templates[29]. For interconnect wiring, a number of approaches exist that go beyond current ultraviolet (UV) or electron-beam lithography. For example, wiring can be nano-imprinted with a resolution limit of more than 10 nm[86], realized with SWCNTs, or "nanostencilled"[87] in high vacuum by using movable shadow masks and apertures in cantilevers or a thin silicon membrane when depositing the metallic wires from a source of metal atoms and/or molecules. In addition to being a resist-free, ultraclean nanolithography technique, nanostencilling is a parallel process that allows the simultaneous use of several thousand apertures. Arrays of electron-beam microcolumns are also being developed for parallel nanolithography technology with a resolution of about 10 nm (ref. 88). The array provide low-voltage electron-beams and increase the throughput, with one microcolumn being responsible for each HME circuit or MME circuit interconnection. The accurate placement of molecules in the appropriate position and orientation to form a device, or building of a small circuit with a few SWNTs[89], is readily achieved through molecular manipulation using scanning-probe microscopy (SPM). But turning this approach into a parallel process will most probably involve patterning of the molecules on surfaces using 'wet' methods, such as self-assembly, combing, cantilever techniques, nanostamping or nanostencilling. Self-assembly is a particularly attractive strategy because it could, in principle, exploit thermodynamic control to achieve high precision[90], but the overall precision with which complex structures can be assembled through molecular self-organization remains to be investigated. Currently, molecular combing can reach a 40% rate of success in connecting SWCNTs[91] between two electrodes. It relies on the force exerted by a liquid meniscus on the SWCNT adsorbed on the wafer and requires a chemical preparation of the wafer surface, a process accessible to nano-imprinting, but not yet applied to oligomers. Nanostamping uses elastomeric stamps made with a pattern of reliefs on their surface. After 'inking'—a term used to describe the coating of the stamp with molecules—the stamp is contacted to a surface, which allows the accurate reproduction of their area of contact by leaving behind a patterned molecular monolayer in a manner similar to printing[105,106]. It can attain a precision of a few nanometres but requires that surface and gas phase diffusion be controlled. Shadow masks are well adapted for ultraclean processes[87], but suitable molecular sources need to be further developed to take into account the MME circuit requirement towards higher molecular weights. Experiments have already explored the use of nonthermal sublimation methods such as matrix-assisted laser desorption (MALD)[92] or injection of aqueous solutions of molecules into ultrahigh vacuum[81]. The ultimate limits of fabrication will probably require the development of "directed self-assembly" methods, where a finite number of molecules or atoms can be assembled and deposited at predefined locations[93]. Self-assembly, directed by molecular recognition, provides a very efficient means to construct helices, and rack, ladder and grid structures[94], and provided suitable assembly and electronic functions are "pre-installed" into a molecule during synthesis, it may be used for the self-positioning of HME devices or MME circuits.

Quantum machines

The first proposals for molecular electronics appeared in the 1970s, but it is only the appearance of a number of scientific and economic developments that has allowed the recent resurgence of activity in this field. Crucial are advances in nanoscale science and technology, such as new fabrication methods and probes, which enable individual molecules or small numbers of molecules to be connected in a controlled manner into actual test devices. The driving force behind this research is clearly the need for suitable alternative technologies to Si-based CMOS, which is expected to reach its limitations in 10–20 years[71]. Our understanding and concepts of what molecular electronics might look like in the future have changed significantly as a result of all of these factors. In particular, electrode effects and the extreme sensitivity of quantum tunnelling to small atomic motions, and switching behaviour and rotation[95] in single molecules, are good examples of possible new operational methodologies that have appeared in the past five years. Finally, the understanding and control of directed self-assembly techniques, combined with developments in synthetic and supramolecular chemistry, increasingly focus on the notion that molecular devices and machines can be synthesized from first principles. The logical progression of this approach is mono-molecular electronics, which integrates many electronic elements, such as wires, switches, and amplifiers, in a single molecule or individual supramolecular assembly. There are many unresolved issues and opportunities for molecular electronic devices in the areas of architecture where a conventional analysis of a molecular device in terms of the linear superposition of its components appears to be invalid. This may make molecular electronics a prime contributor to the building of nanoscale quantum machines using the power of quantum-state superposition. Indeed, as synergistic and cooperative effects in complex molecular systems are understood and controlled, new electronic devices based on unconventional operating principles might be developed. In short, it seems that applying conventional electronic concepts and approaches will not necessarily be the best way to achieve functional molecular devices operating on a dimensional scale where quantum mechanics dominates. □

