Manufacturing and commercialization issues in organic electronics

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Techniques for manufacturing organic electronic devices [organic light-emitting diodes (OLEDs), photovoltaic cells, transistors, and solid-state memory] are reviewed and analyzed with respect to cost and market fitness in comparison to competitive approaches based on silicon electronics. The conclusions are (i) OLED displays will be successful using infrastructure largely borrowed from liquid crystal displays, because they provide fundamental customer value not dependent on lower cost; (ii) OLEDs for general lighting and organic–inorganic hybrid photovoltaic cells currently confront substantial barriers in cost and efficiency, but solutions appear feasible and would lead to very large volume businesses; (iii) organic crossbar memories are promising, but require innovations in driver architecture and interconnection; and (iv) organic transistors have not yet found a viable major market, but have great promise for highly customized, small-volume product runs using digital patterning techniques.

I. INTRODUCTION

The first example of a macroscopic electrical effect (i.e., an effect involving charge conduction that might be used in a practical electronic device) in solid-state organic materials was electroluminescence, first observed in molecular crystals during the 1960s when the foundations of our current knowledge of electronic excitations, energy transport, and photochemistry were all laid.[1] About four decades later, although the research effort is burgeoning,[2] the only commercial products are photocopier photoconductors and organic light-emitting diodes (OLEDs). Even the latter is still a nascent industry, typified by Pioneer's automobile radios and Philips' electric shaver (although several major production facilities are in development, and cell phone and camera displays have begun to appear in limited venues).

Certainly, there remain important materials issues involved in the development of saleable devices from organic materials; these will have been well covered in other articles in this special issue. Our focus here will be on manufacturing, which is inextricably intertwined with understanding product needs. This is a subject not often addressed in scientific journals (for good reason), but electronics is by definition an engineering topic. Basic research into structures and mechanisms is always potentially useful and is judged by other criteria. However, research devoted to the development of ostensibly saleable devices and the improvement of their performance values or cost of fabrication cannot be appropriately evaluated without an understanding of their market potential and constraints.

This review will consider four types of devices that are widely studied today: light emitters (LEDs), light harvesters (photovoltaics), and purely electronic devices (transistors and memory). With respect to each of the four topical areas, we address the following questions: (i) what are the product needs (from the market perspective); (ii) in what ways (if any) are these needs met today; and (iii) what are the characteristics of the associated manufacturing methods with respect to performance, cost, and infrastructure development? Our aim is to evaluate critically the practical prospects rather than to catalogue research results, though an extensive selection of references is included. Space limits preclude serious attention to device reliability, which is obviously a crucial aspect of commercialization.

The single most dominant reason given both in the scientific literature[2] and in commercial pronouncements[3] for pursuing organic electronics is low-cost production; this phrase in fact appears in the call for papers for this issue of the *Journal of Materials Research.* This expectation is based on the belief that *processing* of organic materials will be cheaper than for inorganics, because the materials themselves, as the product of complex multistep synthesis and purification, may be rather expensive. The theme is recurrent throughout the literature; some representative examples can be found in the reports

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of Rogers and colleagues.[4,5] In particular, techniques such as inkjet printing and microcontact printing are expected to decrease substantially the cost of organic transistors.[2] However, these techniques have not previously been applied to products with the yield demands of multilevel-aligned microelectronic devices, nor has it been shown that a tool capable of satisfying production requirements would actually provide cheaper output. If, on the other hand, one is to meet yield and cost demands by relaxing feature sizes or defect specifications, the question must be asked whether the resulting product can be competitively positioned in the market.

A second commonly expressed theme of organic electronics is low-temperature processing.[6] Conventional silicon ICs are fabricated beginning with a thermal oxidation step at well over 1000 °C, and while process temperatures decrease gradually toward the "back end," the final steps may still reach a few hundred degrees Celsius. Amorphous silicon thin film transistors (TFTs) are made at much lower temperatures on glass, but the critical semiconductor and gate dielectric depositions have traditionally been carried out at 300 °C or more. Polysilicon, required to get performance adequate for logic circuits, requires process temperatures in-between the other two. Clearly, these temperatures are fundamentally incompatible with all but a very few plastics,[7] and if transparency is desired, options become even more limited.

However, silicon technology continues to evolve. Amorphous silicon (a-Si) TFTs with basic performance (mobility, turn-on voltage, on-off conductivity ratios, frequency response, and durability) as good as those on glass have been made on plastic at a maximum process temperature of 150 °C and incorporated into a high-resolution liquid crystal display (LCD)[8] Films of polyethylene naphthalate (PEN), with a service temperature around 160 °C and excellent thermal and mechanical stability, are now available. Other relevant advances will be covered later. Here, we emphasize simply that the capabilities of silicon continue to be extended in remarkable ways, and the impact of this competitive landscape on organic electronics is important.

II. REVIEW AND SUMMARY OF THIN FILM FABRICATION TECHNIQUES

Traditional thin film electronic materials deposition is carried out with evaporation, sputtering, and chemical vapor deposition (CVD). Though all of these processes require vacuum, they can be done on very large substrates and at remarkably high speeds[9]; polymer webs over 2 m in width are commonly metallized at 18 m/s for food packaging,[10] with resulting costs in the pennies per square-meter regime (defect densities, not surprisingly, are not in a realm suitable for microelectronics). At the other extreme of product sophistication, however, glass plates over 2 m × 2 m are now being processed for liquid crystal displays, with total time for each process step ("tact time") of a few minutes.

Patterning of these films on glass is accomplished just as with silicon wafers:[11] coating with photoresist, exposing with contact or projection optics, developing the resist, etching the underlying layer, and stripping the resist. Spin-coating is beginning to see competition from so-called slit-and-spin (where the substrate is uniformly coated by a slotted dispenser before spinning, thereby reducing waste) and spinless (essentially slot die or meniscus) coaters (e.g., TOK, Toray) as panel sizes increase toward 2 m and above; little has been published about these technologies. Optical exposure may be by step-and-repeat systems (which are susceptible to stiching errors but have been the industry mainstay), or more recently step-and-scan systems with seamless stitching (Anvik[12]) or large-area holographic systems (Holtronic[13]).

OLED manufacturing uses the LCD toolbase with minimal modification. Thus, for molecular systems, evaporation of the organic components as well as the metal electrodes is standard, whereas polymers are generally applied by spin-casting. Shadow masking is currently the method of choice for patterning small molecules and jet printing for polymers. A higher rate alternative to evaporation, organic vapor phase deposition,[14] in which a carrier gas is used to sweep organic molecules from a heated source chamber into a deposition zone where they condense, is now being provided in commercial tools (e.g., Aixtron).

If web processing were introduced, a whole range of high-speed liquid coating techniques would be available,[15] of which gravure coating is probably the most well-suited to the small thickness of OLED films. Coating of thin films on polymer webs can be accomplished[16] at speeds up to approximately 3000 ft/min, although values in the range 100–500 ft/min are more common. Uniformity can be within ±1–3%. Similar speeds are attainable with vacuum coaters as for liquid coating, though the capital cost of the former systems is higher (by roughly a factor of 2–4), and the resulting film thickness at very high speed is lower (limited by ability to put energy into the target and to remove it from the substrate).

