focused surveys of regulatory-gene expression may help to identify temporal cascades in the mammalian nervous system. ■

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ELECTRONICS

The road to carbon nanotube transistors

Purifying and positioning carbon nanotubes are challenges for the synthesis of electronic devices based on these nanomaterials. Recent advances in such areas reveal trends that are beating an exciting path towards transistor technology.

AARON D. FRANKLIN

For nearly five decades, scientists and engineers have managed to drive revolutionary technology by shrinking silicon transistors, the building blocks for all computing. Now transistors are approaching fundamental roadblocks that mean the devices cannot still be fashioned from silicon if they are to become any smaller. Researchers are therefore looking for materials to replace silicon. The road to producing transitors from single-walled carbon nanotubes (CNTs) — one of the most promising options — has been hedged about by the difficulties of purifying and controllably positioning these tiny molecular cylinders, which have a diameter of about 1 nanometre. Writing in *Nature Nanotechnology*, Jin *et al.*[1] report a method for obtaining arrays of highly purified semiconducting CNTs. This result, when considered with other advances in purifying and placing CNTs, suggests a promising future for CNT-driven electronics.

The motivation for pursuing a computing technology based on CNT transistors includes their ability to operate at low voltages[2] (saving chip power) and their exceptional performance in devices in which the length of the current-carrying CNT channel is less than 10 nanometres[3]. Because CNTs can be metallic or semiconducting, isolation of purely semiconducting nanotubes has been of great concern. For high-performance logic applications, which would require billions of transistors integrated on a chip, the impurity concentration of metallic CNTs would need to be less than 0.0001%. With statistical analyses indicating that 33% of all CNTs are metallic, this is a daunting target.

Jin and colleagues have managed to achieve the selective removal of metallic CNTs from an array of such nanotubes on a chip without damaging the semiconducting nanotubes. Starting with a parallel array of long CNTs, the authors coat the substrate supporting these nanotubes with a special organic thin film (a resist) that is sensitive to thermal fluctuations. Therefore, when a nanotube conducts an electric current, heat is dissipated (a process known as Joule heating), locally breaking down the resist to create a small trench that exposes the nanotube. This useful thermophysical behaviour led the researchers to dub the 25-nm-thick resist material a ‘thermocapillary resist’. When an electric field is applied to a portion of the CNTs, the semiconducting nanotubes are electrically switched off (blocking current flow), leaving only the metallic CNTs to carry electrons. Thus, only the metallic CNTs are exposed in resist trenches and they can be removed using an oxygen plasma.

The advantages of this approach include high selectivity for metallic CNTs, a lack of specificity for nanotube diameter and removal of the entire length of unwanted CNTs — previous methods have failed in one or more of these categories. The use of electromagnetically induced Joule heating may eliminate the

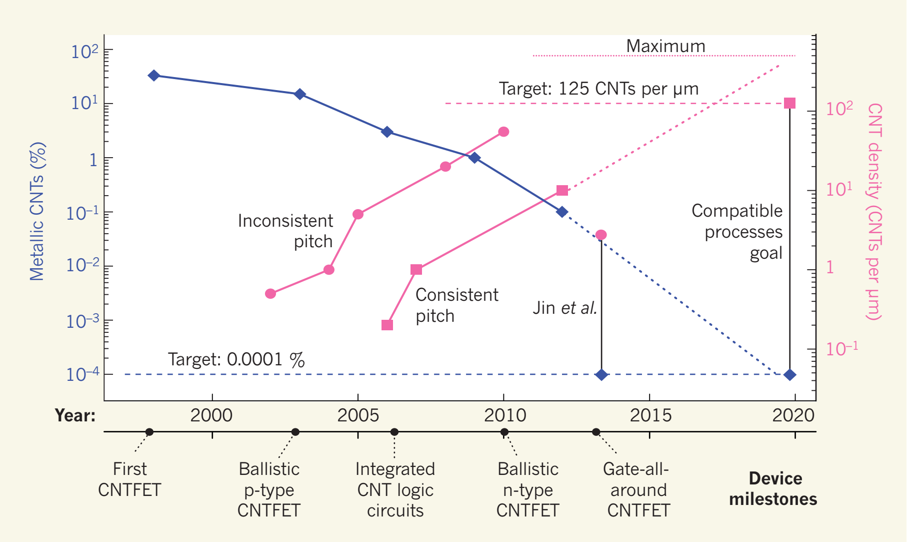

Figure 1 | Targets for carbon nanotube (CNT) transistors. The graph shows the progress in CNT transistor technology since the first demonstration of a CNT field-effect transistor (CNTFET) in 1998. The purity of semiconducting CNT material is plotted in terms of percentage of metallic CNT impurity. The placement of CNTs at a certain density is shown for both consistent and inconsistent pitch (distance) between CNTs, with the target of 125 CNTs per micrometre specified, along with the maximum of 500 CNTs per µm obtained when the CNTs are packed together without a gap between them. Trends in both purification and placement over the past decade suggest the ability to meet their targets before 2020, provided the scientific effort continues (dotted-line trajectories). Jin *et al.* introduce[1] a superb purification technique that is combined with a modest density of CNTs at an inconsistent pitch. Final approaches for achieving both less than 0.0001% of metallic CNTs and a CNT density of more than 125 CNTs per µm with consistent pitch must be compatible.

need for metal electrodes to create current flow in the metallic CNTs.

