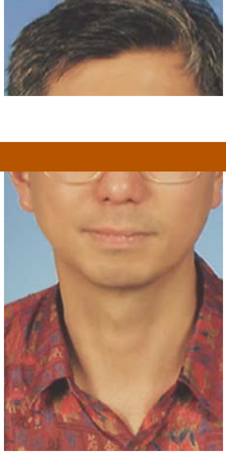

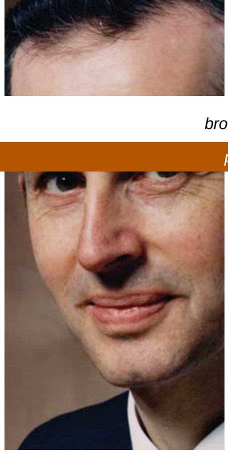

Was Schön ever right?

...Tuck Choy and Marshall Stoneham

A few years ago, Jan Hendrik Schön impressed the world of science with exciting ideas and amazing experiments. Those experiments are believed no more. But were we wrong to admire the ideas at the time, or have we been too ready to turn our backs on novel ideas because they are associated with misconduct?

Schön imaginatively transferred to organics ideas previously established for inorganic systems. If feasible, such proposals would deserve attention. Yet his ideas invoked only a small fraction of the richness of behavior characteristic of organics. After all, for virtually every desirable property of silicon, there is a carbon-based system that outperforms it. True, each carbon-based system will perform much less well in other properties, but one could imagine combinations of carbon-based materials making new and important classes of device possible. Also, the *difficult* is not the same as the *impossible*. Today's standard devices were yesterday's challenges. Neither complementary metal oxide semiconductor (CMOS) systems, in which both *n* and *p* channels are fabricated on a single substrate, nor field effect transistors (FETs), in which the current between the source and drain is modulated by the field from a gate electrode, were ideas easily implemented. High-T_c superconductivity was deemed to be impossible prior to 1987, while today we have low-T_c organic superconductors.

Several of Schön's more promising ideas were based on the field effect, including ambipolar pentacene FETs. What could be the organic counterpart to the inorganic CMOS ambipolar device? Schön's claims for FET and CMOS-like inverters, while apparently unfounded, stimulated work by others. Pentacene does not perform well for several reasons, but the more complex organic PIF or poly(3,9-di-*t*-butylindeno[1,2-*b*]fluorene) proves better. Ambipolar transistors and inverters have been made but they have problems: their high gate voltages (30-40 V) are not compatible with silicon technology and mobilities are low.

Electrostatic control of superconductivity has been sought since the 1960s. Schön hoped to make a superconducting field-effect switch. Electric fields modulate the magnitude of the superconducting electrons' wavefunction, unlike magnetic fields that modulate its phase. A strong electric field modulation effect needs the Debye (Thomas Fermi) screening length to exceed the coherence length. The idea emerged again following the discovery of oxide superconductors, with naturally cautious workers referring to 'modulation' rather than Schön's 'switching'. Even for oxides, the reversible, nonvolatile changes achieved neither zero resistance nor an especially good on-off ratio; energy efficiencies were only of the order of 1% – of significance in dynamic switching. Any scientist working on organic materials will struggle to do as well. Schön retracted his claim for a superconducting field-effect switch. Yet it might be worth exploring C_{60} materials in the just under doped region, since they have qualities closer to the useful range, like mobilities of order 10^{-1} cm^2/Vs.

Another of Schön's dreams extended an organic ambipolar FET to the concept of a light-emitting FET. There seem to be no fundamental objections: at big enough fields, electron and hole injection should be possible. Whether the right balance can be found between light emission and other recombination processes is not clear. The challenge of achieving lasing action and population inversion is still harder. However, the progress in organo-metallic complexes with their superb nonlinear optical properties should continue to stimulate research.

Cyclotron resonance in organics is not easy. The early IBM results for anthracene needed immensely careful sample preparation and characterization. Even then, carrier masses and lifetimes implied mobilities in the 10^2-10^4 cm^2/Vs range. Schön sought a fractional quantum Hall effect (FQHE) in organic semiconductors. Despite significant gaps in our knowledge, the high mobilities seem likely to remain elusive. And, since the claims for FQHE and Shubnikov-de Haas oscillations seem to need mobilities of order 10^5 cm^2/Vs, only an optimist would expect the FQHE to emerge without problems.

Overall, it seems the field effect could yield opportunities. Indeed, one could say it has already provided some novel devices. Ghosh *et al.* describe a flow sensor based on a single-walled carbon nanotube immersed in a flowing liquid [*Science* (2003) **299**, 1042]. No doubt the pursuit of ambipolar FET devices with increased mobility and lower operational voltages will continue in the organic world, further to recent successes [*Nat. Mater.* (2003) **2**, 678]. Organics continue to show surprises. Even the well-known, highly oriented pyrolitic graphite system seems to show the quantum Hall effect and, apparently, can exhibit ferromagnetic and superconducting behavior [*Phys. Rev. Lett.* (2003) **90** (15), 156402]. Perhaps Schön's visions were conservative. As one of us has said [*Nat. Mater.* (2004) **3**, 3], there seems scope for electrons in carbon country.

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