Patterning of webs (for example printed wiring tapes) currently relies on the same photolithographic techniques as rigid substrates. For microelectronics, a wide range of novel patterning techniques have been proposed. Many of these have been described in substantial detail by Rogers and co-workers[17] and will be commented on further below. These include laser thermal transfer,[18] soft lithography or microcontact printing (Xia and Whitesides[19] and Michel et al.[20]), inkjet printing (Calvert[21]), offset printing,[22,23] and imprint lithography (Sotomayor Torres[24]), among others.

III. LIGHT-EMITTING DIODES

There is no competition from silicon in the area of light emission, because silicon is an inefficient emitter, and several years of research into porous silicon has not substantially changed this picture. The competition to OLEDs as pure light sources comes from III-V devices and to a certain extent from II-VI materials and as display media from liquid crystals backlit by primary emitters such as fluorescent lamps or LEDs (a few matrix-addressed displays also make use of II-VI emitters).

Inorganic light-emitting diodes (LEDs) are unparalleled in luminance and lifetime; today one of their major markets is traffic lights, because they are far longer lived than the lamps they replace despite being driven at sufficient current for daylight viewing. However, although low-power LEDs cost less than 1¢ each,[25] this is still far more than the retail cost of a complete TFT-LCD display pixel (with backlight) of about 0.02¢,[26] and does not include the cost of assembling them into a matrix or adding drive electronics. The fabrication of III-V-based LEDs on single-crystal substrates (which are themselves much more expensive than silicon) with epitaxial processes precludes their use in large-area displays. Inorganic electroluminescence, while commercially available for a variety of products, has been hampered by high voltage, low efficiency, and restricted color gamut.

As a consequence of the opportunity provided by these limitations, OLEDs have progressed relatively rapidly toward commercial viability as soon as the fundamental performance (lifetime and efficiency) became reasonable. Today the focus of most OLED companies is on replacements for LCDs in small appliances such as cell phones and personal digital assistants (PDAs). Greater visual appeal and lower power consumption are the primary competitive advantages seen for OLEDs, rather than lower cost, and areas of these initial products are small to maintain compatibility with familiar technology and keep defects manageable. Quality is essential in this market: flat panel displays are a mature product with demanding customer expectations that cannot be met with technology that is perceived to be inferior to the conventional.[27]

One of the major challenges for OLEDs has always been patterning. LCDs depend on a uniform light source and uniform active medium coupled with patterned color filters; the latter materials are simple absorbers having wide compatibility with patterning techniques. Photolithography and etching have been used traditionally, but at least one company (Creo, in collaboration with DuPont) is actively promoting laser thermal transfer.[28] In this process, an infrared laser heats a strong absorber underlying the active film, causing the latter to be ejected and transferred to a target substrate lying in close proximity. Although it is a digital technique (and hence inherently slower than mask-based patterning), it is more direct, has intrinsically high resolution, and is easily adapted to roll-to-roll equipment.

OLEDs require a more sophisticated treatment then LCD color filters, as the sensitive electroactive material (comparable to the liquid crystal) must be patterned for a color display. 3M is actively pursuing the laser thermal technique[29] as an alternative to shadow masking. Some polymer OLEDs have now been patterned by direct optical irradiation and cross-linking with excellent results.[30] Despite the chemical sensitivity concern, a recent report of conventional photolithography for patterning standard polymer OLEDs by etching[31] showed unaffected emission characteristics.

Nevertheless, jet printing is the dominant approach to patterning polymer OLEDs today. It is the prototypical example of "digital" printing. A droplet of ink is placed on demand exactly where one wants it. There may be multiple printheads, but it is a serial deposition technique, analogous to such patterning tools as electron-beam lithography. The advantage is customization: the individual printer user at home or in the office typically wants only one, or at most a few, copies of any document. For the convenience of having those copies in hand with little wait (although still very slowly compared to commercial printers), he/she will pay a premium: inkjet copies cost around 4¢ to 5¢ per page.[32]

If high volume is the desired end, digital printing is not the preferred approach. A bestselling 700-page paperback might cost $5.95 in a retail shop, a cost of under 1¢ per page including binding, author royalties, distribution costs, and revenues for several businesses. If 20% of the publisher's cost goes to actual printing and binding,[33] the differential (compared to consumer inkjet) is around 50×.

At the moment, the leading supplier of jet printing tools for OLEDs is Litrex,[34] which as of a little over a year ago was selling its flagship system capable of handling 0.4 m × 0.5 m glass for a price in the vicinity of $1 million. The current standard printhead is 128 nozzles running at 2 kHz with 117 ppi resolution (3 RGB color sub-pixels per pixel; drop size 30–40 μm); a 256 nozzle head is predicted to achieve a throughput a little over 1 ft^2/min (for printing only; substrate handling not included).[35] The experience of the semiconductor industry is, without exception, that tool costs rise with any increase in performance demands, such as resolution, substrate size, or throughput. As an illustration, an optical patterning tool capable of 1 μm minimum feature size on 4″ diameter wafers was available in 1982 for $500,000. A modern stepper having 0.13-μm resolution on 12″ wafers costs around $15 million (only about half of which is due to inflation).[36] Deposition and etching tools have risen similarly. There is no historical or logical precedent for supposing that the tool cost trajectory of jet printers for high-resolution displays will be any different. Jet printing appears to be highly desirable if not necessary for color polymer LEDs, but it is not used due to any inherent low cost.

Offset printing, in which a cylindrical printing plate transfers liquid selectively from a reservoir to an intermediate transfer cylinder (hence the term "offset") would comprise a quite different cost structure.

In such a system, the entire width of the web is patterned at once by a single mechanism (parallel printing), which currently can run at approximately 600 ft/min. on a 2- to 3-ft.-wide web for high-resolution printing. The intrinsic resolution of such technology is not what prevents its application to OLEDs: both gravure and offset printers are able to produce spots down to 20 μm or less.[22,37] The cost of such systems is difficult to specify without more constraints, but it is not likely to be much more than the jet printer described above (a Heidelberg press suitable for high-volume printing can be gotten for $1 million or less). Thus, the differential found for inkjet printing on paper would be carried over to OLED materials.

However, there are two important problems besides intrinsic resolution: overlay accuracy and the ability to print fluids whose rheological character cannot be tuned as desired. The misregistration of organic material in RGB subpixels to control electrodes cannot exceed at most several percent of feature size. For a modern LCD (subpixels ~70-μm wide), this implies less than 10-μm variation. A company with a reputation for high-precision roll-to-roll screen printing (Preco Industries) guarantees only ±40 μm, although this allows for material and environmental fluctuations that could be reduced in a specific process. At the moment, therefore, such high-speed printing approaches are far from suitable for display patterning. Machine controllability and alignment detection is in the single digit range (of micrometers), however, and it does not seem implausible that with further mechanical development, a well-defined process could meet at least some display requirements.

More problematic is likely to be the issue of fluid formulation. Printing inks are a complex mixture of solvents, colorants, surfactants and other additives that produce the optimum viscosity, thixotropy, surface tension, and drying speed for the desired printing process,[38] whereas organic electroluminescent polymers can tolerate almost no additives of any kind. Even viscosity is not entirely under the user's control; it is affected by optimizing polymer synthesis for luminescence yield, transport efficacy, and device lifetime. Thus, it is not obvious that offset or similar parallel printing techniques can be used at all. However, the success of researchers at the University of Stuttgart in making a ferroelectric LCD with flexographic printing[39] (although limited to fixed segment resolution) suggests at least some hope.

