Organic Light-Emitting Diodes

Emerging Technologies & Business Innovation (Fall 2009)

Patrick Frey
Kwasi Frye
Ankit Shah
Jack Shutzman

Table of Contents

I. OLED Origins

In late 1970s, Eastman Kodak company scientists Dr. Ching Tang discovered that sending an electric current through a carbon compound prompted the organic materials to glow. It was not until 1987 that Dr. Tang and Steven Van Slyke reported the Organic Light Emitting Diode (OLED) structure that became the foundation for today's OLEDs. The first discovered color was green but by 1989 the Kodak research team had demonstrated spectral colors using fluorescent dyes and boosted efficiency and luminance.[1]

II. Technology

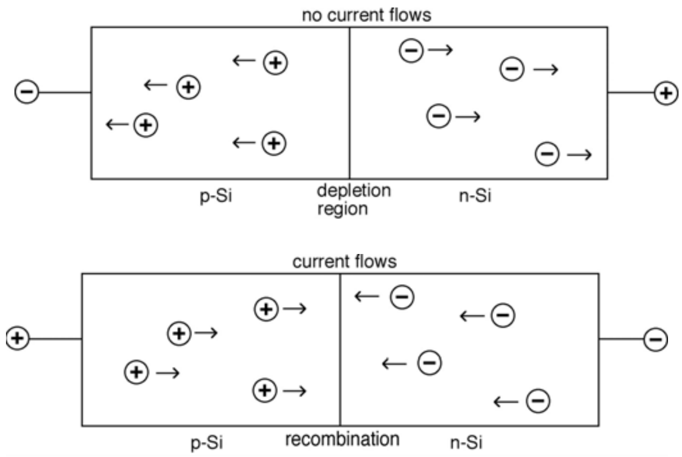
Light-Emitting Diodes (LEDs) [2,3,4,5,6,7]

LEDs are small light bulbs that do not have a burning filament and instead operate by electron movement within a semiconductor.

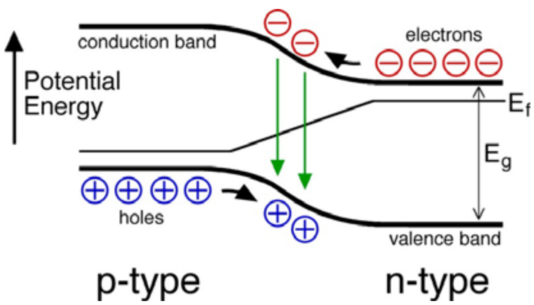
Electrons orbit the nucleus in discrete bands representing different levels of energy. Bands closer to the nucleus are of lower energy. Doping[8] can cause one semiconductor terminal, called N(egative)-type, to carry additional electrons on the valence band[9]. Similarly, doping can create a P(ositive)-type terminal, resulting in an excess of positive charge carriers that can be defined as "holes", i.e. the absence of electrons. Free electrons tend to jump into these holes (attracted by Coulomb force), thereby creating the impression that the holes are moving in the opposite direction.

---

[1] "Kodak OLED History," www.kodak.com
[2] www1.eere.energy.gov/buildings/ssl/highlights_udc04.html
[3] www.ledinside.com/The_Light_Emitting_Diode_Principle_and_Behavior_20080612
[4] http://electronics.howstuffworks.com/led1.htm
[5] http://en.wikipedia.org/wiki/Electric_current
[6] http://en.wikipedia.org/wiki/P-N_junction
[7] http://en.wikipedia.org/wiki/Band_gap
[8] A poor conductor (or near-insulator) can be turned into a semiconductor via doping, the addition of impurities that deteriorate its original conductivity. Aluminum-gallium-arsenide is the most common dopant found in LEDs.
[9] Valence band: the highest state at which electrons are present at zero temperature.



In order to travel from a valence band to a higher-energetic conduction band, electrons require an amount of energy equal to the energy differential, or band gap[10], between both orbitals. This energy can be added via electric charge or heat. A semiconductor's material determines the band gap, as well as many other factors such as charge drift velocity that influence semiconductor performance.



