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Development of OLED's, a Next Generation Flat Panel Display Technology : Experiences from an On-going Collaboration between Industry and Academia

William Leo* and Libero Zuppiroli

*CFG S.A., Av. de Lonay 2, 1110 Morges, Switzerland
Dept of Physics, PHB Ecublens, EPFL, 1015 Lausanne, Switzerland

Abstract

The flat panel industry is one of the fastest growing sectors today with an enormous potential market. Currently, the dominant technology is the liquid crystal display. However, new technologies such as plasma displays, field emission displays and organic electroluminescent devices (OLED's) are now emerging as challengers to this position. Unlike previous innovations, these new technologies are also pushing against the frontiers of science itself. This implies that achieving faster progress would require more active, focused scientific support as well as the technological and engineering development traditionally realized by the developing company. This seems to be born out by the current OLED industry wherein the current industry players are all closely associated with one or more academic laboratories. Lack of such support also seems to explain in part the slower development of earlier flat panel technologies such as the field emission display.

For management, this implies some new issues : the organization of a more intense working relation with an academic laboratory, the management of a science-technology interface and others.

We report on the experiences of a current technology transfer between the Semi-Crystalline Solid State Physics Lab at the Swiss Federal Institute of Technology at Lausanne and CFG SA, a private enterprise active in the flat panel display industry. The collaboration to develop and industrialize (OLED) technology has been on-going for more than two years and continues to this day. To ensure efficient transfer and development of the technology, a « strong coupling » scheme has been implemented between the two and has thus far produced excellent results.

Introduction

One of the important outgrowths of the information/microelectronics revolution has been the creation of the flat panel display (FPD) industry. Most prominently seen in notebook computers, palm-tops, mobile telephones, calculators, camcorders, digital cameras, watches, toys and other devices, flat panel displays today have a market value (1999) of $19.7 billion. Moreover, demand is such that *FPD*'s are expected to become even more ubiquitous in the coming years. Indeed, analysts are estimating market values ranging from a conservative $26 billion in 2004 to double and even triple this figure[1]. This is to be contrasted with the standard

[1] See for example: Dave Mentley, OLED Displays - Out of the Lab and into the Market, *Commercializing OLED's Conference*, San Diego, CA, USA, October 11-13, 2000.;
Ken Werner, Conference Report of First IDMC and FPD Expo Korea, *Information Display*, vol. 16, no.11, p. 30, November 2000.

cathode-ray-tube, (a device which celebrated its *100 th* anniversary in 1998) which had a 1999 market value of $23.5 billion and is also predicted to have a $26 billion market in 2004. Whichever projection is used, however, it is clear that *FPD*'s constitute an enormous market which will become even larger.

Currently, the dominant FPD technology is the liquid crystal display (LCD) which commands over 90% market share. While the technology was invented in North America and Europe, it was the Japanese who invested heavily in its subsequent development and commercialization, in particular, the TFT active matrix technology used in full color displays. Today, Japanese, Korean and Taiwanese companies are the overwhelmingly dominant forces in the market. Nevertheless, the LCD is far from being the perfect display. Most notably it has a limited viewing angle, a slow response and lacks brightness. Manufacturing is complicated with low yields and is costly, requiring heavy capital investment. And while LCD technology has greatly improved in recent years, the market continues to demand better and cheaper flat displays. For this reason, new technologies are now emerging, for example, plasma display panels (PDP), field emission displays (FED) and organic light emitting displays (OLED) - all of which attempt to address some or all of these problems[2].

Organic light emitting device (OLED) technology is the youngest of these new technologies. Invented only about 17 years ago, it has made rapid progress and is today on the threshold of mass production. Over 50 companies are reported to be involved in OLED research or development along with many academic physics and chemistry laboratories. OLED technology makes use of carbon-based molecules which are deposited in extremely thin layers, on the order of a hundred nanometers thickness, between two appropriate electrodes. When an electric current is applied, bright light is emitted by the organic layers. Using the correct architecture and appropriate materials, low-voltage display devices, both monochrome and full color, can be made with this technology. OLED's offer many advantages over the current LCD. These include a much better brightness and 180° viewing angles due to the emissive nature of OLED's. They are thin and lightweight, have fast response times and are less power consuming than displays with equivalent brightness. Moreover, the use of organic molecules, as opposed to semiconductors, makes them easier to handle which should in principle lead to cheaper manufacturing. The almost monolithic structure of an OLED also makes it many times simpler than an LCD - or any of the newer technologies for that matter – further enhancing its advantages. Finally, new display devices such as flexible displays and transparent displays are possible or much easier to make with OLED technology thus enabling new applications. It is no wonder therefore that many in the industry find the OLED to be as close to the perfect display as one can hope.