Besides displays, an intriguing application for OLEDs is solid-state lighting (SSL),[40] in which high-resolution patterning is not required. It is in this application that the objectives under scrutiny here (low cost and large area) would become dominant. Currently, prospects appear good for OLEDs to exceed the efficiency of incandescents (~15 lum/W) in all colors, but the latter sell for roughly 0.05¢/lum. An OLED operating at 1000 cd/m^2 (10 times the nominal display brightness) would have to be sold for $1.50/$m^2$ (including packaging or fixturing) just to equal the price per lumen, and a lifetime of several thousand hours (compared to the incandescent lifetime of ~1000 h) would be needed to offer a serious competitive advantage. (Increased efficiency could offset the price, but the market experience of compact fluorescent bulbs suggests that this is a difficult sell for consumers.)

Though further improvements in lifetime and efficiency for red and blue emitters are needed, several green systems are already well in excess of incandescent levels even without advanced light extraction techniques, and values have been steadily rising over the last several years. To put the price target in perspective, however, a National Renewable Energy Labs project to fabricate a simple silvered mirror for solar concentrators (consisting of two thin metal layers on a steel substrate, with a 2-μm Al_2O_3 protective coating and 100 nm of TiO_2 anti-soiling layer) has a price target of $15/$m^2$, and even using roll-to-roll techniques this has not yet reached its goals despite 7 years of effort.[41]

SSL requires white light, which can be provided either by a mixture of emitting molecules and dopants in a single layer, a stack of different emitters, or laterally patterned units small enough to appear white at the viewing distance of a few feet. Recent work by Forrest and co-workers demonstrated 6 lum/W white efficiency for reasonable intensity in a single-electrode stacked structure.[42] This result was achieved using five ultrathin layers (mostly 10 nm) of evaporated molecules. Even with the advanced deposition tools coming on the market,[43–45] it will be challenging to maintain thickness control and defect levels in such thin films, especially at high speed.

Single-layer white OLEDs have traditionally exhibited rather low efficiencies (a few lum/W or less). Li and Shinar have reported a "single-layer" structure[46] with close to 6 lum/W at 1000 cd/m^2. Though the emission comes from a single layer, it is a few nanometers thick, so manufacturing issues are similar to the Forrest system (there are also several other, nonemissive, layers). Lifetimes for these devices have not been measured. Recently, a General Electric team has reported 15 lum/W from a polymer using a blue emitter and downconversion.[47]

An attractive approach to an organic SSL product could be color pixels of about 0.5 mm lateral extent, which would be small enough to appear white from several feet away but large enough to be printed at high speed if indeed analog printing of OLED films is possible at all. The electrodes need not be structured, and there are no alignment issues except to avoid overlap of the spots (they need not even be highly regular in shape as long as they are uniform in thickness). Most polymer OLEDs today use only two organic layers, one of which would need no patterning. The production of these four layers at around the targeted price may be achievable if volumes are high and a less expensive and more easily deposited transparent electrode than indium tin oxide (ITO) can be found. (Besides the difficulties of ITO deposition, the cost of indium will become an issue; its elemental abundance is similar to silver, and it is a by-product of Zn mining,[48] leading to limited price elasticity).

Clearly, there are formidable challenges to be overcome before an SSL OLED becomes practical. However, the payoff is impressive. The general illumination market is said[49] to be about \$15 billion, which is not as large as the flat panel display market (variously estimated at ~\$25–50 billion). However, lighting typically consumes between 20% and 30% of a country's electricity, which in the United States is 870×10^9 kWh for 2003.[50] At an average price of \$0.08/kWh, this has a value of \$70 billion, which represents potential revenue for a more efficient lighting industry under the right business model. Worldwide, the numbers are four times larger and do not include the growth in light usage that would result in much of the world where it is restricted or nonexistent because of the expense of electricity. All of this potential is relatively available to OLED or inorganic LED innovation with little competition from established lighting technologies, which, though capable of continual improvement, are not likely to see dramatic breakthroughs.

For organic materials to partake in this huge opportunity, production must incorporate thin film coating (and to some extent patterning) techniques operating on flexible substrates at speeds of tens to hundreds of feet per minute. The films must be highly uniform in thickness and free of pinholes (perhaps using a self-healing technique analogous to that used for thin film capacitors[51]), and a rigorous method of sealing against oxygen and water provided within extremely aggressive cost constraints. However, high-resolution patterning and alignment are not required, and the adaptation of converting industry film-forming techniques to this application appears feasible.

IV. PHOTOVOLTAIC CELLS

Harvesting solar energy has been a goal of research in electroactive organic materials for decades, having provided a significant motivation to the study of photosynthesis[52] as well as synthetic polymers and other molecules. However, the early efficiencies were far too low for practicality (mostly less than 0.1%).[53] The 1980s, even as OLEDs were taking off, saw only modest improvement;[54] organic photovoltaics did not become a serious contender until nanostructured materials afforded efficient charge separation.[55] Today there are many academic groups around the world active in this field, and the first international conference devoted specifically to organic solar cells was held in 1998 in France.[56] These developments have been well reviewed by other authors.

Of more pertinence here are the current attempts to commercialize organic solar cells. For while there are several companies working on organic–inorganic hybrids [Nanosys, Nanosolar, Konarka, and Sustainable Technologies International (STI) (Australia)], there are *no* startup companies devoted to organic photovoltaic (PV) technology and few if any targeted large company R&D projects (Cambridge Display Technology has a small government-funded project in the area). Half of the companies cited (Konarka, STI) are working on dye-sensitized nanostructured TiO_2 (sometimes called "Grätzel cells"[57]), while both Nanosys and Nanosolar use a nanostructured inorganic element combined with an organic polymeric component to facilitate efficient charge separation.

If technical difficulties could be surmounted, PV would constitute an "ideal" example of large-area, low-cost electronics for organic materials. Certainly, the area is large. To become[58] a significant factor in worldwide energy production, PV needs to be bringing several GW_p on-line each year; 13 GW_p/yr would supply about 5% of the world's 1996 generating capacity.[59] At 10% efficiency, this corresponds to a production volume of $1.3 \times 10^8 m^2$/year. Though still small compared to the 4×10^9 m^2 of thin film capacitors manufactured each year as of 1990,[51] it is certainly enough to sustain a robust high-volume, roll-to-roll processing industry with room for many companies.

Low cost is paramount, however. Unlike displays, where sensory appeal to the customer is vital (even SSL has to have a certain color balance), all that counts with energy is cost and reliability. The relation between consumer rates (\$/kWh) and manufacturing costs (\$/W_p) depends on several factors (especially cost of capital), but under a fairly typical set of assumptions[60] current residential rates of around 8–10¢/kWh would require PV cost per installed W of about \$2. This in turn means module costs of well under \$1, allowing for balance of system components and installation cost.