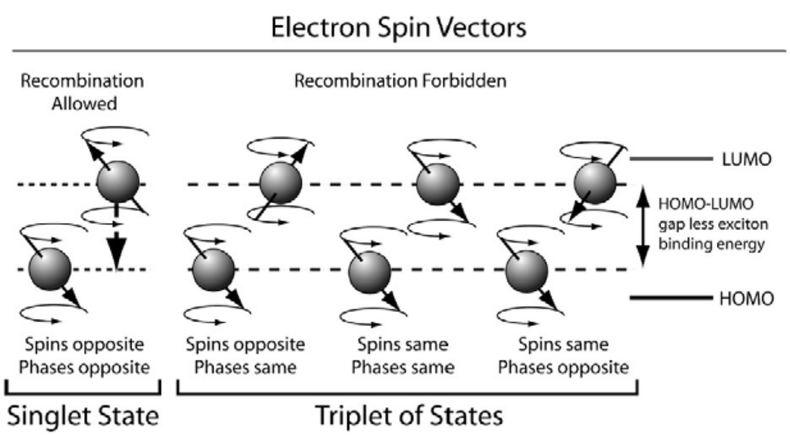
In insulator state, electrons from the N-type material fill the holes in the P-type material at the junction between both terminals (P-N junction), creating a depletion zone, which acts as an insulating layer that prevents charge from flowing. Attaching a circuit with the negative electrode at the N-terminal (cathode) and a positive one at the P-terminal (anode) will cause electrons from the cathode to flow towards the anode, lifting them out of their holes, and making the holes "move" the other direction. If the attached voltage is high enough to supply the energy necessary for the electrons to

[10] Semiconductors are defined by band gaps that are greater than zero but smaller than 3-4 eV; insulators have larger band gaps; conductor band gaps zero or close to zero.

cross the band gap, a current will begin flowing through the junction and across the diode from P to N. Inverting the voltage will have the opposite effect, causing the diode to revert to insulator state.[11]

In the same way as an electron requires additional energy to jump across the band gap to the conduction band, it releases additional energy when dropping from the conduction band into a hole on the lower energetic valence band. The fleeting pairing of an electron with its "original" hole results in an exciton, a quasi-particle bound by electrostatics. In a process called radiative decay, excitons die down within nanoseconds, emitting either phonons (heat) or photons (light) at energies (i.e. frequencies) corresponding to the crossed band gap.

There are four basic exciton states that depend on the spin and phase of the electron and the respective hole. An electron can only recombine with a hole if the latter has the opposite spin and phase. This singlet state occurs only about 25% of the time and results in photonic emission. 75% of the time, one of a triplet of states occurs, resulting in heat emission.[12, 13,14]



The energy released as a photon of a certain frequency (i.e. color) corresponds to the size of the band gap the electron had to overcome. If the frequency of the photon is high enough its energy will be visible as light. This effect is called electroluminescence.

---

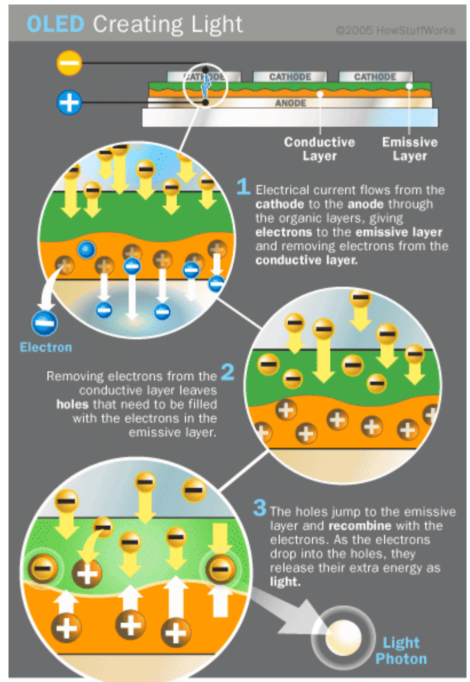
[11] http://www.imagesco.com/articles/photovoltaic/photovoltaic-pg3.html
[12] http://www.uni-regensburg.de/Fakultaeten/nat_Fak_IV/Physikalische_Chemie/Yersin/OLEDvde.htm
[13] Rockett, 2008
[14] Service, 2005

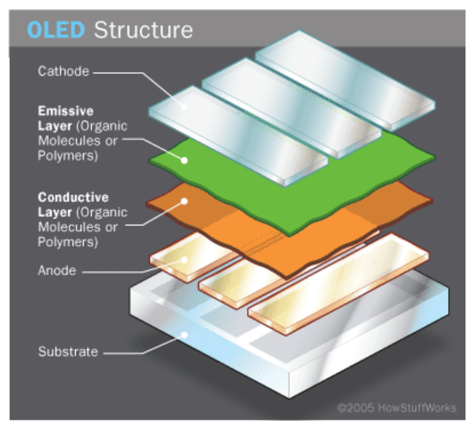
Organic Light-Emitting Diodes[15,16,17,18,19]

