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had to be grasped rather than with object pictorial aspects (*18*). Therefore, objects appear to be described in F5 more in motor than in visual terms. Admitting that the basic transformation process is analogous in the various ventral premotor cortex sectors, the fact that in F5 objects are coded in motor terms suggests a similar motor interpetation for space coding in F4.

Finally, the motor interpretation offers a better or at least a more economical explanation for the location of spatial receptive fields around the body. If the visual interpretation were correct, one would have to postulate an ad hoc, complex visual mechanism able to eliminate visual information coming from points outside the peripersonal space. In contrast, the three-dimensional properties of premotor receptive fields are easily accommodated by a motor interpretation. According to this view, movements progressively carve out a working space from undifferentiated visual information. The anatomical basis underlying this process may be represented by the fronto-parietal connections. These connections would constrain motorically the visual parietal neurons, through a visuomotor coupling between visual stimuli and movements directed toward them. The functional properties of bimodal parietal neurons of areas VIP (*19*) and PF (*6*, *20*), both strictly linked to F4 (*21*, *22*), are consistent with this interpretation. The movement-based space (which may be subserved also by other fronto-parietal circuits) becomes then our experiential peripersonal visual space.

The data reviewed above and the hypotheses we discuss are at odds with the traditional view of cognitive sciences that percepts are built from elementary sensory information via a series of progressively more and more complex representations. In contrast, they stress the importance of motor areas and motor-to-sensory pathways for the construction of object and space perception, and the artificiality of constructing a rigid wall between sensory and motor representations. It is interesting to note the closeness of this view, emerging from single-neuron recordings, and the philosophical stance of phenomenological philosophers on space perception. Space is "not a sort of ether in which all things float.... The points in space mark, in our vicinity, the varying range of our aims and our gestures" (Merleau-Ponty) (*23*).

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OPTOELECTRONICS

Stacked Organic Light-Emitting Diodes in Full Color

James R. Sheats

The proliferation of portable electronic devices such as pagers, cellular telephones, personal digital assistants, and hand-held computers has driven designers to search for a new generation of display technology. These portable tools demand something more sophisticated than the simple alphanumeric displays of kitchen appliances yet must be smaller than a full-fledged laptop computer. Although a monochromatic display is adequate for some applications, full color is necessary for many and desirable for most; yet it is not easy to achieve in inexpensive, battery-powered devices. Recently, Shen *et al.* (*1*, page *2009*) described a novel approach to full-color organic electroluminescent (EL) displays that could satisfy this need and demonstrates dramatically the versatility of thin-film organic optoelectronics.

Portable display technology is constrained by the need for low-cost battery-compatible drive voltage, high efficiency, reasonable lifetime, and resistance to the temperature extremes of outdoor or automobile use. Most approaches, such as plasma displays, vacuum fluorescence, and inorganic thin-film electroluminescence, face some combination of these obstacles. Inorganic light-emitting diodes (LEDs) are simply too expensive. As a result, the market has been largely left to liquid crystals (generally without backlighting), which leave much to be desired in the way of viewability.

Organic electroluminescence, a subject with roots in the 1960s, has now reached the point where commercialization of small, pixel-addressed displays seems close to reality (*2*). Device lifetime, a major concern only a few years ago, is now several thousand hours for many systems, and in the tens of thousands for the best; it remains acceptable for temperatures up to at least 60°C or more. Efficiencies are superior to most of the other competitors. A bias of 10 V or less is sufficient to drive a passive matrix-addressed 64 × 256 pixel display, and the voltage drop along the metal and indium-tin-oxide (ITO) lines is acceptable for a display of this size. Drivers with adequate current capacity are available at reasonable (though significant) cost. Thus, despite the difficulties involved in the introduction of such a new technology,

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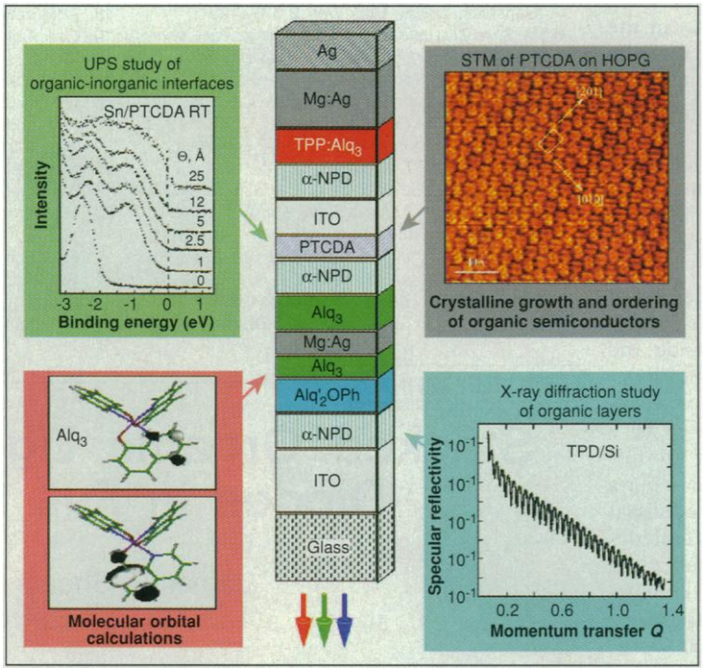
monochrome organic EL displays with a few hundred to a few thousand pixels are likely to appear imminently.