Currently, there are only two companies marketing roll-to-roll produced solar cells in significant volume: Energy Conversion Devices (ECD) (through its subsidiary Unisolar) and Iowa Thin Film Technologies. Both of these are amorphous silicon; the former on stainless steel foil, and the latter on polyimide. (There is also a 3½-year-old Swiss startup, VHF Technologies, which has a-Si on plastic PV modules available, but the prices are still in the boutique range). Although ECD has a production volume of over 30 MW/year, their products sell on the Internet for around \$5/W_p. The stabilized efficiency of these cells is around 5% single layer, or up to approximately 13% for triple-layer tandem cells.[61]

However, well-crafted business plans have been prepared[62,63] containing far more agressive goals. A Dutch group concluded[62] that they could achieve \$0.50/W_p with a-Si technology (including one layer of SiGe alloy in a tandem cell) in a roll-to-roll process on metal foil. This process is under development by a Shell-Akzo Nobel joint venture at the present time. Several other research projects involving roll-to-roll fabricated a-Si PV cells with results comparable to glass have been described.[64–66]

From this, we can conclude that a roll-to-roll fabrication process for solar cells can meet requirements for worldwide commercialization. On the other hand, this proof of principle comes from an inorganic device structure based entirely on vacuum processing. Once again, the unique suitability of organic materials to cover large areas of flexible substrates at low cost is called into question. Is there anything about an organic PV cell that will actually lead to substantially lower costs compared to amorphous silicon?[67]

A thin-film PV cell contains a substrate, a metal electrode, a *p-n* or *p-i-n* semiconductor structure, a transparent electrode, and some encapsulation.[68] Conversion of native voltages and currents to product-specified values requires series interconnection, which is commonly accomplished by laser scribing.[69] Metallic busbars are applied to collect and handle the large final output currents. All of these layers and processes that are additional to the photovoltaic material itself are a necessary part of any useful system and add cost that dilutes the effect of any reduction in cost of the semiconductor. The expense of ITO was mentioned earlier. The use of a conducting polymer with a metal mesh has recently been reported[70] (though this would be equally useful for inorganic cells).

a-Si PV cells are presently limited by the deposition rate of satisfactory quality silicon, which has up to now been about 1 Å/s, and by light-induced degradation (Staebler–Wronski effect),[71] which limits stabilized efficiency to approximately 5%. Deposition rates are increasing,[72] and 10 nm/s with nearly conventional quality has been reported.[73] Microcrystalline or nanocrystalline silicon[72] (which is obtained from the same process as a-Si by appropriately controlling ion bombardment) has no instability,[74] as well as better initial efficiency. Currently, the deposition temperature is approximately 300 °C, but this may be reduced.

Thus, in order for organic (or organic–inorganic hybrid) PV cells to be competitive, the deposition process has to be cheaper per unit area than amorphous or microcrystalline silicon at comparable efficiency; approximately 7–10% is probably required. Though the cost appears attainable, so far no one has approached this efficiency. The best all-organic cell was reported by the Saraciftci group,[75] at 2.5% from a blend of conjugated polymer and substituted fullerene. An inorganic–organic hybrid cell with 1.7% efficiency was obtained by Alivisatos and co-workers[76] with CdTe nanorods dispersed in poly(3-hexylthiophene). Monochromatic irradiation at 515 nm at low power gave 6.9% efficiency, suggesting that optimization of absorption characteristics and loss processes at higher intensity should have major significance.

Dye-sensitized cells, employing a nanotextured TiO_2 electron transport matrix in contact with a liquid electrolyte, achieved 10% efficiency a decade ago,[57] but these systems suffer from sealing and lifetime issues. Recently, Grätzel's group obtained 2.6% efficiency with a solid electrolyte.[77] The voluminous literature on these and other systems makes it clear that charge separation and electron transport efficiency are the crucial issues, and organic–inorganic hybrids present the best approach because one can take advantage of the numerous ways to structure electron-transporting inorganic materials on the nanoscale, while relying on the effectiveness of organic hole transporters (especially polymers).

Module lifetimes outdoors must also be considered. A product with half the life expectancy of crystalline silicon (>25 years) will be more than twice as expensive because of replacement labor. UV degradation can probably be eliminated by a protective film that may be replaced periodically if it can be cheaply laminated or even painted on. The lifetimes of OLEDs suggest that photochemical stability should not be a fundamental limitation for at least one class of absorbers.

The complexity of thin film silicon deposition affords organic materials a window of opportunity if the necessary device efficiency can be attained. A plasma enhanced chemical vapor deposition (PECVD) system typical of what would be required for a-Si PV in high-volume production can be found at Southwall Technologies in Tempe, Arizona, where SiO_2 films are currently deposited on plastic (PET) webs up to 24″ wide from silane at a few m/min; the cost of this machine is probably around \$5 million. A liquid phase film deposition tool for photovoltaic polymer, which would run at higher speed (possibly several times as much), would cost perhaps a third as much.

V. FIELD-EFFECT TRANSISTORS

The research activity in organic field effect transistors (OFETs) has exploded recently; the roster of large companies with active programs in the area includes at least IBM, Philips, Infineon, Xerox, 3M, DuPont, Motorola, Honeywell, Avecia, and Dow Chemical, as well as one start-up (Plastic Logic).

Basic scientific results have been well summarized in a recent book[2] as well as elsewhere in this journal. In general, one can say that the most fundamental and widely emphasized electrical parameter, mobility, has reached parity with a-Si for vacuum-deposited devices based on pentacene, and is within one to two orders of magnitude of this value for polymers. The on/off ratio is reported in at least some cases to be 10^6 or greater, as desired for display switching operations. Both *n*- and *p*-type devices have been made and incorporated into integrated circuits (although *n*-type materials are just emerging), with clock frequencies in the kilohertz range. Threshold and operating voltages, of vital import due to their effect on power consumption, are usually high (20–50 V), and long-term stability has not been seriously studied; in general, threshold voltage shifts as well as some long-term parameter drifts are observed, but at least *p*-type devices can routinely be operated at their maximum frequency without direct use-dependent degradation. Thus, with some important caveats one can say that OFET performance is within a practically significant range. Does this set the stage for the realization of a large-area, low-cost organic electronics industry?

Radio frequency identification (RFID) tags, which the MIT Auto-ID Center envisions attached to essentially every object of commerce, are often perceived to be among the simplest of integrated circuits and are frequently cited as an early application for OFETs. Though they have no function other than to impose some modulation on a backscattered (not actively transmitted) rf signal that conveys a set of bits to the reader (which is both transmitter and receiver), even the simplest tags require a few thousand transistors (>2000; 5000–10,000 is typical). Would an OFET RFID tag compete with silicon? Alien Technologies asserts that it will be able within a few years to provide tags at 5¢ each, as fully packaged labels including the antenna; the silicon portion (including processing for the "Nanoblocks" and their connection to the antenna) is about 2¢. Though this ability is not yet proven, they are delivering product today to a customer who has ordered nearly half a billion tags, and recent reports disclose the price to be under 10¢/tag.[78] Other companies (Blackstone, Smartcode, and so forth) are promising similar results. The 5¢ price point is widely considered to be the market requirement for item-level tagging (as opposed to pallets, shipping cartons, and so forth), resulting in volumes in the trillions per year.