An OLED is a LED using an organic compound as P-N-junction. While OLED systems do not exactly correspond to the discrete band systems in inorganic semiconductors, they are very similar. An OLED's P-type material is referred to as the conducting or hole-transport layer (HTL), the N-type material as the emissive or electron transport layer (ETL). Similarly, the OLED conduction band is commonly known as Lowest Unoccupied Orbital Unit (LUMO), the valence band as Highest Occupied Molecular Orbit (HOMO). The principles of radiative recombination are almost identical, with singlets emitting energy corresponding to the orbital energy gap between electrons and respective holes.

Effective radiative recombination usually depends on:

- The balance in the rates by which electrons and holes are "injected" into the device through the electrodes. If the balance is off, electrical current will flow without generating light.
- The efficiency of radiative recombination, i.e. how many singlet states occur relative to triplet states. The efficiency can be influenced through doping-metals and organic materials used.
- Diffusion of impurities from the electrodes into the organic layer. The higher the diffusion rate, the lower the efficiency of radiative recombination.
- The amount of light reflected back into the OLED device. Undesired reflection can be lowered by using antireflective surface coatings, or by altering the metal of the back contact.





Basic OLEDs utilize two different types of organic materials, each suited for either HTL or ETL purposes and doped accordingly. One of these materials needs to be transparent so light can escape. OLED structures are aggregated as large grids, with each structure corresponding to a single dot or pixel. Emitted RGB photons need to be balanced to create white light. A substrate, which can be flexible or rigid, functions as a protective outer layer.

[15] http://electronics.howstuffworks.com/oled.htm
[16] http://met.usc.edu/research_projects_OLED.html
[17] www.oled-info.com
[18] www.about-oled.com/
[19] Rockett (2008)

III. Technology Advantages

General Lighting Technology[20,21,22,23]

Because they can only convert singlet excitons into photons, incandescent and fluorescent lighting technologies are highly inefficient, expelling as much as 80-90% of energy as heat.

The much higher native share of useable singlets that is generated by LED technology can be augmented by doping which allows the conversion of triplets into singlet. Phosphorescent dyes such as those used in OLED doping boast especially high conversion rates of over 80%, resulting not only in higher efficiency but also much lower material temperatures that yield much longer diode lifetimes and faster start-up times than incandescents or fluorescents. Efficiency is further boosted by LEDs better directionality and control thereof. Moreover, as they are composed from sturdy solid state materials, free of heavy metals, OLEDs are hard to break, more compact, lighter, and less environmentally harmful.

Display Technology[24,25]

In general, modern LCDs utilize light-emitting LEDs as backlight and then selectively filter and polarize light to generate images. This results in relatively higher electricity consumption, shallow or “untrue” colors, and the need for acute viewing angles. In addition to being much more efficient, OLEDs emit light on their own and thus do not require backlighting, filters, polarizers, or acute viewing angles. This results in higher brightness, refresh rates, and contrast ratios, as well as better depth and range of color.

Most interestingly however, it is possible to manufacture OLED systems as thin as 0.6% the thickness of a human hair by applying substrate films to surfaces via common inkjet printing technology. Such parsimonious structural requirements predestine OLEDs for use on extremely thin, light, sensitive, transparent, or flexible surfaces.

---

[20] Galing, 2009
[21] Service, 2005
[22] www.netl.doe.gov
[23] “New LED Lights Are Way Up to Par”, Product News Network, February 8, 2008
[24] www.about-oled.com
[25] www.oled-display.net

IV. Technology Disadvantages

Lifetime

OLEDs require that each pixel represent a complete system. Consequently, excitron decay times differ among pixels depending on amount and type of colored light emitted by each pixel. As different organic materials are used for different light compositions, pixel lifetimes can vary across different OLED systems depending on usage and type of embedded organic materials. The larger the display, the more pronounced becomes this problem, since more pixels have to be coordinated.

To date, however, some OLED screens already command lifetimes of approximately 50,000 hours and time comparisons of degradation TV screen luminescence degradation show that lifetimes are improving steadily, approaching those of LCD screens.[26]

Table: % of screen initial luminescence after 1000 hours

	Red	Green	Blue
Kodak OLED screen (2004)	62%	69%	38%
Sony OLED screen (2008)	93%	92%	88%
4-yr Improvement	**540%**	**388%**	**517%**

Economics[27,28,29]

While LED technologies such as OLED are already more economical compared to fluorescent and incandescent lighting when taking into account relative lifetimes, current prices are still at levels that are psychologically challenging for end-users who have to be persuaded to spend $35 on a single light bulb. In addition, good OLED performance starts visibly diminishing around 20,000 hours, especially within the blue spectrum, which is crucial for generating white light. Advanced sealing technologies to shield the sensitive organic materials from dust or humidity are also still limited and drive up cost.