Nevertheless, OLED technology faces many challenges. Indeed, making an OLED device will not only require further development of the organic materials and the device structure, but also new developments in many other technologies on which the making of a complete device will depend. For example, substrates with planarities on the nanometer scale, encapsulation materials with a high degree of impermeability to oxygen and humidity, electronics, patterning methods, manufacturing techniques.and equipment and more. These issues are intimately linked and their roles are far from complete understanding even at the scientific level.

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[2] These are the three emerging electronic display technologies receiving the most attention, but they are by no means the only ones around. One interesting class of technologies is *electronic paper* which may turn out to be a true disruptive technology (see for example, The Economist Technology Quarterly, Dec. 9th-15th , 2000).

Lessons from the Flat Panel Industry

It becomes clear then that developing OLED technology also involves developing the science as well. This is probably true of many of today's newer technologies also. Indeed, the development of the flat panel industry is probably illustrative of the high-tech sector as a whole. It is interesting therefore to look at the development histories of the dominant LCD and the two other principal emerging technologies : the *plasma display panel* (PDP) and the *field emission display* (FED). The development of each of these technologies contains lessons for technology management as a whole and illustrates how high-tech development strategies are now changing.

The Liquid Crystal Display

The history of LCD development is briefly summarized in Table 1 below. The development of this invention essentially follows the traditional scenario where there is a long time lapse between the discovery of the phenomena itself and the development of real devices. In this case, it was the application and development of the class of liquid crystals known as *twisted nematic* which ultimately led to viable display products in watches, games, telephones, appliances, etc. These are the monochrome, text displays which are found on many appliances today and go almost unnoticed by the average person.

Table 1
Brief History of LCD Development

1889 - Discovery of liquid crystal phase by Friedrich Reinitzer and Otto Lehmann
1963 - First demonstration of a liquid crystal display by R. Heilmeier at RCA Sarnoff Laboratories.
1971 - Twisted nematic (TN) liquid crystal display invented at Hoffman-La Roche
1973 - TFT Driver (thin film transistor) invented by Westinghouse
1983 - Super twisted nematic (STN) display demonstrated by BBC

It was the advent of the notebook computer and the need for flat, full color graphics displays, however, which drove the next wave of LCD technology development. Once again, the initial innovation was a North American idea : the *active matrix, thin film transistor* (TFT) driving technique. This is a complex semiconductor technology which requires making a panel with a matrix array of transistors, one for each color pixel on the display. For a simple VGA display with 640 x 480 display pixels (each display pixel consisting of three color pixels: red, blue and green), a calculation shows that close to one million transistors per panel are required. Not surprisingly, manufacturing yields were low because of the high probability of having one or more bad transistors on a given panel.

Unfortunately, management in American and European companies quickly rejected this technology as being too complex and expensive. This was not the case of the Asian companies, in particular the Japanese, who took a longer term view and continued to invest in active matrix technology well through the 1980’s and up to this day. Development during these years was essentially technology oriented with advances made through pure engineering ingenuity. Very little scientific research was actually performed nor required. The development of active matrix technology again illustrates the traditional technology transfer scenario wherein the new technology is essentially developed by engineering ingenuity within the confines of the company.

Despite its complexity, active matrix technology has been quite successful, and is now in fact undergoing a second explosion driven by a second *killer app*: desktop monitors! The challenge here is to make still larger panels at lower prices. Although some Western critics have referred to the Asian investment in this technology as a “race to lose money”, it would seem that today it has paid off. Indeed, active matrix LCD technology is by far the dominant flat panel technology today and almost entirely in the hands of Asian enterprises. In contrast, the number of American and European companies in the industry can be counted on the fingers of one hand and are all limited to niche markets such as military applications.

The Plasma Display Panel (PDP)

While the LCD is a general platform display suitable for many different applications it is still limited to relatively small sizes. The plasma display panel, in contrast, is basically aimed at one particular application : flat, large screen television.

At its simplest, a plasma panel consists of an array of miniature glass cells containing an inert gas, electrodes and a color phosphor. By applying a high voltage to the electrodes, an electric discharge is created which causes ultraviolet light to be emitted by the gas. The ultraviolet rays then strike the color phosphor which in turn emits colored light. Again the technology was invented in North America in the 1960's, while heavy investment was made mainly by Asian companies. Products are only now becoming available some 35 years later.