To analyze the case further, we need to understand more about the cost of OFET processing. Most of the cost of making silicon integrated circuits is in patterning, partly because each photolithography cycle requires several steps (resist deposition, softbake, exposure, development, hardbake, etch, and resist removal), but largely because the key component (the stepper) is so expensive. This is in turn because of the exquisite mechanical, optical, and cleanliness standards required to reproducibly make microscale features over large areas without defects.[11] This is not a recently developed situation: even machines with several-micrometers resolution are by far the most complex process tools in the production line for which they provide the critical patterning.

The hope has been expressed that OFETs will dramatically reduce these costs by using cheaper patterning techniques, replacing photolithography by the patternwise deposition (printing) of active organic materials.[79] Jet printing has already developed to the manufacturing stage for OLEDs. In the foreseeable future, critical dimensions (CDs) will in general be limited[80] (Fig. 1) to somewhat more than the minimum droplet size of approximately 20–30 μm[21] by placement accuracy, edge straightness, and drying characteristics.[81] Suppose one makes transistors with 40-μm CDs. The minimum possible footprint is then about 160 μm,[2] assuming a very small W/L value, and the absolute minimum size of a low-end practical RFID chip is well over 1 cm^2. Can OFETs be made for less than 1¢/cm^2?

A detailed technical cost model of the relevant process has not been published. We can make a very useful estimate, however, by comparison to existing commercial a-Si TFT processes. Samsung, for example, projected in 2002 a-Si TFTs on glass at about 8¢/cm^2 by 2005.[82] Canon's TFT lithography system (0.9 m × 1 m panels, vintage 2000) with 3-μm resolution at 7 ft^2/min, was $6 million. To achieve the same throughout with the Litrex jet printer system mentioned above would require capital outlay of several times that much (about $50 million if the 256 nozzle system costs the same as 128, only 1/5 of the substrate area is to be covered, but 2.25 drops per drop area are used to achieve uniform coverage and edges, and no additional time is required for substrate handling).

One must of course account for all the lithographic steps not present with direct printing (resist coating, development, etching, and resist stripping as well as

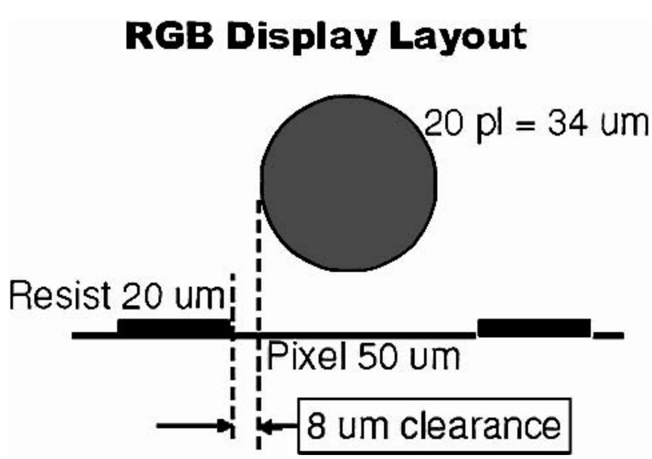

FIG. 1. The inkjet drop placement accuracy budget for a typical OLED display. The drop trajectory error must be less than 0.5°, which necessitated a nozzle redesign (from Ref. 80).

deposition of the active film). However, all of those processes run in much cheaper machines with easier process control. Resist coating and development tools are together not more than about 1/10 of the cost of stepper-based exposure; stripping is a batch process with wide process latitude in most cases. Even plasma etching (a more sophisticated process than metal or dielectric deposition) costs substantially less than pattern generation, which is where all the delicate sensitivities to mechanical and optical imperfections lie.

Starting from the general observation that relative costs can be largely accounted for by capital cost per unit throughput,[83] a useful approximation to more detailed cost calculations can be obtained by subsuming all steps under a "patterning step" unit P. A basic a-Si TFT process for LCDs consists of four masks, along with four depositions and four etches.[84] For IC fabrication, deposition and etching tools average under 1/3 of the cost of the lithography tools for the corresponding generation;[85] nevertheless we will take each deposition and etch to be 0.5P, for a total of 8P.

A fully jet-printed OFET[86] lays down essentially the same number of layers with four printing steps that cover only the active area (including wiring), and one that covers almost the entire substrate (passivation). Passivation can be uniform spin-coating plus printing of a few vias for contact pads, and in the current context will be negligible. However, cach printing step dwarfs the cost of conventional processing; the numbers above suggest 7P for each, or a total of 28P. Major improvements in the drop dispensing rate and number of nozzles per unit can be expected, but these will not come without increased capital cost. It is exceedingly difficult to see how jet printing can ever compete with established processing for densely patterned IC fabrication. The fundamental problem here is simply that high-accuracy patterning in microelectronics is both unavoidable and costly, regardless of the material set.

Thus, without breakthroughs in equipment cost and performance that cannot be objectively anticipated and that would be contrary to historical experience, the cost of a jet-printed OFET RFID tag will certainly not be less than the cost of silicon chip-based tags. Moreover, it will be inferior in both frequency response and power consumption. A high-frequency (13.56 MHz, 900 MHz, or 2.45 GHz) device must be present to convert incoming radiation into dc power for the tag. A single silicon diode can do this, but adding it to the OFET RFID tag is yet one more factor moving away from the all-printed, low-cost vision. Although 125 radiation is currently used for some tags, standards committees are moving away from this frequency, and it is not likely to represent a major market in the future.

Voltage is an equally serious problem. Organic devices have rarely shown operating voltages less than 10 V; nearly all published data to date are over 20 V and in some cases much higher. The square of the ratio of this number to the CMOS operating voltage (now IV or less for most circuits) is approximately the ratio by which power consumption will be higher (ignoring for the moment the further difficulty of the absence of *n*-type OFETs). But the trend for RFID tags of all types is toward larger read ranges (to keep reader costs down, and to allow rapid reading in varying locations while keeping power within regulatory limits) and hence lower power. Some RFID experts believe that neither a-Si nor even polysilicon TFTs will be able to satisfy market demands.[87]

Lower voltages may be obtained with high-dielectric constant inorganic materials such as barium zirconate titanate.[88] This is not a printable material, however. Low voltage has also been reported using ultrathin dielectric layers (e.g., 2 nm)[89] or with extremely short (0.1 nm) channels.[90] Though scientifically noteworthy and well worth further research, the processing of these devices does not fit the demanding low-cost flow required for RFID circuits that might compete with silicon microchips.

The assumption of $W/L = 1$ and CDs related to drop size is also not consistent with actual device performance. The width required with low mobility materials has typically been a few mm.[86] Thus, the all-polymer IC fabricated by Philips[91] with 326 transistors ($W = 1$ mm) required an area per transistor of 83 $\times 10^3$ μm^2, rather than the minimum value of 26 $\times 10^3$ assumed above (which makes the IC > 3× larger).

A novel circuit architecture might be developed that dramatically lowers the transistor count and allows useful organic RFID tags to be much smaller. Si tags would also shrink: 15-μm-square silicon chips (~25-μm thick) have been demonstrated (Fig. 2),[92] accompanied by research into handling and packaging techniques.[93] With current design rules (0.13 μm), at least 500 transistors can be incorporated into such a chip,[94] which would cost (after thinning) well under 0.01¢ each. The vision of a "tag on everything" (cereal boxes, and so forth) does not necessarily exclude conventional silicon.