[26] Forge & Blackman, 2009
[27] www.about-oled.com
[28] “OLED, the Future of TV”, Gizmodo, May 28, 2008
[29] “LED Thermal Management”, www.lunaraccents.com

Manufacturers are particularly struggling to lower prices on OLED display technologies, relative to the products' performance. Sony's current 11" TV, for instance, still costs about $2,000, clearly a first adopter premium.

V. Applications and Magic Quadrant of Business

The breadth of potential OLED uses is astounding. The most attractive applications include:

- Display technologies: consumer electronics (such as cell phones, PDAs, TVs, camcorders, laptops, etc.), or new surface displays such as transparent transportation aids (e.g. GPS or dashboard intelligence) that can be embedded directly into autos' windshields

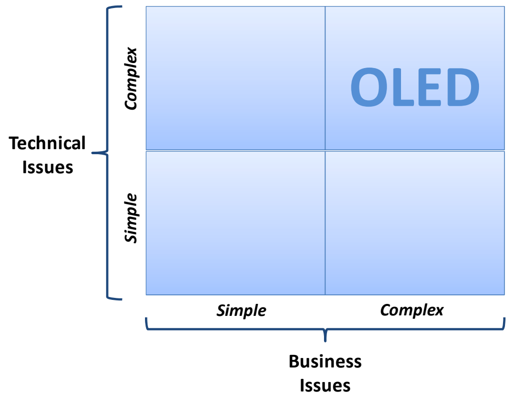
- General illumination: OLEDs enable the fusion of object (walls, ceilings, furniture, streets, vehicles, etc.) and object lighting

- Signage and signaling devices: billboards, traffic lights and signs, maps, etc.

- Medical applications such as surgical and endoscopic equipment

Many of these applications already utilize LEDs and once sufficiently economical, OLEDs will doubtlessly take over in a variety of new areas as well as in those that would benefit from lighter, thinner, more rugged, or more flexible lighting technology.

Magic Quadrant of Business & Technology



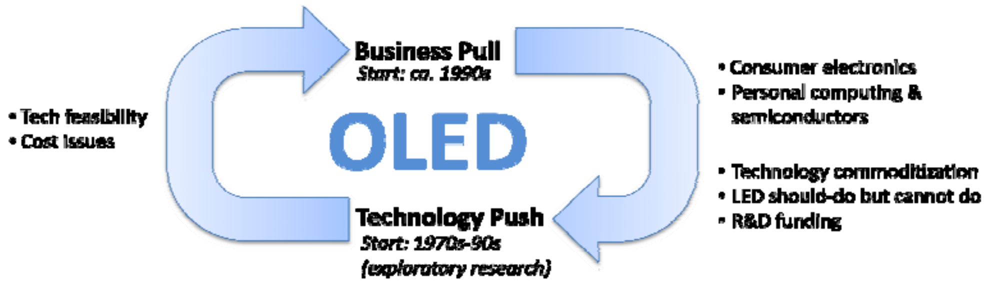
Overall, complex semiconductor technology, organic chemistry, and material science applications underlie OLED. Applications target complex business issues such as rugged or transparent displays or integration of object and lighting.

