cannot yet replace the Sanger sequencing approach for some of the more demanding applications, such as sequencing a mammalian genome, as it has several limitations.

First, the technique can only read comparatively short lengths of DNA, averaging 80–120 bases per read, which is approximately a tenth of the read-lengths possible using Sanger sequencing. This means not only that more reads must be done to cover the same sequence, but also that stitching the results together into longer genomic sequences is a lot more complicated. This is particularly true when dealing with genomes containing long repetitive sequences.

Second, the accuracy of each individual read is not as good as with Sanger sequencing — particularly in genomic regions in which single bases are constantly repeated. Third, because the DNA 'library' is currently prepared in a single-stranded format, unlike the double-stranded inserts of DNA libraries used for Sanger sequencing, the technique cannot generate paired-end reads for each DNA fragment. The paired-end information is crucial for assembling and orientating the individual sequence reads into a complete genomic map for *de novo* sequencing applications. Finally, the sample preparation and amplification processes are still quite complex and will require automation and/or simplification.

Church and colleagues[9] also recently hit upon the idea of using massively parallel reactions to speed up sequencing, although their method is still only at the proof-of-principle stage rather than being a full production system. They use a similar principle to Rothberg and colleagues[4], that is, sequencing-by-synthesis on a solid support. However, the two approaches diverge in terms of library construction, sequencing chemistry, signal detection and array platform. These differences greatly affect the characteristics and reproducibility of the data, as well as the scalability of the platform. For example, Church and colleagues' method can read paired-end sequences; however, its average read-lengths are approximately a fifth of those generated by Rothberg and colleagues' system. These differences are key factors in determining the sequencing application for which each technique might be most suited.

It may be years before Rothberg and colleagues' system, or other similar approaches[9,10], can tackle all three billion letters of the human genome with the same reliability and accuracy as current methods. Nevertheless, it looks extremely promising, and it is certainly one of the most significant sequencing technologies under development. ■

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DEVICE PHYSICS

Enlightening solutions

Klaus Meerholz

White-light-emitting diodes are becoming increasingly important, but what is the best way to build compact devices possessing high efficiency? Bright prospects are offered by multi-layer organic devices grown from solution.

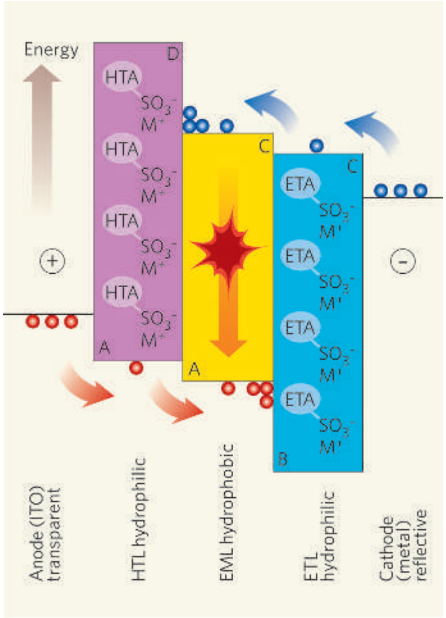

Figure 1 | Cross-section through the multi-layer OLED developed by Gong and colleagues[2]. The staggered height of the layers indicates their different energies; electrons (blue) favour moving to lower energies, whereas holes (red) tend towards higher energies. The emissive layer (EML) is sandwiched between a hole-transport layer (HTL) and an electron-transport layer (ETL) consisting of transport agents (HTA/ETA) containing sulphonate groups (SO_3^-). (M^+ stands for a metal counter-ion.) This structure serves three purposes: first, to facilitate the injection of holes and electrons (A and C) into the emissive layer by reducing the energetic barriers to their passage; second, to enhance the recombination efficiency (formation of excitons) by blocking the passage of one type of carrier (B or D) from the emissive layer into the opposite transport layer through a large step in energy; and third, to avoid quenching reactions of excitons at the electrodes (+/ −). The layers of the OLED are deposited alternately from water or ethanol (HTL and ETL) and from organic solvents (EML). The light emitted through recombination in the EML passes through the transparent anode to the left; the colour of the emission depends on the material or mixture of materials that forms the EML.