So far we have only considered jet printing. As discussed previously in connection with OLEDs, continuous parallel printing (e.g., offset, and so forth) does not have the alignment capability for transistors, nor is it known how to make the requisite materials printable. Laser thermal transfer,[18] which is digital and avoids solvent intermixing problems (although it forms interfaces that may behave differently from those obtained by wet or vapor film formation), avoids both problems. It has higher resolution than jet printing (Creo, for example, provides a standard 5-μm-square beam) and needs no additional beam system to provide position feedback information.

Like jet printing, it is a digital process and hence serial

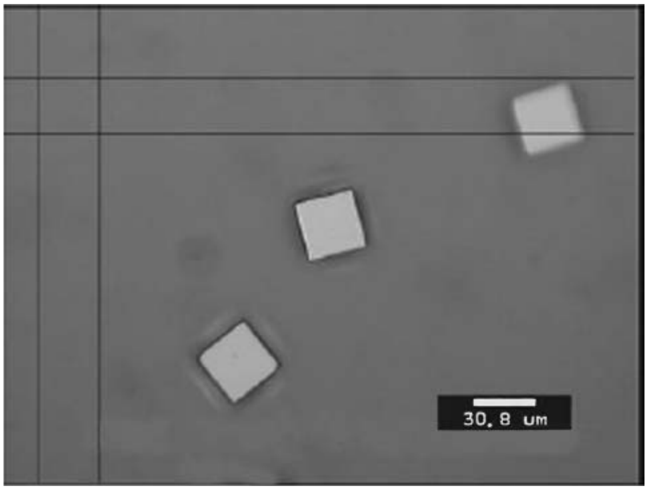

FIG. 2. 30 × 30 × 25 μm silicon chips, thinned from conventional processed CMOS wafers and diced by plasma etching. Note the smooth edges. 15 × 15 μm widths have been made this way, and thicknesses down to about 10 μm. Courtesy of Dr. Karlheinz Bock, Fraunhofer IZM (Institute for Reliability and Microintegration).

as opposed to parallel, although the formation of multiple light beams from a single source is well established (Creo provides 240). Laser direct write processes were extensively developed beginning in the 1980s, with impressive (sometimes submicrometer) resolution, yet never reached widespread commercial use due to the greater cost-effectiveness of (massively parallel) lithography. The recent development of high-power, efficient near-IR solid-state lasers, coupled with the simplicity of thermal transfer (which avoids many complications of handling gaseous or liquid sources) may have altered this landscape. Of course, one must also consider the cost of the uniform film deposition systems required to make the donor sheets.

The demonstration of a commercial benchmark source for this application is not as far advanced as for jet printing, so a similar quantitative comparison cannot be made, but Creo's systems suggest that the throughput/cost ratio is undoubtedly greater than for jet printing, probably by many times. Certainly, the linear writing speed of approximately 0.2 m/s is far greater than jet printing. Depending on the ablation thresholds, the laser system will be capable of up to a few ft^2/min, and should not be substantially more expensive than the jet printer. Whether a system properly engineered for microelectronic fabrication will be able to make RFID circuits at a cost competitive with crystalline silicon remains to be seen; the prospects certainly appear far better than for jet printing. Unfortunately, the electrical performance would be no better.

In summary, though the future capabilities of organic FET devices can of course not be predicted, and fundamental physics does not preclude their achieving levels of performance that could satisfy RFID demands, realistic prospects appear to fall into two categories: (i) relatively low-cost fabrication techniques (various types of printing) with conventional device architectures, resulting in performance that is certainly not competitive and (ii) small molecules (primarily pentacene) or possibly polymers in extreme architectures (ultrathin or narrow gates, and so forth), combined with inorganic films, relying on techniques that are fundamentally similar to a-Si processing, and resulting in performance that might, if major progress is made on a variety of fronts, meet some RFID needs at a cost that is very unlikely to be smaller than for silicon at that time.

If RFID tags are not the proverbial "killer app" for organic FETs, what about displays? The concept of flexible organic electronics coupled with flexible (probably organic) display media seems to be a logical fit and has been demonstrated many times.

As attractive as is the concept of flexible displays, few economically noteworthy applications have yet emerged that really demand the attributes of a flexible plastic display; this has been the conclusion of working groups at two recent US Display Consortium conferences on the subject. To win on cost alone requires an advantage factor of the order of ten, while losing nothing in performance.

The prospects for meeting the cost demands of display products are far better than they are for RFID tags, principally because conventional backplane technologies have to process the entire display area even though the transistor may occupy only a small fraction of each pixel, so digitally printing large-featured transistors is not such a serious limitation. The problem of high bias voltage is also less significant, as there are display uses that do not demand the lowest possible power consumption.

Nevertheless, 8¢/cm^2 is a formidable number to beat (and of course it will still continue to decrease with time). Some of the gain that comes from processing less area is offset by the larger features inherent in jet printing. The analysis just presented suggests that it will be very difficult to produce OFET display backplanes for 0.8¢/cm^2. One may argue about whether the factor of 10 is really necessary, but clearly success for OFETs will demand extremes of achievement in all aspects of fabrication. In the meantime, glass-based TFT manufacturers will continue their relentless drive toward lower costs.

Applications in which flexibility or other plastic attributes (e.g., thin, lightweight) command a premium may yet be identified. It is a fallacy, however, to believe that OFETs are the only viable flexible large-area backplane technology. a-Si backplanes of far greater complexity than anything reported with OFETs (more than 300,000 transistors) have been made on plastic and incorporated into functioning (zero or low defect count) displays (Fig. 3).[8,95] In the following several paragraphs,

FIG. 3. A TFT-LCD display made by Sharp, exhibited at the 2002 IDW (Ninth International Display Workshop), Hiroshima, Japan. This example has 240 (RGB) × 240 pixels. The display in Ref. 8 exhibits more visual complexity, but the publication does not show color (from SID Web site, www.sid.org; photo by Ken Werner).

we discuss a-Si display technology in some detail because it is in direct competition to organic backplanes.

Toshiba researchers showed[8] that performance of a-Si TFTs was equivalent to that on glass until deposition temperature dropped below 150 °C. This has also been demonstrated by Gleskova and Wagner.[96] PEN, with a long-term service temperature of 160 °C, is therefore well suited to this application, is as transparent as PET (as well as being superior in several other parameters), and costs only about three times more at present (higher volume would probably decrease this figure).

So far, with only one exception,[9] all a-Si TFTs on plastic have been fabricated on small wafers using conventional equipment. Roll-to-roll processes are the natural way to handle plastic, and the equipment necessary to make a-Si transistors in this way exists today;[9,97] however complexity, risk and expense have prevented more than tentative exploratory experiments. Nevertheless, such processes are likely to emerge in time, further lowering costs and providing true large-area flexible displays of high quality.

a-Si transistors on plastic are often dismissed because of concerns about thermally induced distortion in polymers and the mismatch of coefficient of thermal expansion (CTE 2.7 ppm/°C) and polymers (some of which may be well over 50 ppm/°C). These issues and their solutions have been discussed elsewhere.[9,97] There exist substrate polymers with CTEs virtually identical to silicon, and other materials can also be used as matching layers. Two-sided coating with inorganic dielectrics[98] and removal of the silicon except in the transistor "islands"[99,100] likewise help substantially.

