NANOFABRICATION

Pristine quantum devices on demand

A technique combining direct nanotube transfer with scanning probe microscopy can be used to create ultraclean one-dimensional electron systems in suspended carbon nanotubes.

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Carbon nanomaterials such as carbon nanotubes[1] and graphene[2] are low-dimensional materials that can have defect-free lattices over microscopic length scales, which is a feature that only a few other nanomaterials can offer. Despite the excitement that these materials have generated in the condensed-matter physics community due to their potential as playgrounds for quantum transport study, the creation of ultraclean carbon nanotube devices remains challenging. Writing in *Nature Nanotechnology*, Shahal Ilani and co-workers at Weizmann Institute of Science and Harvard University have now shown that pristine carbon nanotube quantum devices can be created by using a combination of direct nanotube transfer and scanning probe microscopy[3]. These devices exhibit highly tunable electronic characteristics and can have complex architectures.

Most carbon nanotube devices are fabricated by post-growth processing (Fig. 1a), where nanotubes are first grown on a device substrate, then lithography is carried out to define the functional devices[4]. Although this method is widely used, nanotubes are inevitably contaminated by organic residues from the lithography and solution processing steps, resulting in electronic disorders in these quantum systems. To eliminate post-growth contamination, direct chemical vapour deposition synthesis of carbon nanotubes on metal electrodes has also been developed[5]. However, due to the lack of control over carbon nanotube growth yield and orientation, quantum devices with complex electrostatic gating schemes are not possible with the approach. More recently, a one-step direct-transfer technique has been developed to fabricate pristine nanotube devices (Fig. 1b). In this approach, suspended nanotubes, synthesized on the growth substrate, are aligned and directly transferred onto a pre-patterned device substrate with no further lithography needed[6]. This technique has provided some of the cleanest samples so far[7], but it is intrinsically random and offers low yield.

Ilani and colleagues were able to deterministically create nanotube devices with ultralow disorder with the help of scanning probe microscopy manipulation. In particular, the researchers designed and fabricated electrical circuits with complex gate structures directly on the cantilever of a scanning probe microscope. On a separate growth chip, they synthesized long parallel nanotubes suspended over wide trenches. The scanning probe microscope was then used to insert the cantilever into a chosen trench and 'mate' it with a nanotube. Unlike previous direct-transfer techniques, this process enables *in situ* transport measurements, which can be used to ensure the electronic cleanliness of the transferred nanotubes.

With the technique, Ilani and colleagues create nanotube devices with complex configurations that could have up to 7 gates in a single suspended nanotube. Very high mirror symmetry in transport spectra confirmed negligible electronic disorder. With a 5-gate device, they showed that electrons could be localized at any position along the nanotube by engineering one-dimensional electrostatic potential. In addition to these functionalities, they also demonstrated the capability of multi-tube devices with independent gate control by placing multiple nanotubes at chosen separations (Fig. 1c). This deterministic nanoassembly is enabled by the scanning probe manipulation and expands the reach

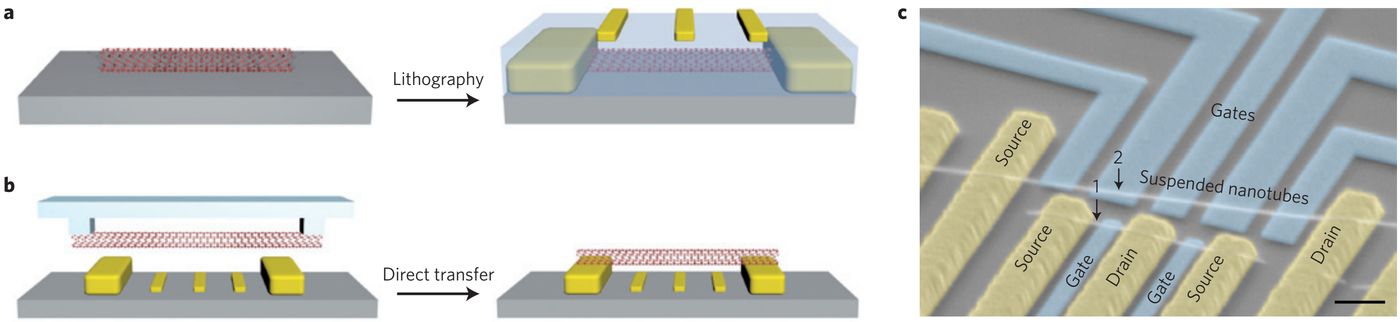

Figure 1 | Deterministic creation of ultraclean and locally tunable carbon nanotube quantum devices. **a**, Conventional nanotube devices are fabricated by post-growth lithography and are subject to electronic disorders due to processing-related defects and contaminants. **b**, A direct-transfer technique can suspend pristine carbon nanotubes over pre-designed electrodes and eliminate contaminations from post-growth lithography. **c**, The combination of direct transfer and scanning probe microscopy allows the deterministic creation of ultraclean and locally tunable one-dimensional electron systems with complex architectures in suspended carbon nanotubes, such as the double-tube device described here[3]. The first nanotube is suspended over 5 gate electrodes for local electrostatic tuning. The second nanotube is placed, by design, adjacent to the first one with independent gate control, yet it is electrostatically coupled to the first nanotube. It can serve as a local single electron detector for interrogating the one-dimensional electron systems. Scale bar, 300 nm. Panel **c** reproduced with permission from ref. 3, © 2013 NPG.

of direct-transfer techniques, allowing the realization of locally tunable and coupled one-dimensional electron systems.

