amplifiers. Compared with III–V transistors, silicon RF MOSFETs offer higher levels of integration with logic circuits at drastically reduced cost[1]. They have made wireless-communication devices economically accessible even in the developing world and thus have had a profound effect on our economy and society. However, the silicon transistors have intrinsic limitations in terms of speed and linearity. As a result, they are increasingly inadequate as operating bands migrate to millimetre-wave frequencies for next-generation high-bandwidth applications such as 5G, 60 GHz Wi-Fi and WirelessHD[2]. Writing in *Nature Electronics*, Christopher Rutherglen and colleagues now show that carbon nanotube arrays can be used to build RF transistors with higher operating frequency and better linearity than silicon technology, and with a process that is scalable to wafer-scale manufacturing[3].

Carbon nanotubes have long been considered a promising material for building RF transistors and circuits due to their exceptional intrinsic properties. Compared with single-crystalline silicon, carbon nanotubes have significantly higher mobility. This means electrons can move much faster under the same applied electric field, which translates to faster

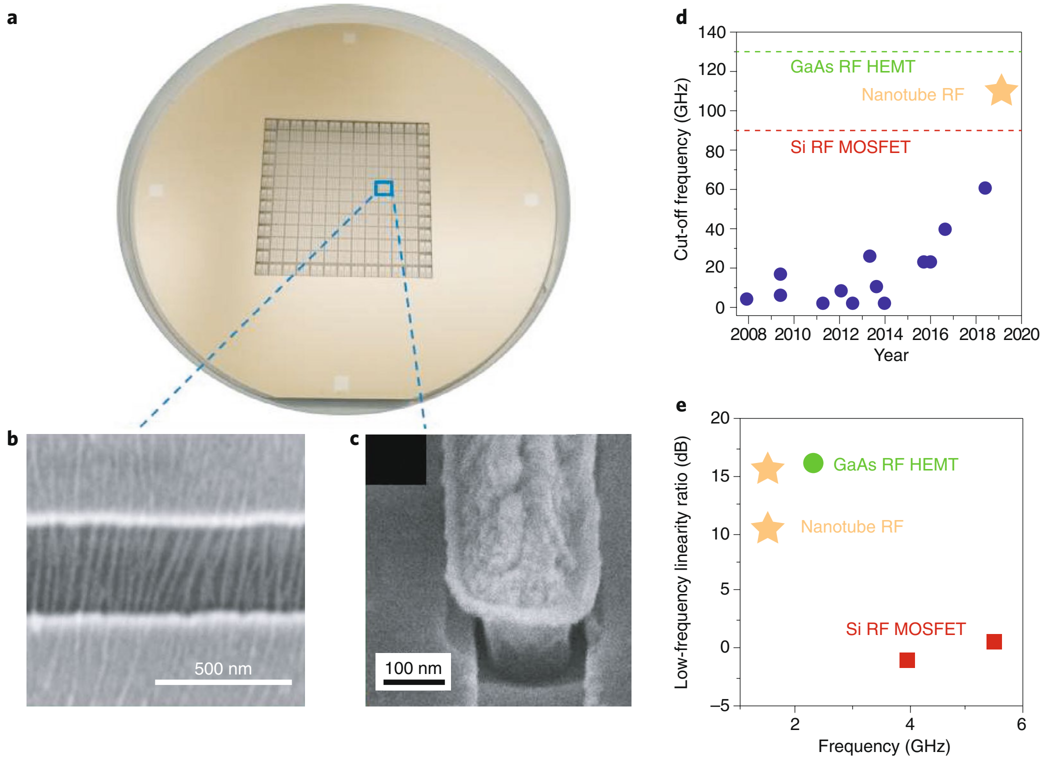

Fig. 1 | **Nanotube RF transistors. a**, Optical photograph of nanotube RF transistors fabricated by Rutherglen and colleagues in the form of a 7 × 7 array of dies on a 100 mm wafer. **b**, Scanning electron micrograph showing the nanotube arrays in the channel. **c**, Tilted view of the T-gate with increased head and height dimensions to minimize parasitics. **d**, The improvement in cut-off frequency of nanotube RF transistors during the past decade (blue circles), up to the devices developed by Rutherglen and colleagues (orange star), which can outperform silicon RF MOSFETs (cut-off frequency of 90 GHz; red line) and approach GaAs RF HEMTs (130 GHz; green line) at the same 100 nm gate length. **e**, The linearity figure of merit of the nanotube RF transistors (orange stars) also exceeds that of silicon RF MOSFETs (red squares) and is on par with GaAs HEMTs (green circle). Figure adapted from: **a**–**c**, ref. [3], Springer Nature Ltd.