Plasma displays have excellent definition and color, are about 10% the thickness and 1/6 the weight of an equivalent CRT. They can thus be hung on the wall like a painting. Unfortunately, at prices between $12000 to $20000, they are about three to four times too expensive for the mass market. Indeed, whereas only a few years ago a total of 2 million units were projected to be shipped in the year 2000, today, that number is closer to 200 000 at best[3]. For the moment, PDP's are thus limited to niche applications where cost is not a factor. Moreover, having been designed for large screen applications, smaller screens with high resolution are difficult to make with plasma technology so that other applications which are less price sensitive, for example, computer screens, are excluded.

Although the technology is intrinsically simpler than TFT technology, PDP's are plagued by the high cost of components and complex manufacturing steps. The electronic drivers and the glass panel alone account for 50% of the cost, for example. Indeed, development was along "traditional" lines, as we have noted, so that manufacturing issues for PDP's were not addressed until the product was almost ready for production. The result is that today, sales of PDP's will be limited for at least another three years while alternative manufacturing materials and methods are investigated.

The basic lesson learned from this experience is that manufacturing issues in new technologies are an integral part of development and should be considered early on.

[3] Didier Jousse, The Choice of a Glass Substrate and Some Other Challenges for the Manufacturing of Low Cost PDP, *Ecrans à Plasma*, Journée d'Etudes 16 mars 2000 edited by Le Club Visu, Society for Information Display - France.

The Field Emission Display (FED)

Chronologically, the next new display technology to appear was the *field emission* display (FED). The FED essentially operates on the same principle as the cathode ray tube, i.e., electrons are made to impinge upon a phosphor screen which then emits light at the point of impact. However, in the FED the source of the electrons is different. In a CRT, this is an electron gun which emits a beam of electrons by thermionic emission. In a FED, an array of micro-points in the form of metallic cones, one for each color pixel, emits electrons under the application of a strong electric field only, without any heating of the material. This phenomena is known as the *field emission effect*, whence the name for the display. The use of a micro-point array thus allows the display to be very flat.

Table 2 briefly outlines the history of FED development. Although the application of the field emission effect to displays was already made in the 1960's, the FED was essentially launched by the development of micro-point technology some 20 years later. Thereafter, the time to market was considerably shorter than the LCD or the PDP.

Table 2
Brief History of the FED display

1928 -	Fowler-Nordheim Theory of field emission
1961 -	Application of field emission to displays by K.R. Shoulders
1968 -	Development of cathode matrix array using thin film technology by Carl Spindt at SRI
1986 -	R. Meyer of LETI in France demonstrates feasibility of micro-point matrix cathode
1990 -	LETI demonstrates 6-inch monochrome FED display
1991 -	LETI demonstrates full-color FED display
1998 -	First monochrome FED products appear

The FED is indeed a rugged, flat display which has drawn a particular interest from the aviation and military sectors where harsh environmental conditions are the norm. However, the FED is a very complex device and many fundamental manufacturing, engineering and materials problems remain to be solved. For this reason, the FED is currently limited to small sizes and monochrome devices. And despite the quick development time relative to the LCD or the PDP, the market perception is that the FED is "late", i.e., it is missing its window of opportunity.

This impression has been reinforced by the defection of a number of companies from the industry (most notably the *FED Corporation* which has taken up OLED technology instead and has renamed itself *eMagin*). Indeed, a lack of cooperation in the industry and a lack of academic support for more technologically oriented problems have been cited as the reasons. This can be attributed perhaps to the "go it alone" attitude of the players - an attitude, which in retrospect, is inappropriate when given the complexity of the technology.

Thus, a lesson which can be taken from the FED experience is that technology is becoming so complex that industry cooperation is necessary in order to solve all the basic problems within an ever decreasing window of opportunity. In this context, academic research groups can play an important, indeed an essential role in the development as well.

The OLED

The discovery of electroluminescence in organic materials dates back to the 1960's when light emission from anthracene, a solid organic crystal, was first observed. At the time, the intensity was too weak to be useful however. It was not until 1983 that researchers at Kodak discovered a strong light emitting organic compound known as Alq_3 with which they were able to produce a working, light emitting device. This was followed in 1989 by the discovery of light-emitting polymers at Cambridge in the UK. Although they are also organic compounds, the different physical properties of polymers open a different technological path to the production of light emitting devices. As we have mentioned, development has been rapid. In 1999, the first OLED product : a car radio with an OLED display by Pioneer, appeared on the world market and more recently in September 2000, a mobile telephone with OLED display by Motorola.