Sources of white light are found almost everywhere — in lighting and signage generally, but increasingly as backlights in all sorts of displays, for example in laptop computers or smart phones. The development of organic light-emitting diodes (OLEDs) promises further innovation in the field: such diodes are lightweight, provide high brightness at low power, and can be fabricated on flexible substrates to form thin devices at potentially low production cost[1]. Writing in *Advanced Materials*, Gong *et al.*[2] demonstrate the use of semiconducting electrolytes to grow highly efficient, multi-layer, white-light OLEDs from solution.

The structure of an OLED is quite simple; it uses an organic material that either fluoresces or phosphoresces. (Both processes involve the re-emission of absorbed light at a longer wavelength; in phosphorescence, the quantum-mechanical processes that lead to re-emission are more complex, so the emission is delayed.) The light-emitting material is sandwiched as a thin film, typically 70–100 nanometres thick, between two electrodes. Of these, the anode is typically transparent and the cathode acts as a mirror that ideally reflects any incident photons back towards the transparent side.

When a voltage is applied to the electrodes, positive and negative charges ('holes' and electrons, respectively) are injected into the film and move towards each other, forming a body known as an exciton on meeting. This exciton can become de-excited by emitting a photon, which leaves the device through the transparent anode. Excitons are divided into two categories according to the alignment of the spins of the electrons involved relative to one another: if these are antiparallel, a 'singlet' with a total spin of zero is formed; if they are parallel, the state is a 'triplet' with a spin of one. In terms of quantum mechanics, three-quarters of excitons must be triplets and only one-quarter singlets. The prospect of achieving higher efficiency with OLEDs emitting from triplets has led to the investment of considerable effort[2,3] in their development.

OLEDs are generally produced by one of two routes: the sublimation of small molecules in a vacuum, or the wet-chemical deposition of polymers onto a substrate. Which of these approaches will ultimately survive in a production environment is still a matter of debate. Although the small-molecule approach improved device performance, especially device lifetime, wet-chemical deposition is the more attractive technique for mass production. This is because it allows layers of polymers to be laid down cheaply in a roll-to-roll process using common techniques such as those used for screen and inkjet printing. It is therefore the method of choice for Gong *et al.*[2] and many others.

Multi-layer OLEDs are generally more efficient than single-layer types. In the most efficient OLEDs, the emission layer is sandwiched between a hole-transport layer and an electron-transport layer (Fig. 1). Fabricating such multi-layer structures from solution is challenging (vacuum deposition of small molecules is relatively straightforward). It is crucial to ensure that layers already deposited from solution are totally resistant to the solvents used to deposit subsequent layers, to avoid intermixing.

There are three main ways to do this. The first is to use 'orthogonal' solvents for the individual layers — that is, the solvent used in one deposition does not dissolve any previous layer. For example, the conductive polymer poly(3,4-ethylenedioxy)thiophene (PEDOT), commonly used for OLED anodes, is deposited from an aqueous suspension. After drying, further organic layers can be deposited from typical organic solvents such as toluene without redissolving the PEDOT. A second method is to change the polarity or solubility of the deposited material. An example here is the first luminescent polymer ever discovered, poly(*p*-phenylenevinylene), or PPV (ref. 4), where a polar sulphonium precursor molecule is transformed by heating into a nonpolar polymer that is insoluble in all organic solvents.