VI. Virtuous Cycle & Can-Do-Should-Do

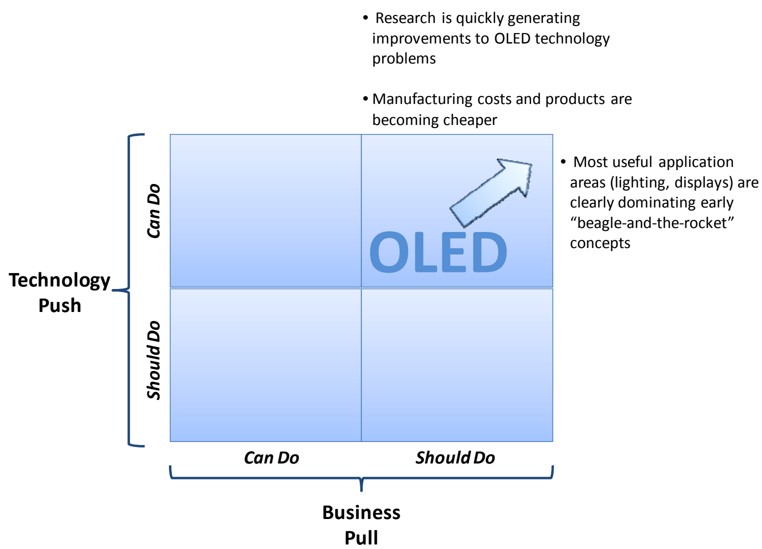
Although the initial invention of OLED technology was done in a commercial enterprise, OLEDs discovery was the result of exploratory research -- a classic technology-push beginning. And although OLED's scope of applications was visible from the beginning it, too, continued to exist primarily in the realm of exploratory research.

The past two decades' boom in semiconductors and handheld consumer electronics, as well as the resulting penetration of LEDs into many different areas, along with the rapid commoditization of these technologies eventually reignited the interest in OLEDs as a solution for value-added (and thus, higher margin) devices and for novel applications that regular LEDs could not fulfill. Novelty has been the greatest driver for resulting OLED business pull dynamics, particularly in the general illumination space, while display markets have mainly exerted their "pull" via higher margin potential for existing devices such as TV screens, PDAs, etc. Interestingly, compared to lighting new device display technologies, although fascinating, have only been a secondary driver in recent research development.

Technology Push vs. Business Pull & Virtuous Cycle



Can-Do vs. Should-Do



Similarly, OLED is steadily moving towards the Northeast in the can-do-should-do quadrant. As manufacturers are well aware of the costs and R&D efforts required to develop OLED applications, they mainly target applications with strong business potential and within the realm of what appears technologically feasible.

For most current electronics applications, OLED represents sustaining innovation that improves on LED or LCD technologies. For other applications such as flex-surface lighting, OLED has the potential to become a truly disruptive innovation as it would do away with the separation of lighting source and target object altogether. In general, OLEDs represent an advanced version of LED technology, which is realized in completely new ways by incorporating organic materials. OLEDs could therefore be perceived as next-generation LED devices – incremental relative to its predecessor, yet radical in its approach.

VII. Patents

As a discoverer of the original OLED technology Kodak held numerous patents, many of which have since expired as OLED commercialization had been a long, long time coming. Most of today's important OLED patents, held by Kodak or other companies, are related to remediating the technological and economical problems of OLED manufacturing, and since 2007 more than 180 OLED patents have been awarded.[30]

Kodak, for example, holds an influential patent (No. 7,279,063) about OLED bonding plates that form electrical "interconnect areas", which prevent undesired electron flows on the surface of substrate cover plates, thereby reducing the seal leakage from thermal expansion.[31]

Other notable Kodak patents include OLED systems that offer protection to both circular light polarization and environmental influences.[32]

A patent assigned to Canada's Nova-Plasma, Inc, describes a roll-to-roll manufacturing method for substrate surface application, which uses two bonded coating layers that prevent oxygen and water penetration.[33]

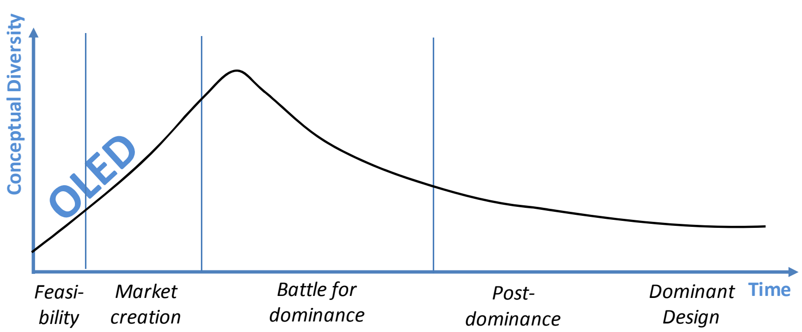
Belgian inventors Tanghe, Thielemans, and Dedended hold a patent on display element that compensates for operating parameters, such as supply voltage, temperature, and that optimize light output and OLED lifetime.[34]

[30] Galing 2009, 99
[31] US Pat. 7279063
[32] US Pat. 7259505
[33] US Pat. 7074501, 7298072, 12297812
[34] US Pat. 7262753