While the OLED industry is still forming, it is clear that the lessons from the PDP and FED experiences have been learned. Most notable are the industry alliances that have been formed and that are continuing to be formed; for example, Kodak and Sanyo who have teamed together to develop a full color active matrix OLED or Cambridge Display Technologies and Seiko who are collaborating to develop an ink-jet method for depositing polymer OLED's. In this same vein are the industry/academic alliances, for example, Cambridge Display Technologies with Cambridge University, Universal Display Corporation with Princeton & USC, Uniax with UCLA, Opsys with Oxford U., and not least CFG with EPFL. Moreover, manufacturing issues are taking on an early importance as new methods such as roll to roll processing are already being investigated by companies. Indeed, it is tempting to ask if these alliances are not the value chains of the future OLED industry in formation.

Thus, despite its complexity, the application of these lessons seems to have led to the rapid progress and success of OLED technology. The industry is, of course, still evolving and more changes are surely yet to come.

A "Strong Coupling" Experience

It is in the context of OLED development that we present here our own experiences in the transfer of this technology from the Swiss Federal Institute of Technology at Lausanne (EPFL), a Swiss academic institution to CFG S.A., a microelectronics company with an offering in the custom design and assembly of complete LCD modules for the industrial sector. This collaboration is on-going at the time of this writing so that our experiences are less than conclusive. Nevertheless, we hope they will be of use to others entering into such ventures.

The collaboration was initiated in 1997 when CFG was first introduced to the work of one of us (LZ) in the area of organic electroluminescence. CFG, at the time, was looking for new opportunities to offset competition from forward integrating LCD manufacturers while the EPFL was also seeking industrial support for its developments. Recognizing the opportunity presented by this technology, CFG purchased exclusive licenses to the EPFL's patents while the EPFL transferred the basic know-how to CFG. The two parties also agreed to enter into a project to further develop the technology with partial funding from the Swiss Commission for Technology and Innovation (CTI).

Traditionally, transfer of technology agreements are limited to just that: a simple transfer of knowledge and information from the research institution to the industrial company after which it is up to the latter to develop the technology into commercial processes and products. The research organization then retains only a consulting role. This has also been a common process in larger companies where new technologies are passed from a research department to an independent development department with no more interaction than required. However, it became clear that this traditional "weak coupling" scheme could not work here. Indeed the complexity and novelty of the OLED technology were such that *active* scientific support would constantly be required to answer specific scientific questions as they arose in the course of development.

For this reason it was decided to enter into a "strong coupling" scheme in which a very close relationship between the two parties is maintained. To this end, a group was formed with members from both parties. The principal place of work was the Laboratory for Semi-Crystalline Solid State Physics at the EPFL. CFG also offered additional support through its mechanical design services, electronics laboratory and clean room facility. From CFG, a "resident" physicist was assigned to the EPFL first to learn the technology and then to actively participate in the development work. With support from the Swiss CTI, additional scientific and technical personnel were also hired to participate in the project. While officially under the responsibility of the EPFL, recruitment and hiring decisions were made after consultation with the other partner.

It should be noted that this technology team existed in parallel with the laboratory's scientific staff who continued to pursue their normal academic activities independently. Since the environment was relatively open, confidentiality issues had to be considered. The members of the working group were sensitized to the problem and asked to sign non-disclosure agreements. Requests for information from non-team members were also systematically referred to the group leader.

Weekly meetings were instituted with formal minutes being taken (Note that formal minutes of group meetings is not commonplace procedure in academic research!). In addition, CFG's project management (WL) was also invited to attend and participate in the information exchange.

The group was officially constituted in June of 1999 with the double goal of increasing the lifetime of the EPFL-CFG OLED and of developing a suitable encapsulation scheme for protecting the OLED from humidity and oxygen. A first milestone was set at achieving a lifetime of 1000 hours within one year. Note that OLED lifetimes in June 1999 were only on the order of 100 hours.

Current Status

As of this writing, 18 months have passed and rapid progress has indeed been made. The first milestone of 1000 hours lifetime was actually reached and surpassed in December 1999, a full six months ahead of schedule. Indeed, at the end of January 2000, device lifetimes were already measured at over 2000 hours and are currently at better than 5000 hours.

This achievement was made possible largely by a better understanding of the main degradation mechanisms, one of the more important outcomes of the project. As well, many other insights and discoveries were also made in the course of this work which although not directly related to the objectives, help nevertheless to advance understanding into making better OLED's.

As to the second goal: encapsulation, a new promising method has been developed for which a patent has been deposited. And as if to underscore the lesson, this method was invented through old fashion ingenuity without too much scientific support! Development on this method still continues however.

A Comparison

Given the results, there is no doubt that the "strong coupling" scheme has been very successful and produced the rapid advances being sought with this new complex technology. This is not to say that there have not been any problems; however, our overall experience has been very positive so far.