1. Aviram, A. & Ratner, M. Molecular rectifiers. *Chem. Phys. Lett.* **29**, 277–283 (1974).
2. Riordan, M. & Hoddeson, L. *Crystal Fire: The Birth of the Computer Age* (W. W. Norton & Company, New York, 1997).
3. Taube, H. The electron transfer between metal complexes: a retrospective. *Science* **226**, 1028–1036 (1984).
4. Patoux, C. *et al.* Long-range electronic coupling in bis(cyclometalated) ruthenium complexes. *J. Am. Chem. Soc.* **120**, 3717–3725 (1998).
5. Davis, W. B., Svec, W. A., Ratner, M. A. & Wasielewski, M. R. Molecular-wire behaviour in p-phenylenevinylene oligomers. *Nature* **396**, 60–63 (1998).
6. Fraysse, S., Coudret, C. & Launay, J.-P. Synthesis and properties of dinuclear complexes with a photochromic bridge: switching "ON" and "OFF" an intervalence electron transfer. *Eur. J. Inorg. Chem.* 1581–1590 (2000).
7. Patoux, C., Coudret, C., Launay, J.-P., Joachim, C. & Gourdon, A. Topological effects on intramolecular electron transfer via quantum interference. *Inorg. Chem.* **36**, 5037–5049 (1997).
8. Delamarche, E., Michel, B., Biebuyck, H. A. & Gerber, C. Golden interfaces: the surface of self-assembled monolayers. *Adv. Mater.* **8**, 719–729 (1996).
9. Mann, B. & Kuhn, H. Tunnelling through fatty acid salt monolayers. *J. Appl. Phys.* **42**, 4398–4405 (1971).
10. Geddes, N. J., Sambles, J. R., Davis, D. J., Parker, W. G. & Sandman, D. J. Fabrication and investigation of asymmetric current-voltage characteristics of a metal/Langmuir-Blodgett monolayer/metal structure. *Appl. Phys. Lett.* **56**, 1916–1918 (1990).
11. Metzger, R. M. *et al.* Unimolecular electrical rectification in hexadecylquinolinium tricyanoquinodimethanide. *J. Am. Chem. Soc.* **119**, 10455–10466 (1997).
12. Gimzewski, J. K., Stoll, E. P. & Schlittler, R. R. Scanning tunnelling microscopy on individual molecules of copper phthalocyanine adsorbed on polycrystalline silver surfaces. *Surf. Sci.* **181**, 267–277 (1987).
13. Eigler, D. M., Lutz, C. P. & Rudge, W. E. An atomic switch realised with the scanning tunnelling microscope. *Nature* **352**, 600–603 (1991).
14. Joachim, C., Gimzewski, J. K., Schlittler, R. R. & Chavy, C. Electronic transparence of a single C_{60} molecule. *Phys. Rev. Lett.* **74**, 2102–2105 (1995).
15. Joachim, C. & Gimzewski, J. K. An electromechanical amplifier using a single molecule. *Chem. Phys. Lett.* **265**, 353–357 (1997).
16. Dorogi, M., Gomez, J., Osifchin, R., Andres, R. P. & Reifenberger, R. Room-temperature Coulomb blockade from a self-assembled molecular nanostructure. *Phys. Rev. B* **52**, 9071–9077 (1995).
17. Reed, M. A. *et al.* The electrical measurement of molecular junctions. *Ann. NY Acad. Sci.* **852**, 133–144 (1998).
18. Reed, M. A., Zhou, C., Muller, C. J., Burgin, T. P. & Tour, J. M. Conductance of a molecular junction. *Science* **278**, 252–254 (1997).
19. Kerguelis, C. *et al.* Electron transport through a metal-molecule-metal junction. *Phys. Rev. B* **59**, 12505–12513 (1999).
20. Bezryadin, A., Dekker, C. & Schmid, G. Electrostatic trapping of single conducting nanoparticles between nanoelectrodes. *Appl. Phys. Lett.* **71**, 1273–1275 (1997).
21. Rousset, V., Joachim C., Rousset, B. & Fabre, N. Fabrication of co-planar metal-insulator-metal nanojunction with a gap lower than 10 nm. *J. Phys. III* **5**, 1983–1989 (1995).
22. Di Fabrizio, E. *et al.* Fabrication of 5 nm resolution electrodes for molecular devices by means of electron beam lithography. *Jpn. J. Appl. Phys.* **36**, L70–L72 (1997).
23. Yanson, A. I., Yanson, I. K. & van Ruitenbeek, J. M. Observation of shell structure in sodium nanowires. *Nature* **400**, 144–146 (1999).
24. Porath, D., Bezryadin, A., de Vries, S. & Dekker, C. Direct measurement of electrical transport through DNA molecules. *Nature* **403**, 635–638 (2000).
25. Tans, S. J. *et al.* Individual single wall carbon nanotubes as quantum wires. *Nature* **386**, 474–477 (1997).
26. Ebbesen, T. W. *et al.* Electrical conductivity of individual carbon nanotubes. *Nature* **382**, 54–56 (1996).