The past few years have seen significant business activities and agreements around OLED patent usage. On December 4 2009, Eastman Kodak announced the sale of its OLED screen technology unit to LG Electronics. The transaction included a patent share agreement that ended a long-standing dispute about LG's use of technologies for which Kodak claimed patent protection, and the potential violation of some of LG's digital camera patents by Kodak.[35]

In April 2005, Samsung SDI reached an agreement with Universal Display to use UD's proprietary OLED technologies in Samsung SDI's active-matrix OLED display products. According to Samsung, PHOLEDs have been shown to be up to four times more efficient than traditional fluorescent OLEDs, a key factor for lower power consumption, less heat generation, and longer operating lives.[36]

Innovation & Progress towards Dominant Design



As illustrated above, OLED is in the early stages of market creation and the technology is still struggling with feasibility issues related to device performance such as pixel lifetime or dust and humidity shielding. In addition, as original technology patents have expired and current patents primarily deal with mitigating performance issues, the path to a dominant design will be a long one. Market dominance is likely not going to result from core technology exclusivity, but either from cost advantages in manufacturing efficiency or the control of manufacturing process technology.

[35] Reuters Business News, December 4, 2009
[36] Electronic News, April 4, 2009

VIII. Key Market Participants

Eastman Kodak has played a key leadership role in bringing OLED to a wider market. By using its expertise in optical, imaging, chemicals, and color sciences, device physics, and thin film manufacturing, Kodak has continuously improved OLED technology. The company also has license agreements with 15 companies to help speed OLED development using Kodak technology (and thus creating potential for future patent licensing revenue streams).[37]

OSRAM, a subsidiary of German Siemens AG and one of the world's largest lighting manufacturers, is one of the key participants in the German government's OLED 2015 initiative, which bundles research and funding to increase the lifetime, brightness, and efficiency of OLEDs. OSRAM is at the forefront of OLED lighting research and has already developed a transparent white OLED that is invisible by day and whose lighting direction can be controlled.[38]

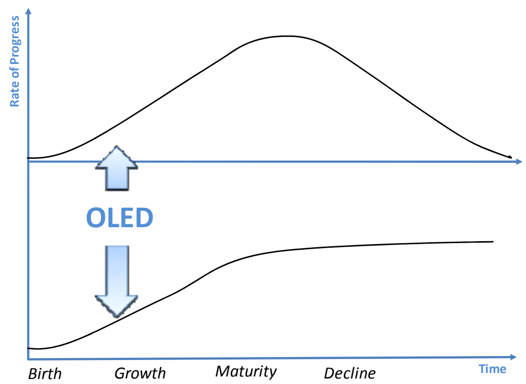
Samsung SDI has made strides in OLED display development and currently commands a 60% market share in active-matrix OLEDs[39] (AMOLEDs).[40] The company recently began mass-manufacturing 14-inch OLED displays and is gearing up to start producing 40-inch and 42-inch displays within the next year. The company expects demand for OLED products to rise over the next few years and is actively developing low-end passive-matrix OLEDs (PMOLED) as well as high-end AMOLEDs.

IX. Technological Progress

OLEDs are currently only beginning to cross the threshold to mass consumer markets and the technology is rapidly progressing as a response to the need for dealing with problems such as cost-efficient manufacturing or product performance and lifetime.

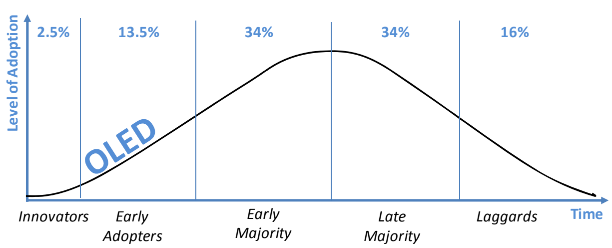
[37] Galing 2009, 160
[38] Business Wire, December 13, 2007
[39] "OLED pixels that have been deposited or integrated onto a thin film transistor (TFT) array to form a matrix of pixels" (Wikipedia: AMOLED)
[40] Korea Times, May 28, 2008

Rate of Technological Progress



Similarly, most small displays and basic lighting devices are extremely new, costly to manufacture, and thus priced to appeal mostly to early adopters. Large-scale displays, lighting, and tertiary applications are still firmly within the domain of innovators.

