A History of Field Emission Displays

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Introduction

It has taken more than three decades for field emission displays (FEDs) to go from idea to commercial product. The purpose of this essay to trace the history of FEDs and to assess the future prospects for the successful commercialization of FEDs.

In 1968, Charles A. "Capp" Spindt at the Stanford Research Institute (now called SRI International) had the idea of fabricating a flat display using microscopic molybdenum cones singly or in arrays (FEA's). This development was the enabling technology the concept for using FEA's in a matrix addressed display (FED) conceived by the SRI team of which Capp was a member, and patented by Crost, Shoulders and Zinn in 1970 (US Patent 3,500,102). However SRI was unable to obtain funding for developing this concept in the decades of the seventies and early eighties, and the initiative for developing the technology moved to the *Laboratoire d'Electronique de Technologie et de l'Informatique* (LETI), a research arm of the French Atomic Energy Commission, in Grenoble. LETI picked up on the technology and publicly demonstrated an operating display in 1985. The SRI team were finally funded by Boeing and Commtech International (a venture capital patnership) to develop a full color display and were able to demonstrate the first color FED in 1987. The technologies developed at SRI were licensed to a start-up company called Coloray. Coloray was not successful but some key members of the staff were able to join Silicon Video Corporation (SVC), a company which subsequently became Candescent Technologies Corporation (CTC). The technologies developed at LETI became the basis for a firm called Pixtech, which developed a new strategy of building multiple partnerships for the manufacturing and commercialization of FEDs. Firms like Raytheon, Futaba, Candescent, Motorola, and Micron Display developed their own FED programs with variants of the original Spindt cathode. Of these firms, only Candescent and Micron were not partners with PixTech. By the middle of 1999, the race for commercialization was reduced to one between Candescent and the PixTech alliance.

The Fowler Nordheim Law

The Fowler-Nordheim Law explaining field emission as a quantum effect became the basis for research on FEDs. A potential barrier at the surface of a metallic conductor called the "work function" binds electrons to the material.

> For an electron to leave the material, the electron must gain an energy which exceeds the work function. This can be accomplished in a variety of ways, including thermal excitation (thermionic emission), electron and ionic bombardment (secondary emission), and the absorption of photons (photoelectric effect). Fowler-Nordheim emission or field emission differs from these other forms of emission in that the emitted electrons do not gain an energy which exceeds the material work function.
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> Field emission occurs when an externally applied electric field at the material surface thins the potential barrier to the point where electron tunneling occurs, and thus differs greatly from thermionic emission. Since there is no heat involved, field emitters are a "cold cathode" electron source.[1]

The original work of Fowler and Nordheim resulted from efforts to understand the causes for the interruption of transatlantic radio broadcasts from the Rocky Point, New Jersey, transmitter of the Marconi Company in the 1920s. These interruptions resulted from arcs in vacuum tubes in the radio equipment. Careful examination revealed that the arcs occurred at sites on the tungsten filament of the tubes where there was a bump or a whisker. B.S. Gossling, an employee of the Marconi firm, published a paper to this effect in 1926. He noticed that the arcs occurred only when certain currents and voltages were reached.[2]

Ralph H. Fowler was Professor of Physics at Cambridge University[3] and Lothar W. Nordheim had a research position there in 1928 when the two published an article that

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[1] Robert B. Smith, "Electronics Developments for Field Emission Displays," *Information Display*, v.14, no. 2 (February 1998), p. 12.

[2] B.S. Gossling, *Philosophical Magazine*, v.1 (1926), p. 609. I am taking most of this section from Ivor Brodie, "Keynote Address to the First International Vacuum Microelectronics Conference, June 1099: Pathways to Vacuum Microelectronics," *IEEE Transactions on Electron Devices*, v. 36, No. 11 (November 1989), pp. 2637-2640.

[3] Fowler earliest work in physics was on a dynamic theory of gases using insights from quantum mechanics. He was the son-in-law of Ernest Rutherford and later became the head of the Cavendish

explained the arcing at Rocky Point in terms of quantum mechanics. The Fowler-Nordheim equation contained in the article linked the voltage and current of the field emission to the surface area of the emitter, the average work function of the emitter surface, and the magnitude of the electric field at the emitting surface.[4] One of the reasons for the arcs experienced at Rocky Point was the very small surface area of the emitter (the bump or whisker) combined with the high intensity of the electric field at that point.