Full color, on the other hand, involves many more difficulties, because of the greatly increased processing complexity. Organic LEDs are made by depositing the active material (either by vacuum evaporation of suitably volatile molecules or by the casting of polymer solutions) on top of an ITO-coated transparent substrate, followed by the evaporation or sputtering of a cathode with a low work function (commonly Mg, Ca, or Al alloys). Usually two or even three organic layers ~500 to 1000 Å thick are needed. To obtain the red, green, and blue required for full color, the material with the desired emission wavelength must be placed at the appropriate pixel location. Shadow masks are not currently considered suitable for manufacturing use.

The first method developed, patented by Kodak (*3*), involves the patterning of tall photoresist walls with two different heights and the evaporation of the three organic EL materials at different angles of incidence (two oblique, in opposite directions, and the final one normal). For each layer, the walls either protect or expose a specific area, depending on the angle. The process control required to ensure the correct coverage is clearly an important issue, and this technique cannot be used with polymers.



How the organics stack up. A multilayer organic light-emitting structure fabricated by Shen *et al.* (*1*). Several examples of fundamental measurements and calculations that can be undertaken on these materials are shown in the insets. UPS, ultraviolet photoelectron spectroscopy; STM: scanning tunneling microscopy. The other acronyms refer to molecules described in Shen *et al.* (*1*). [Data courtesy of S. Forrest, A. Kahn, C. Kendrick, and P. Fenter, Princeton University, and M. Thompson, University of Southern California]

Another concept, originated at Bell Labs (*4*), is to add a multilayer dielectric stack on the other side of the ITO from the organic layers; this stack, along with the metal cathode, forms a resonant cavity with a narrow bandpass that can be selected by varying the optical thickness of the cavity. With an emitting layer that has a very broad (essentially white) spectrum, the three primary colors can be obtained by patterning different dielectric thicknesses. Again, close control of the etching process is required, but the technique is promising.

The third "conventional" method, favored by Idemitsu Kosan, is to use only blue light emitters (*5*) and to place suitable fluorescent dyes in front of the red and green pixels so that the blue light is fully absorbed and re-radiated at the desired color. The optical efficiency of this process can be close to 100%, but blue emitters have so far not proven to be as stable as those in the green regions and are slightly less efficient.

Shen *et al.* have introduced another method (*1*). In their technique, the layers that emit different colors are stacked on top of each other along with the required electrodes to independently address each layer. This approach makes two extreme demands on the materials science: It is necessary to deposit ITO on top of an active organic layer and to provide a transparent, low–work function cathode. The first requirement is filled by a thin layer (100 Å) of hole-transport layer consisting of a highly crystalline perylene derivative (PTCDA in the figure), which is not harmed by the ITO sputtering. The second requirement is filled by an equally thin layer of Mg (110 Å).

The advantages of this approach in processing are that the patterning steps and process control requirements are now essentially the same as for a monochrome display. Adequate thickness control and defect density in the ultrathin layers is yet to be demonstrated, and the effect of metal thickness on conductance is a concern with passive addressing; nevertheless this highly original scheme is certainly promising.

Perhaps most interesting, however, is the remarkable materials science that has gone into the fabrication of the 13-layer stack (see figure). This assembly includes amorphous, highly crystalline, and semicrystalline morphologies, both organic and inorganic in composition. In conventional solid-state device fabrication, elaborate care must be taken to achieve lattice matching between successive layers; the possible combinations of materials are quite limited. Molecular organic semiconductors tend to take on their quasi-equilibrium morphology independently of the substrate (PTCDA is highly ordered even when deposited on amorphous polymers). Equally noteworthy is the robustness of organic molecules, which might have been expected to readily degrade under such conditions as evaporation and bombardment by sputtered atoms. Recently, it has been also shown that metals can be sputtered onto poly (phenylene vinylene), an EL polymer, yielding devices with very good efficiency and lifetime (*6*).

Organic materials have for some years been used as active materials in xerography, where a molecule must typically transport about 10^5 charges during the life of the drum. For an EL display running at the expected brightness for 10,000 hours, approximately 10^{10} charges will be transported by each molecule or conjugated polymer segment. It is thus a significant advance to see organics achieving commercial potential in the solid-state world, where long-term reliability is taken for granted. At this point, perhaps the greatest hurdle is no longer in basic science, but in manufacturing: Can it really be done as inexpensively as hoped? At the same time, the chosen methods cannot compromise the operating quality. The pace of developments today suggests that we may know the answer in a few years.

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