transistor switching speed. The nanoscale size of a nanotube also leads to favourable electrostatics in scaled devices, which allows further improvements in speed through shortening the travel distance of electrons within the transistors without inducing detrimental short-channel effects. Moreover, the one-dimensional charge transport within nanotubes ensures an intrinsically linear amplification of input signals. Linearity is essential for wireless communication, as nonlinear response of input power will distort the information encoded by amplitude modulation, diminish dynamic range and degrade the signal-to-noise ratio. Lastly, high-quality nanotubes can be deposited on top of silicon wafers at room temperature without any lattice-matching requirement. As a result, and similar to silicon RF MOSFETs, nanotube RF transistors can be readily integrated with silicon digital circuits in a system-on-chip architecture on a common substrate, which is a critical advantage compared with III–V HEMTs. However, despite these intrinsic capabilities, their actual performance has lagged behind that of the incumbent silicon and III–V technologies due, principally, to parasitic resistance and capacitance.

To build nanotube RF devices that can outperform their silicon-based counterparts, there are three main issues that need to be addressed. First, nanotubes are typically produced as a mixture of semiconducting and metallic species, and the metallic nanotubes have to be effectively removed otherwise the power gain will be severely degraded (this is an intrinsic problem for graphene RF transistors). This issue has been essentially addressed with various nanotube-sorting techniques developed in the last decade, from the density-gradient ultracentrifuge to selective extractions[4]. Second, the enriched semiconducting nanotubes have to be organized into high-density aligned arrays so that the overall device capacitance is dominated by the intrinsic gate capacitance rather than parasitics. Third, the contact resistance between the nanotube and the metal electrodes, the resistance of the gate electrode, and the parasitic capacitance between the gate and the drain electrodes, all have to be minimized. Rutherglen and colleagues — who are based at Carbonics, the University of Southern California and the National Center for MEMS Technologies of Saudi Arabia — have made significant advances in both of these unresolved issues.

To fabricate their nanotube arrays, the researchers used an established floating evaporative self-assembly process, which they modified in order to eliminate the bare substrate regions between the aligned bands of nanotubes but still maintain high linear densities of 40–60 aligned nanotubes per micrometre on a wafer scale (Fig. 1a,b). Removing these bare regions is essential as they only contribute to parasitic capacitance. They also optimized the fabrication flow with the purpose of preserving a clean nanotube surface before metallization, which improves the nanotube/metal interfaces, and they redesigned the geometry of the gate electrode, using a taller and wider T-shaped structure (Fig. 1c). The accumulative result of these efforts, compared with the previous best nanotube RF transistors, was that the device channel transconductance was increased by 90%, and the total series resistance decreased by 30%, the gate resistance by 90% and the parasitic capacitance by 30%. These improvements helped them reach a remarkable technology milestone: nanotube RF transistors that outperform their silicon competitors in both frequency and linearity without any de-embedding (Fig. 1d,e). Without any de-embedding, which indicates that the numbers reported here are not processed after measurement to remove the impact from parasitics, is important as it means that these nanotube RF transistors can beat comparable silicon devices in practical scenarios, rather than just in terms of their 'intrinsic' channel properties. The prospect of rapid progress starting from here is significant, with techniques capable of further increasing the nanotube density and reducing the contact resistance becoming available in recent years[5,6].

The excitement around nanotubes as the 'next silicon' began over 20 years ago. We are now, finally, close to a tipping point in which nanotubes become a serious competitor to silicon in almost all areas of microelectronics, from logic chips[7] to wearable thin-film electronics[8], and from RF transistors[3] to analogue devices[9]. It is especially encouraging to see that the current resurgence of nanotube electronics is led by researchers in industry, from established companies such as IBM and Analog Devices[8–10] to start-ups such as Carbonics[3], despite the fact that interest from academia has diminished. This indicates that the private sector has seen enough maturity and opportunity in carbon nanotubes that they are willing to bet on the future of the technology. However, assistance from the public sector is still essential in order to maintain momentum for nanotube electronics to safely traverse the last miles in the valley of innovation death. ❐

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