Dimensional stability is also a moving research target, with improvements in materials quality (PEN being especially noteworthy[101]) as well as process techniques.[97] No one, using either inorganic or organic materials, has demonstrated the ability to fabricate useful transistors on meter-wide polymer rolls at any cost, let alone a saleable one. An objective consideration of the relevant possibilities, however, does not lead to the conclusion that silicon will be necessarily inferior to organic semiconductors for this purpose.

Transfer techniques provide further options for using silicon. Researchers at Seiko-Epson and Sony have published[102,103] techniques for transferring polysilicon TFTs from glass onto plastic substrates, which are not subject to any patterning or above-ambient temperature processes. The cost of such transfer techniques, extended to plastic rolls, will necessarily exceed the cost for the glass devices alone, but most likely by much less than 2× (especially if the glass can be recycled as Seiko-Epson's process allows).

Fluidic Self-Assembly (Alien Technologies) provides yet another way to introduce crystalline silicon to plastic.[104,105] It is arguable whether one can cost-effectively make high-resolution displays this way, but it is almost perfectly suited to ultralarge, low-resolution displays such as highway signs (where pixels may be ~1 mm or more). In addition, smaller "microchips" would be cost-effective for present-day high-resolution displays if suitable automated means of placing them are developed.

As has been cogently pointed out by Howard,[2] low cost has been achieved in electronics during the past 40 years not by the invention of any new device architectures or materials, but by the shrinking of size in the existing one. The single example of "large area electronics" that is a major industry today, amorphous silicon, exists because this shrinking paradigm did not satisfy the needs of displays. Successful implementation of the theme represented by Fluidic Self-Assembly (which is only one manifestation and not the ultimate version of this approach) would return even displays to the conventional silicon fold.

These observations do not preclude the possibility that organic transistors may find use as display backplanes in some products. Indeed, Philips has recently announced a venture (Polymer Vision) for the production of pentacene-based backplanes for a roll-up electrophoretic display,[106] and a prototype with close to two thousand transistors has been demonstrated. What is clear is that lower cost is not a given, while matching performance of silicon-based approaches will be difficult.

VI. ALTERNATIVE PATTERNING TECHNIQUES

As noted in the introduction, a major research focus has been patterning methods[17] with the promise of lower cost than the techniques used with ICs today, revolving around the "printing" theme. Prominent among these is soft lithography,[19] using poly(dimethylsiloxane) stamps to transfer ultrathin films of some "ink" (usually a self-assembled monolayer) onto a surface where it may be used, in some cases, as an etch mask and in other cases simply as an alterant of surface energy. There are also variants of this such as "MIMIC" (micromolding in capillaries) which will not be discussed for lack of space.

This has proved to be a very effective laboratory tool and enabled the fabrication of patterns (especially at very high resolution) that would have been otherwise possible only with much more expensive machines. From the industrial viewpoint, however, microcontact printing is a variant of parallel printing in the same class as offset lithography, except that it has no reliable and supported tools commercially available for its practice. It has no suitable alignment technology; no experience with stamp durability; and no proof that the extremely thin masking layers are adequate for production-worthy etch processes. At best, several more years of infrastructure development will be needed before it can have significant commercial impact.

High-resolution roll-to-roll imprint lithography has been practiced for some time.[107] Recently, Hewlett-Packard has reported the use of such a process to make a-Si transistors,[108] using a novel etchback-based self-alignment process. Though the tools for roll-to-roll imprint patterning are still not standard commercial items, the imprint masters used by Epigem are hard relief structures, familiar to the industry from gravure rollers. These techniques have so far been used only to pattern etch masks, not for direct patterning of active materials. Active material patterning would be problematic because of the small but finite thickness of residue that is inevitably left under the raised imprint master features.

3M has pioneered the use of thin (25–50 μm) polyimide shadow masks[109] in connection with their OFET development; these masks (patterned by laser ablation) are currently 6″ × 6″, and they forsee scaling these to 1-m widths and using them in a roll-to-roll step-and-repeat process. Because the masks are patterned in a laser direct writing system, cycle time (from design to product) can now be as rapid for evaporated molecules as for any liquid-phase printing process.

Laser thermal transfer[18] has potentially great value for small fractional coverage of large areas, although much more needs to be done to understand its cost, materials compatibility, and the resulting device properties. It appears ideally suited for connecting patterns (such as long wires) made by offset printing to other features, combining the speed of the latter process with the alignment in the laser.

Mention should finally be made of other "digital" techniques, such as simple liquid dispensers (e.g., Ohmcraft), which are truly inexpensive and surprising fast (0.25 m/s) with a comfortable resolution in the 100-μm range, and aerosol jetting (Optomec), which has probably claimed the world's record for step coverage (~100-μm lines continuous over a 500-μm near-vertical step), and can produce 10-μm lines in a variety of electronic materials, with maximum linear speed of approximately 0.2 m/s. They lack the extensive multiple-head capability of jet printing but are in an earlier stage of development.

VII. ORGANIC MEMORY

There have been several proposals for high-density rewriteable memory based on electronic effects in organic materials;[110–113] space limits will preclude more than a brief comment on the patterning issues. All organic solid-state (or quasi-solid state[112]) memories rely on a crossbar architecture, in which data is written to and read from a material, preferably with at least two stable states, by application of a bias to crossed electrodes; the architecture is similar to a passive-matrix display.[114] This highly repetitive structure is relatively simple compared to transistors, and alignment is much less of an issue: if the top and bottom electrodes are misaligned by a few micrometers or a few degrees (e.g., during roll-to-roll lamination), it results only in the loss of a small fraction of the potential bits (which can be catalogued and excluded from use by software). These facts auger well for the potential of large-area, low cost techniques to prepare such systems, as the active material can be coated (most likely from solution), and electrode patterning can probably use relatively high-speed techniques such as imprint lithography.

The chief limitation, which affects all such crossbar technologies, is the supply of electronics. Each electrode must be connected to a transistor, which leads to a multiplexer and further circuitry that provides the read and write signals. The connection of the electrodes (which will probably have to be a maximum of 1 μm for acceptable bit densities) to these transistors is a high-resolution lithography process, and if the electrodes have not been placed with corresponding precision, there is a serious problem in this interconnection.

Customer expectations of memory performance implies that the transistors themselves must be high speed ($\geqslant$1 MHz). The drive electronics package and its integration with the actual memory elements will most probably dominate the cost of the product.

The cost of any solid-state memory product must be well under that of Flash memory, with which it will inevitably be in competition; thus it will have to begin under \$0.10/MB (Flash is now dropping below \$1/MB retail sales price), with prospects for steady decrease. At 1-μm feature size (line/space), this implies roughly 15¢/cm^2 (manufacturing cost, at 1/2 of sales price), which sounds attractive compared to previous discussion, except for the electronics and integration issues.