Adoption



X. Market Development and Hype & Gloom

Commercial OLEDs arrived at the scene in 1999, hailed as disruptive LCD replacement and with explosive sales projections. Many expected OLED to command a dominant market position by 2003. Although sales growth slowed between 1999 and 2003, the hype continued, fueled by new product ideas (business pull), exploding unit sales, rapidly increasing market sizes for LEDs and LCDs, and overly optimistic manufacturing cost estimates. Worldwide sales grew to $408M in 2004 (from $251M in 2003) and passed $600M in 2006, causing new players to enter the market. At the time, large displays and general illumination industries were still bogged down with R&D and small displays for small cell phones and MP3 players achieved an 89% market share by 2004, most of which was controlled by Samsung, RiT, and Pioneer.[41]

Growth slowed dramatically between 2005 and 2006 for both LED and OLED markets. Demand had been slower than anticipated and producers could not cope with technology problems and cost issues. Players such as Toshiba, Sony, and Epson decided to exit the OLED market altogether.

Growth eventually resumed in 2007, driven by new breakthroughs in substrate materials and application technologies, and most players returned to the market. Recent growth was due in particular to rapid advancements in AMOLEDs and further cost reductions. Larger displays quality had improved and become cost efficient enough to pique the interest of TV makers. In 2008, the first OLED lighting products finally reached the market. The effort was spearheaded by OSRAM and GE.[42,43]

The relevant technological advances of the past two years then snowballed, creating significant business pull and prompting the introduction of OLED laptops, larger-screen TVs, cameras, automotive displays, home office lighting, even clothing.

The OLED market is expected to continue its steep growth trajectory in the foreseeable future. This time, the hype is rooted in fundamental improvements in manufacturing equipment and relevant capital expenditure commitments. Moreover, the burgeoning lighting market is for the first time becoming viable demonstrating that OLED can also exist beyond high-tech.[44]

Overall, however, although OLED is currently experiencing explosive growth, improving economies, and new hype due to technological breakthroughs in remediating advantages such as pixel lifetimes or substrate applications, the technology is still most viable as a niche technology for devices with short lifetimes. In fact, many LCD panel makers are investigating OLEDs as a mere protective move that would

---

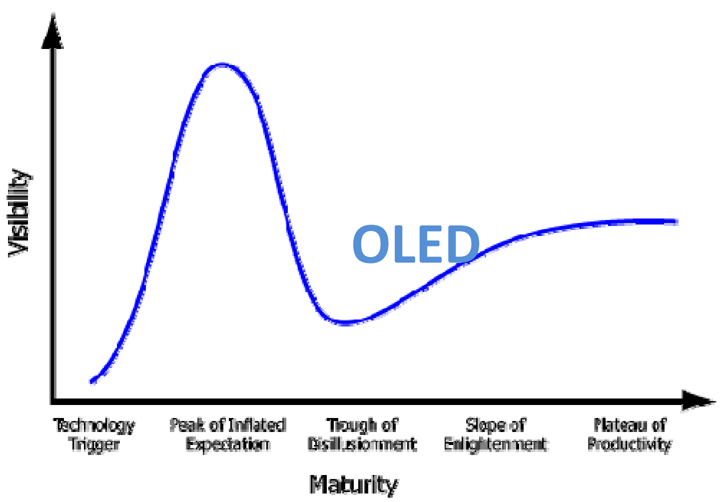
[41] Galing, 2009
[42] *Ibidem*
[43] Peterson, 2007
[44] Kanellos, 2008

allow them to jump on the bandwagon if OLED turned out to prove more mass potential. But for the time being, LCD clearly represents the bread and butter of the display business.

On the other hand, manufacturers of general illumination devices such as OSRAM are more upbeat about lighting applications for OLED and expect the technology to become competitive within the next five years.

On the whole it appears that while OLED technology had been written off for many years as too expensive, it is now experiencing a cautious but deliberate research revival across multiple applications. Heavy R&D spending on the illumination side and the arrival of more and more OLED consumer products suggest that the technology is entering the more enlightened stretch in its hype cycle.

Hype-Cycle



XI. Conclusion

OLED is a complex and fascinating technology that started out as a technology push effort and that has over several decades unfolded tremendous business pull for a variety of applications, some of which such as light bulbs it may eventually displace. For the time being however, most OLED applications represent a mere augmentation of LED and LCD technologies. Manufacturers are still struggling with quality and cost issues and relevant OLED consumer products are only beginning to gain traction with early adopters. Nevertheless, the technology and its purveyors continue to grow at astounding rates and OLED may well finally realize the incredible market potential that it has promised for over thirty years.

Bibliography

Czeremuszkin, Grzegorz, Mohamed Latreche, and Michael Wertheimer. "Transparent support for organic light emitting device". United States of America Patent 7,298,072. November 20, 2007.