A third, highly attractive approach is to introduce several reactive molecular groups into a semiconductor material. These can be polymerized after deposition to yield totally insoluble crosslinked layers, a process that can, in principle, be repeated indefinitely. In recent years, many materials that can be processed from solution and possess the ability to form multi-layers have been proposed, the most promising being oxetanes[5], styrenes[6], dienes[7] and trifluorovinyl ethers[8]. The efficiency of OLEDs at incorporating such materials (most of which are hole-transporters) is in many cases greater than that for reference devices using just PEDOT as anode, or the transparent metal indium tin oxide (ITO).

Gong *et al.*[2] propose an extension of the first, orthogonal-solvent approach. They developed derivatives of two commonly used organic semiconducting materials — the hole-conducting poly(*N*-vinylcarbazole), or PVK, well known from the early days of xerography, and the electron-conducting oxadiazole derivative PBD. The authors achieved this by incorporating into them ionic sulphonate groups, which make the derivatized material soluble in highly polar solvents such as water and ethanol but insoluble in organic solvents. This trick allowed them to create the layers using aqueous or ethanol solution, as the components of the emissive layer of the OLED were totally insoluble in either solvent. (The emissive layer contained a fluorescent polymer emitting green and blue light, doped with a phosphorescent molecule that sends out red light, yielding an overall white emission.)

By alternating deposition from hydrophilic and hydrophobic solvents, Gong and colleagues built a three-layer device (Fig. 1). Because the emissive layer acts as a barrier against the redissolution of the first deposited layer (the hole-transport layer) during the deposition of the third layer (the electron-transport layer), it was of crucial importance that all layers were free of pinholes. The resulting OLEDs produced a luminous intensity of around 10 candelas per ampere of supplied current — around 2.5 lumens per watt. The efficiency of the device is thus among the highest to date for solution-processed white-light-emitting devices[1], and one-and-a-half to three times better than reference devices in which either of the two transport layers was missing.

It might be thought that the introduction of sulphonate groups and the consequent presence of mobile metal counter-ions might impair the device's performance. Certainly, devices using transport layers show slightly increased onset voltages — the minimum supply voltage at which emission will occur. According to Gong and colleagues, this is due to the greater thickness of the device compared with other OLEDs and could thus presumably be improved by adjusting the layer thicknesses, or by using different hole- and electron-transport materials containing sulphonate ions or other ionic groups.

The big question, however, is whether devices based on such sulphonate materials can reach the operating lifetimes necessary for practical applications (typically more than 10,000 hours). The presence of mobile metal ions could cause similar problems here to those seen with electrochemical emissive devices. Although such questions remain unresolved, Gong and colleagues' contribution[2] is a step towards a more flexible, lower-cost source of white light. ■

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50 & 100 YEARS AGO

50 YEARS AGO

The Spirit of Liberty: Papers and Addresses of Learned Hand — The papers and addresses collected in this book range for the most part over fields with which the man of science is concerned rather as citizen than as scientist...Supremely the book testifies to the truth of Judge Hand's contention that there is no substitute for an open mind enriched by reading and the arts, and that the scientific worker who would influence the thought and action of his time must have some acquaintance, the wider the better, with what others have thought and felt in circumstances as near as possible to those of the groups in question...The plea for the open mind and free discussion in which these words occur is much more than championship of dissent and a direct rebuke to the excesses of McCarthyism and secrecy and security procedures: it is an outstanding statement of the case for general education as the basis of a free society.

From *Nature* 17 September 1955.

100 YEARS AGO

At the present time by far the most serious problem which the automobilist has to face is the abatement of the "dust nuisance". A great deal of bad feeling has arisen against the motorist on account of the dust which he too frequently produces, and there is no doubt that there are very good grounds for the irritation which has arisen, particularly in agricultural districts...Although a permanently good road may be made by the use of materials such as Tarmac, and dusty roads may be cured temporarily by various means, yet such measures can be taken only over a small proportion of our roads owing to the cost. In towns and large villages the roads might be suitably treated, but the average motorist seeks the country, and the greater part of the routes which he wishes to traverse will not pay for any special treatment.

From *Nature* 14 September 1905.