This impressive advance is best considered in light of the ultimate targets for CNT transistors. From an industry perspective, CNTs are among the most viable options for a transistor technology involving minimum device-feature sizes of less than 7 nm, which is slated for production by the early 2020s. There have been many breakthroughs in the isolation of semiconducting nanotubes dispersed in a solution[4], leading to promising progress that is on track to yield the target purity of 0.0001% by 2020 (Fig. 1). However, a challenge with all solution-based processes is that they must be compatible with a strategy for positioning the CNTs. The thermocapillary-resist approach of Jin *et al.* is encouraging because it works on CNTs that are already positioned in aligned arrays — although improvements are needed to thin the resist and shrink the resulting trench widths (at present, about 250 nm) to be compatible with a higher CNT density. The authors' technique is a superb approach for applications that do not require very high CNT placement density, such as thin-film transistors, which drive displays, and could potentially lead to high-performance CNT transistor technology.

In a technological application, each transistor will require several parallel CNT channels to drive the required current. Therefore, the CNTs must be placed at a small pitch (distance between CNTs) to maximize the current per transistor width. CNTs grown on quartz substrates are excellent for yielding[5] parallel nanotubes at a density of up to 55 CNTs per micrometre. However, they do not provide consistent pitch, which is essential for achieving a high density of integrated devices in which the number of CNT channels per device is constant.

In the mid-2000s, it was shown that CNTs could be coated with certain molecules to tune their attraction to different surfaces[6]. This attribute has been exploited[7] most recently to boost the density of nanotubes placed at a controlled pitch to 10 CNTs per μm. As was the case for the trend in increasing purity of semiconducting CNTs, progress in increasing nanotube density with a regular pitch indicates that the baseline target of 125 CNTs per μm should be attainable before 2020 (Fig. 1).

We have known for years that a silicon-based device will not be able to provide the necessary performance at the dimensions desired for 2020 technologies[8]. Although the postulated trajectories shown in Figure 1 indicate that CNTs can be ready by this time, without substantial effort by the scientific community these trends will undoubtedly flatten. Neither of the required targets is fundamentally impossible, yet neither is possible without sustained, even increased, global scientific effort to yield more discoveries like those of Jin and colleagues. Some 10 years of data suggest that, with enough effort, this News & Views article could be viewed on an electronic device driven by CNT transistors before the end of the next decade. In short, the road is before us — will we take it? ■

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CELL SIGNALLING

Nutrient sensing lost in cancer

Cells can sense and respond to fluctuations in nutrient availability. Mutations that disrupt such lines of nutrient communication with the cellular growth machinery seem to contribute to the uncontrolled growth of cancer cells.

SUCHITHRA MENON & BRENDAN D. MANNING

Various signals, including those stemming from nutrients such as carbohydrates and amino acids, tightly coordinate cell growth. These signals can be altered in disease states, such as obesity and cancer. Reporting in *Science*, Bar-Peled *et al.*[1] identify a protein complex called GATOR that is crucial for linking nutrient sensing by the cell to the control of cell growth. They also find that this complex is disrupted in some cancers, hinting at a mechanism by which cancer cells disconnect their growth from normal growth-control signals.

Cells monitor nutrient levels through both systemic and local lines of communication. The systemic signals reflect the nutrient status of the whole organism and come in the form of secreted factors, such as the hormone insulin, which can travel to all parts of the body. Local signals come from nutrients within cells, because cells closely monitor their own levels of glucose, amino acids and other nutrients or their metabolic products.

One component of the cellular nutrient-detection system is the protein complex mTORC1, which senses both systemic and local nutrient signals. Under nutrient-rich conditions, mTORC1 is activated to promote the conversion of nutrients into cellular building blocks — proteins, lipids and nucleic

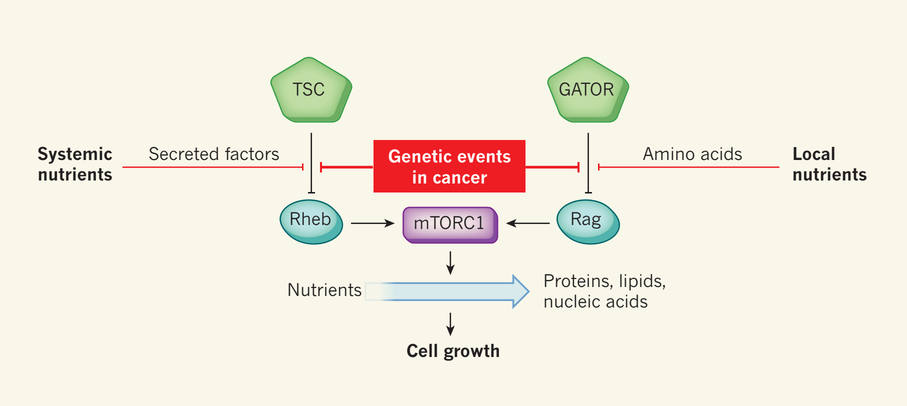

Figure 1 | Nutrient sensing and mTORC1. The protein complex mTORC1 senses systemic and local levels of nutrients through two parallel regulatory circuits that control Rheb and Rag proteins. Secreted factors such as insulin relay systemic nutrient status to cells, initiating pathways that relieve the inhibition of Rheb by the protein complex TSC. Bar-Peled *et al.*[1] report that the GATOR protein complex inhibits Rag proteins to signal local (intracellular) shortage of amino acids. In the presence of nutrients, Rheb and Rag proteins act together to induce mTORC1 activation, which results in the conversion of nutrients into proteins, lipids and nucleic acids — macromolecules that are required for cellular growth. In cancer cells, genetic changes can disrupt these two regulatory circuits and activate mTORC1 independently of nutrient availability.