Emma. "The Light Emitting Diode Principle and Behavior", *LEDinside: Let there be light*, http://www.ledinside.com/The_Light_Emitting_Diode_Principle_and_Behavior_20080612 (accessed November 21, 2009)

Forge, Simon, and Colin Blackman. "OLEDs and E-Paper: Disruptive potential for the European display industry". *JRC Scientific and Technical Reports* (2009). http://ftp.jrc.es/EURdoc/JRC51739.pdf (accessed December 11, 2009)

Frazer, Lance. "Organic Electronics: A Cleaner Substitute for Silicon". *Environmental Health Perspectives* (2003) 111, 5: A288-A291. www.jstor.org/stable/3435084 (accessed November 21, 2009)

Freudenrich, Craig. "How OLEDs Work". *HowStuffWorks*. http://electronics.howstuffworks.com/oled.htm (accessed November 21, 2009)

Galing, Bernie. "World Market for LEDs and OLEDs". *SBI Business Report*, Rockville: SBI, 2009.

Harris, Tom. "How Light Emitting Diodes Work". *HowStuffWorks*. http://electronics.howstuffworks.com/led1.htm (accessed November 21, 2009)

Kanellos, Michael. "The Global Lighting Market by the Numbers, Courtesy of Philips". *Seeking Alpha*. www.seekingalpha.com, October 23, 2008 (accessed December 12, 2009)

Kodak. "Method of making an OLED display device with enhanced optical and mechanical properties". United States of America Patent 7,279,073. October 9, 2007.

Kodak Website. http://www.kodak.com/eknec/PageQuerier.jhtml?pq-path=1683&pq-locale=en_US (accessed December 12, 2009).

"New Transparent White OLED from OSRAM Opto Semiconductors Achieves High Level of Performance". *Business Wire*. December 13, 2007.

OLED Display. www.oled-display.net (accessed December 11, 2009).

OLED info. www.oled-info.com (accessed December 11, 2009)

Peterson, Cynthia Ann. "LED The Way". *Malaysian Business*, November 16, 2007

Rockett, Angus. "Organic Semiconductors". In: *Material Sciences of Semiconductors*, 395-453. New York: Springer Science, 2008

"Samsung Licenses OLED Patents from Universal Display." *Electronic News*. April 20, 2009. http://www.edn.com/article/CA526386.html?partner=enews (accessed December 12, 2009).

Service, Robert F. “Organic LEDs Look Forward to a Bright, White Future”. *Science* (2005) 310: 1762-1763.

"UPDATE 2-Kodak sets patent pact, OLED unit sale, with LG". *Reuters*. December 4, 2009. http://www.reuters.com/article/idUSN0415667320091204?rpc=77 (accessed December 12, 2009).

U.S. Department of Energy. “Solid State Lighting: Low Voltage White Phosphorescent OLED Achievements”. *USDE: Energy Efficiency & Renewable Energy*. www1.eere.energy.gov/buildings/ssl/highlights_udc04.html (accessed November 21, 2009)

Wikipedia contributors. "Active-matrix OLEDs". *Wikipedia, The Free Encyclopedia*. http://en.wikipedia.org/wiki/AMOLED (accessed November 21, 2009).

Wikipedia contributors. "Band Gap". *Wikipedia, The Free Encyclopedia*. http://en.wikipedia.org/wiki/Band_gap (accessed November 21, 2009).

Wikipedia contributors. "Cathode Ray Tube". *Wikipedia, The Free Encyclopedia*. http://en.wikipedia.org/wiki/Cathode_ray_tube (accessed December 11, 2009)

Wikipedia contributors. "Contrast Ratio". *Wikipedia, The Free Encyclopedia*. http://en.wikipedia.org/wiki/Contrast_ratio (accessed December 11, 2009)

Wikipedia contributors. "Electric Current". *Wikipedia, The Free Encyclopedia*. http://en.wikipedia.org/wiki/Electric_current (accessed November 21, 2009).

Wikipedia contributors. "Organic Light Emitting Diode". *Wikipedia, The Free Encyclopedia*. http://en.wikipedia.org/wiki/ Organic_light-emitting_diode (accessed December 11, 2009).

Wikipedia contributors. "P-N Junction". *Wikipedia, The Free Encyclopedia*. http://en.wikipedia.org/wiki/P-N_junction (accessed November 21, 2009).

Yoo-chul, Kim. "SDI Sets Global Trend". *Korea Times*, May 29, 2008.