It would be interesting, of course, to compare this to what would have happened had another scheme, such as "weak coupling", been used. Sometime after the start of the collaboration, one of us (WL) had the opportunity to exchange experiences with a participant in another technology transfer project involving a similar organic molecular technology. Although the application domain was different, the technological challenges were very similar. This particular technology transfer actually took place 6 or 7 years earlier, but unlike the CFG license, non-exclusive licenses were sold to different companies in the same industry. Typically, a "weak coupling" technology development scheme was implemented. Because the technology turned out to be more complex than imagined, progress by the licensee companies was very slow. Moreover, collaborative development with the licensor, an academic institution, was also hampered because of the presence of other licensees, each a potential competitor. Information exchange and discussion was therefore difficult. The result was that six years later, the licensees still had not made much progress in developing marketable products. In fact, many, including our interlocutor, were considering abandoning the project altogether.

This very suggestive example would seem then to validate our "strong coupling" hypothesis. One additional point which comes out of this case was the hampering effect of multiple licenses. A "strong coupling" scheme would certainly not have been possible had there been multiple licensees. Such a situation is advantageous for the licensor in the short run. However if it impedes the ultimate development of the technology, neither licensee nor licensor wins.

Culture Differences

While our "strong coupling" collaboration has produced good results, there have nevertheless been moments of tension and stress making for less than optimal operation. Much of this can be explained by differences in professional culture between the members. In the group were physicists with a background in academic research, EPFL-trained engineers, technical-school trained engineers[4], technicians and the project manager from CFG (WL) who had both a marketing and scientific research background. From a normal management point of view this would be considered a homogeneous group with all members having the same cultural values. Under normal conditions this is true. However, under stress conditions, the existence of subcultures within the group may start to become apparent. Indeed, each subgroup has its own professional values which the subgroup will emphasize or consider as higher priority under times of stress or conflict. Figure 1 summarizes these cultural values.

Figure 1

Professional Values of Technical and Scientific Personnel

Scientists → Ideas

Engineers (EPFL) → Design

Engineers (Tech. School) → Work, Process

Marketing → Product

For example, scientists will tend to favor the central ideas as more important than say the apparatus for demonstrating these ideas, whereas the engineers will consider the proper design and construction of the apparatus as primordial. Under a stress condition when delays become too long, some scientists will consider any additional work on the apparatus beyond its primary design capability as unnecessary attention to detail. The engineers in contrast will consider this as unprofessional "tinkering". Even among the engineers themselves there is a value difference between the EPFL-trained engineers and the technical-school engineers. The former will tend to value the design concept while the latter the process itself. Recognizing these differences is therefore an important task for management.

Similarly, there will also be many ideas which will be emitted in the course of development, all with merit and all exciting. This is inevitable and it becomes tempting for individual members to pursue these ideas. This, of course, has the potential of dispersing the group. Such problems emphasize the necessity of having a strong leader with recognized scientific authority. This person will set priorities in cases of conflict and refocus the group onto the work at hand.

Summary

Whereas technological innovation could proceed independently of science in previous years, the increasing complexity of new technologies are now pushing against the frontiers of science itself[5]. Given the rapidity with which these new technologies must be brought to

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[4] In Switzerland, two types of engineering training exist. The Swiss Federal Institutes of Technology consisting of the EPFL and the ETHZ in Zurich offer a more theoretical based training leading to graduate level degrees. In addition, there are technical schools at the cantonal level which offer a rigorous, but more practical level of training.

[5] Indeed, it has been estimated that as much as one quarter of the US GNP is generated by quantum related technologies. See "Just Thanck Planck", The Economist, Dec. 7, 2000

market, the traditional separation between science and technology is becoming blurred. This seems to be the case for the flat panel industry and in particular OLED's where academic research institutions are playing an important role in the overall development of the technology. For similar reasons, industry to industry collaborations are also becoming necessary.

For companies entering into high-tech technology transfers, it then becomes very important to judge the extent to which scientific support is an essential element. This may imply a different mode of collaboration between the academic and industrial partner. In the context of our own technology transfer this is the case so that we have opted for a "strongly coupled" mode of development, i.e., the formation of a unified project team consisting of members from both sides. The results thus far have been very encouraging. The milestones of the group have been reached well ahead of schedule and have already been surpassed by several fold. Another notable outcome has been the deposition of a new patent application. Moreover, comparison with a less successful but similar technology transfer case where a more traditional ("weak coupling") mode of transfer was used would seem to lend validity to this type of operation.