High-performance devices using organic semiconductors

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New device architectures overcome the limitations of organic semiconductors and could accelerate development of large organic LEDs.

Synthetic control over the molecular constituents of organic semiconductors allows unprecedented control over their aggregate solid-state properties. Band-gap-like and band-edge-like properties can be tuned, seemingly at will (through the sweat and toil of brilliant synthetic chemists). This power comes, however, with a Faustian bargain. In contrast to inorganic semiconductors where atoms fully concede their individuality to collective quantum states, resulting in charge-carrier mobilities measuring in the hundreds to over a thousand square centimeters per volt second (cm$^2$/V·s), the molecular individuality retained in organic semiconductors leads to localization and mobilities typically amounting to less than 3 cm$^2$/V·s. That creates a problem for applications requiring appreciable currents such as, for example, organic LEDs (OLEDs).

OLED brightness is directly tied to the current fed to it by its drive transistor. For an organic semiconductor in a conventional, lateral-channel thin-film transistor (TFT, see Figure 1), the current needed for high brightness can be achieved in any of three possible ways. First, the voltage across the TFT source-drain electrodes can be made large, but, since the same current flows to the OLED from the TFT, a large voltage drop across the latter means high power dissipation in the transistor (not contributing to light generation). Second, the organic semiconductor channel width ($C_W$) can be increased, but each pixel is only allocated so much space, and room taken by the drive transistor is room not available to the OLED. Smaller OLEDs, for equal brightness, require higher current density, which degrades OLED lifetime. Finally, the source and drain electrodes can be brought close together, making the channel length ($C_L$) short. But that requires high-resolution patterning, and the other great lure of organic semiconductors is the low expense of vapor and/or solution processing (think ‘printing’) techniques for their fabrication. Hence, the comparatively low mobility that bedevils organic semiconductors is problematic for their commercial relevance in TFTs for OLEDs (or other similar high-current drive applications).

In 2008, we reported a new architecture transistor that circumvents this mobility limitation (see Figure 2). The continued on next page
carbon nanotube-enabled vertical field effect transistor (CN-VFET) turns the lateral-channel TFT architecture on its side. Onto the gate dielectric lying above a bottom gate electrode, the source electrode, channel layer, and drain electrode are sequentially deposited as a vertical stack. To permit the gate field unscreened access to the channel material, through the electrically conducting source electrode, that electrode is made from a dilute layer of well-interconnected single-wall carbon nanotubes spread across the gate dielectric, but with open spaces between the meandering nanotubes. The gate field need not penetrate far into the channel layer because the device operates as a Schottky barrier transistor with the gate field modulating the natural contact barrier between the nanotubes and the channel material. Current flows from the source contact through the nanotubes and up through the channel layer, to the drain. The thickness of that channel layer is now the channel length ($C_L$), which can be made almost arbitrarily thin (benefiting high-current applications) without the need for high-resolution patterning.

Although the CN-VFET clearly showed promise, some problems were also evident. The use of a thick gate dielectric required a high gate-voltage range for only two orders of magnitude on/off ratio. More problematic was a large hysteresis in cyclic transfer curves. By 2010, we had overcome these problems, and the real potential of the architecture became apparent. The devices now operate over a voltage range of less than five volts (both gate and drain voltages, with the source grounded) exhibiting on/off ratios of $10^4$–$10^5$. Moreover, using low-resolution fabrication as a criterion for comparison against the best published lateral-channel TFT performance, we showed the CN-VFET to possess on-state currents, for comparable device footprint, and voltages that were a factor of four greater (at less than half the gate capacitance).

But there was still more to come. Early in CN-VFET development, we realized that the device architecture lent itself to combining the function of an OLED and its drive transistor into a single integral device. This comes about by inserting the charge-transport and light-emitting layers of an OLED stack between the CN-VFET channel layer and its drain electrode, the latter now made of a low-work-function, electron-injecting metal (see Figure 3). The gate-field-permeable nanotube source electrode is also 98% transparent to light. Consequently, with the previously opaque gate electrode replaced by a transparent conductor (indium tin oxide) on a transparent substrate (glass), the light escapes across the full aperture of the bottom emitting device.

This category of device is called a light-emitting transistor, leading to its designation as a carbon nanotube-enabled vertical, organic light-emitting transistor (CN-VOLET). The advances in the CN-VFET led to comparable advances in the CN-VOLET such that this device has now defined a new state of the art in light-emitting transistors. Indeed, the devices operate with brightness and power efficiency that are comparable to OLEDs driven by polycrystalline silicon transistors in commercialized OLED displays, a first for devices in which the brightness is controlled by an organic channel material. The development is significant. OLEDs provide brighter colors at reduced energy consumption, without the viewing angle sensitivity of liquid-crystal displays. By the same token, the inherent difficulty of making the polycrystalline silicon used in the commercialized displays uniform over large areas has limited commercialized OLED displays to the size of handheld devices. The CN-VOLET makes the organic semiconductors competitive in this application, allowing for this very large class of materials to be brought to bear on this problem. Work remains to demonstrate that this architecture and organic semiconductors can lead to larger OLED displays, but so far this solution remains most promising. Next for us in this effort is building arrays of CN-VOLETS, where their pixel-to-pixel uniformity can begin to be quantified.

Figure 3. The carbon nanotube-enabled vertical, organic, light-emitting transistor (CN-VOLET) architecture. The light-emitting and charge-transport layers of the organic LED (OLED) stack are inserted into the CN-VFET between the channel layer and the drain electrode.
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Andrew Rinzler is a professor of physics. His research is focused on exploiting the remarkable properties of carbon nanotubes for scientific and technological gain. He, Mitchell McCarthy, and Bo Liu are co-inventors of the devices described in this article and continue further development of this technology at the University of Florida.

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References