It is unlikely that this nanoassembly technique could be scaled up for the large-scale production of nanoelectronic circuits. However, it could be an appealing solution for condensed-matter physicists who are longing for ultraclean and perfect one-dimensional electron transport test beds. Moreover, the multi-tube capability offers the intriguing possibility of integrating local detectors for electromechanical and quantum measurements. Integrating magnetic fields into the existing technique could be straightforward, and the degree of complexity offered by these devices could lead to new experiments for electron spin-based quantum information science using carbon nanotubes. Furthermore, the technique developed by Ilani and colleagues could be used to fabricate pristine low-dimensional nanosystems in other materials, including one-dimensional semiconductor nanowires and two-dimensional atomic crystals such as graphene and monolayer MoS_2. ❐

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QUANTUM COMPUTING

Atomic clocks in the solid state

Experiments on Bi-doped silicon demonstrate the existence of atomic clock transitions that can be used to enhance the coherence of solid-state qubits.

Sven Rogge and Matthew J. Sellars

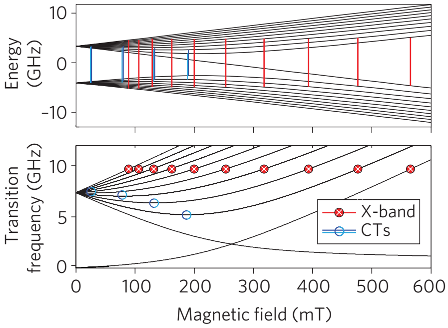

Figure 1 | Magnetic field dependence on the energy of the Si:Bi spin system. At high magnetic field, the transition frequency varies linearly. At low magnetic field there are regions where both the spin-down and spin-up levels are close to being independent of magnetic field, allowing for a transition frequency that is almost independent of magnetic field, the clock transition (CTs; blue). In contrast, the conventional X-band transitions occur at a fixed frequency in the linear regime (red). Figure modified with permission from ref. 1, © 2013 NPG.

Quantum computing has the potential to solve problems that cannot be tackled in a realistic time using a conventional computer. Examples are the factorization of large numbers or the simulation of large molecules. The basic element of any type of quantum information processing, including quantum computing, is the qubit, which is usually a two-level quantum mechanical system. A system that can be used as a qubit is the spin of an impurity atom in a crystal. A great deal of effort is currently being made to realize qubits in the solid state, as they offer the potential of long coherence times and to be controlled by electric gates. The main problem, however, with the realization of reliable solid-state qubits is that their quantum state tends to be disturbed by their surrounding environment, for example the nuclear spins in the host crystal. In technical terms, the qubit is said to lose its quantum coherence. Now writing in *Nature Nanotechnology*, Gary Wolfowicz and co-workers demonstrate the possibility of extending a technique that is used in the field of atomic clocks to spin qubits in silicon, which allows them to drastically increase the time during which the quantum information is preserved[1]. The authors — who are based at institutes in the UK, the US, Germany and Canada — carry out electron-spin-resonance experiments on an ensemble of bismuth donors, which represent spin qubits, in silicon. In their solid-state experiment they use a so-called clock transition[2] that has been developed for frequency standards based on optical transitions of atoms in vacuum. The aim of the frequency standard is to have a stable transition energy that acts as an ultra-precise clock. To achieve this, a transition is chosen such that it is as independent as possible from external parameters such as the magnetic field. Solid-state electron-spin-resonance experiments are typically carried out at fixed microwave frequencies. Wolfowicz and colleagues chose a different approach and selected a range of magnetic fields in which the transition is insensitive to small variations of the magnetic field. A strong source of decoherence for a spin solid-state qubit in silicon is represented by the fluctuation of the local magnetic field due to continuous flips of the nuclear spins of nearby ^{29}Si atoms. There are complex dynamical decoupling techniques[3] that take advantage of controlled rotations of the qubit to counteract this dephasing mechanism. However, this is usually achieved through microwave pulses that tend to introduce other types of dephasing, and the best option remains to simply decouple the qubit from its environment. The origin of the clock transition for Bi in silicon can be evinced from Fig. 1, which shows the energy of the Bi nuclear and electron spin system as a function of magnetic field. The electron spin resonances occur due to transitions between the spin ground and excited states that are driven by microwave radiation. At zero field only two levels are present, which evolve into the two linear Zeeman branches