VIII. DISRUPTIVE TECHNOLOGY

Several years ago (1997), Prof. Clayton Christensen (at the Harvard Business School) published a book[115] that has attracted attention well beyond the normal business audience. Its theme has been widely embraced by the organic electronics community and has been used to argue that the cruder performance of OFETs is not inconsistent with their success. Christensen himself has taken note of the technology in published work.[116] It is worthwhile, given the significance of the disruptive technology theme and corresponding strategy, to step back to the fundamentals that are exposited in the book and other publications.[117]

Within the limits of this article, these fundamentals can be summarized as follows: a disruptive technology is one that is in general inferior in performance to some (at least logically related) existing technology and that is more expensive per unit of functionality, but which is cheaper as a complete product and serves a new set of customers or serves customers in a new way. Disruptive technologies can only enter markets that are "overserved"; that is, where improvements being introduced are more than most customers really need. Once they find a "beachhead" with this new customer set, they are steadily improved and are able to appeal to a larger market; eventually, they may completely extinguish the previous technology or relegate it to a minor niche.

Organic transistors do not meet the disruptive litmus test for either RFID tags or display backplanes. These markets are nowhere near overserved. RFID customers want more of virtually everything: more read range, more data, lower power consumption, more durability, and smaller form factor—all at lower cost per unit. Similarly, display customers are still willing to buy each new version that offers greater resolution, more vibrant color, lower power consumption, and lighter and smaller form factor—provided cost does not increase. Though there may in fact be some new display applications where existing technology is overkill (e-paper is often mentioned), conventional alternatives exist that have better performance at a comparable, if not lower, price (Christensen refers to this as the "response of the incumbent"). The alleged failings of silicon are to a large extent simply not real: it is neither high cost, nor incompatible with large areas or temperature-sensitive materials.

Though jet and other digital printing methods are not inherently "low cost"; however, they *are* inherently capable of small product volumes. That is precisely what brought about the inkjet industry, and it is this property that points the way to a truly disruptive development path for organic FETs. Silicon of useful quality is not and never will be directly printable. (Though one flex circuit company has been said to have built an inkjet head that successfully dispensed copper for a day, this hardly seems like a fruitful avenue to pursue! Laser thermal transfer is probably also not applicable due to interface issues.)

The advantage of the printability of organic materials is not lower cost per transistor, but the ability to economically supply a small number of transistors *in a small number of products.* Even if ultrathin silicon "microchips" can be made and packaged as discussed above, the cost is reasonable only with large volumes of identical wafers; for example, the *minimum* order for application specific integrated circuits (ASICs) (not necessarily the point at which price is minimized) is around 5,000–20,000 units.[118,119]

Though the initial market size is not obvious, there are without doubt many electronic products for which some customers would pay good money[120] and for which OFETS could be ideally suited, because ultralow cost is not the *raison d'etre,* but the ability to quickly supply small volumes at reasonable cost is vital. Not only is the initial design and fabrication cost likely to be lower with direct printing, but subsequent modifications to adjust to changing customer desires become readily feasible, almost analogous to software updates. Thus, ironically, low cost is indeed the feature of organic devices that can make them successful, but the cost must be assessed *with respect to the entire product and its customer needs.*

Disruptive technologies require an entrepreneurial, experimental exploration of the marketplace to find the niche that can strongly benefit from the innovation, rather than formal analysis of already large markets. Those who wish to commercialize organic transistors must find the customers who really need the customizability and sensitivity to environment that make their product unique. Once there is a revenue-producing foundation to support further innovation, some of the limitations may indeed be surmounted. As sophisticated as our knowledge of organic electronic materials is, the industry appears more like silicon in the 1960s than silicon today, and a shorter development time should not be expected.

IX. SUMMARY AND CONCLUSIONS

Perhaps the principle theme of this article has been an effort to dispel the notion, quite prevalent in the scientific literature, that organic electronic technology = low cost. The reality is far more complex and subtle: cost is determined by processing, the latter is accounted for predominantly by equipment capital cost and throughput, and anything "micro," involving feature size control, registration, and defect elimination on a microscopic scale, requires engineering that adds cost and limits speed. Techniques that seem simple and cheap in the lab become expensive when developed for production.

Organic LEDs are on their way to becoming a major success. Although patterning them is not cheap, they provide a superior basis for vibrant emissive flat panel color displays. However, they will coexist (and compete) with LCDs for many years and will share roughly the same market. Lighting constitutes a huge, substantially new opportunity for organic electronic materials despite current technological limits, but very high-speed roll-to-roll processes that have yet to be even tested seriously would have to be adapted. The investment is not large compared to semiconductor or flat panel displays scales, but it will take imagination, courage, and probably some multipartner collaborations to make this happen.

The nascent organic PV industry has exactly the opposite problem. The equipment is largely conventional and the economic requirements would not push its limits. However, no one has yet demonstrated the requisite efficiency. Nevertheless, the appropriate research strategies are clear and reasonable, and the reward is massive. Both of these products would lead to industries producing billions of square meters of product (and billions of dollars), with major social and environmental benefits along with the profits.

The arguments summarized here suggest that OFETs, on the other hand, are not suited to any identified large-scale market today. The chance for OFET RFIDs in anything but the distant future, if ever, is remote. Display backplanes make much more sense, but will still be a very tough competitive slog with various forms of silicon, which has the advantage with designers in terms of familiarity, known reliability, and understood physics, and a large infrastructure and momentum behind it. There are no characteristics of organic FETs that actually provide real superiority in displays compared to silicon, whereas in many cases the opposite is true. OFET researchers need to become more familiar with the actual state of development of the competition in this area if they are to be effective.

One may well ask why such extensive research efforts are being targeted to such questional market prospects. Any answer will of course be speculation, but the discussion of disruptive technology is certainly pertinant. Large companies (and to a great extent venture capitalists) plan technical strategy on the basis of procedurally well-defined market analyses, whereas the definition of the successful market niches for OFETs will come only from exploratory experiments with quick feedback and will initially be small opportunities (though the long-range growth potential may be huge).

A second problem is the seductive vision of "printed electronics." One actually finds marketing communications seriously asserting the expectation that organic RFID tags, for example, will be printed in the same process, at the same time, as the printing of visual labels on packaging. No one familiar with both the science of organic electronic processes and materials and the graphic arts printing environment would put such a vision forward, yet just this idea is probably responsible for driving a significant portion of the R&D investment in the field. And if so many people are saying it, who wants to be left out?

Those who believe that either the expenditure of vast sums of money or the presence of many participants are strong indicators of commercial success would do well to consider such historical examples as the Josephson junction computer (IBM, 1969–1983), or the more prosaic but instructive case of HP's Kittyhawk 1.3″ disk drive (chronicled by Christensen[115]). It would be most unfortunate if organic transistors followed the venerable path blazed in these examples, which were technically brilliant but economic failures (of major magnitude) because their markets were not properly analyzed.

There is little doubt that organic electronic materials are commercially valuable; a few of these value propositions have already emerged, and more will come as innovative and nimble entrepreneurs find the market niches for which they have a good fit, and customers select what is really valuable and support growth of those technologies. There is a great danger, however, in attempting such visions as "all-organic electronics," and attempting to replicate existing electronic products from organic materials just because one is able to do so. The nature of the materials used will be just one aspect of the total performance and cost of the product, which are the features evaluated by the customer. But if an objective product focus and customer-needs sensitivity can be maintained by those whose job is to translate basic science into applications, then there will certainly be an exciting future for organic electronics.

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