It took eight more years for experimentalists to adequately test the theory of Fowler and Nordheim. According to Ivor Brodie:

> Gossling tried to make electrolytically polished spherical points, but these did not quantitatively verify the Fowler-Nordheim theory, again due to whisker growth under high fields. The theory was not quantitatively verified until Mueller grew single-crystal points…in 1936.[5]

Erwin W. Mueller not only helped to verify the Fowler-Nordheim equations, he also contributed to later work on FEDs by accidentally inventing the field electron microscope (FEM). Again according to Brodie:

> Mueller was the first man to truly resolve atoms with his field ion microscope -- he once told me how he discovered the effect by accidentally reversing the field on a field electron emission microscope and momentarily seeing an atomic resolution image. Afterwards he wondered if he was dreaming since he could not repeat the experiment. But by perseverance and a clearer understanding of what was occurring, he finally achieved his goal.[6]

The scanning electron microscope (SEM) now used for inspecting the surface of semiconductor devices in all world-class integrated circuit laboratories and plants is based on the same principles as the FEM discovered in 1936 by Mueller.[7] The work on electron microscopes also led to the development of electron-beam (e-beam) lithography, which made it possible to write patterns smaller than one micron on a thin-film device before it was possible to do this with photolithography.

The theoretical work of Fowler and Nordheim and the experimental work of Mueller paved the way for the work of Spindt and his colleagues at SRI and for all subsequent efforts to fabricate field emission displays.

Laboratory at Cambridge. See Jagdish Mehru and Helmut Rechenburg, *The Historical Development of Quantum Theory*, v. 4 (New York: Springer Verlag, 1982), pp. 55-69.

[4] R.H. Fowler and L.W. Nordheim, "Electron Emission in Intense Fields," *Proceedings of the Royal Society of London*, v. 119 (1928), p. 173.

[5] Brodie, "Keynote...," p. 2637.

[6] Ibid, p. 2639.

[7] For more detail on this, see http://inaba.nrim.go.jp/ifes/fem.html.

The Work of Spindt and His Colleagues at SRI
There had been many attempts by researchers to improve upon the cathode ray tubes that were used for television displays and scientific instruments (like oscilloscopes), and particularly to make these displays flatter, thinner, and more energy efficient. Some of the earlier work on flat CRTs focused on creating an array of thermionic emitters of electrons inside a flattened vacuum tube, but these efforts did not pan out.

In 1961, Kenneth R. Shoulders at the Stanford Research Institute (now called SRI International) had the idea of micro-miniaturizing cathode ray tubes by using field emission as the source of electrons and using electron beams for micro-patterning the emitters.[8] Before leaving SRI, Shoulders hired Capp Spindt and gave him the mission of developing a method for manufacturing a field emission display like the one outlined in his 1961 article.

Spindt's idea was to use thin-film deposition and etching techniques together with e-beam lithography to build conical emitters (he called them triodes) on a silicon substrate. In 1968, Spindt published the results of his efforts to fabricate an array of polycrystalline molybdenum (Mo) microtips on a substrate.[9] Subsequent work with Ivor Brodie and others was funded by a variety of U.S. government agencies (particularly the Army Research Office, the Naval Research Laborararatory and NASA).[10] One of the early problems in this research program was sharpening the tips of the cathodes in order to reduce the voltage required to start the tunneling effect. The sharper the tip, the lower the voltage needed. Jules D. Levine at RCA's Sarnoff Laboratory discovered that it was possible to sharpen the tips by growing a layer of copper oxide on fully-formed copper tips and then etching away the oxide layer leaving tips composed of a few atoms of copper.[11] Levine received a patent on this process in 1975.

At the beginning of the research on Spindt cathodes, it was not unusual for FEDs to require gate voltages of 400V and anode voltages of 1,000V or more. Such high voltages often resulted in arcing, especially if there were any gas molecules between the cathode and anode. The arcing would damage the cathode surface even though it did not necessarily damage the cathodes themselves. Arcing might result, however, in the formation of metallic whiskers on the cathodes that could eventually destroy the device. The better the vacuum, the lower the likelihood of arcing; but it was not practical to build a display that required an almost perfect vacuum. Therefore, tip sharpening using oxidization techniques was a very important step forward in making it possible to manufacture FEDs.

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[8] K.R. Shoulders, "Microelectronics Using Electron Beam Activated Machining Techniques," in Franz L. Alt, ed., *Advances in Computers*, vol 2 (New York: Academic Press, 1961), pp. 135-293.
[9] Charles A. Spindt, "A Thin-Film Field-Emission Cathode," *Journal of Applied Physics*, v. 39 (1968), p. 3504.
[10] Heinz H. Busta, "Review: Vacuum Microelectronics," *Journal of Micromechanical Microengineering*, v. 2 (1992), p. 44.
[11] Email correspondence from Dev Palmer, July 15, 1999.

By 1972, the SRI group had solved enough of the engineering problems to demonstrate to their satisfaction that it was feasible to manufacture FEDs.[12] Patents for their fabrication methods were issued to Spindt, Shoulders, and L.N. Heynick in 1973 and 1974.[13] However, it was not until1985 that they were able to find backers for the next stage of the research program, namely the development of a fully operational protoype display. The work was intially funded by Boeing through Commtech International (a venture capital company formed to capitalize on SRI's inventions headed by Dr. Gerald Marxman).

A 12-inch diagonal flat display for individual passenger usage was required for a new aircraft that was then on the drawing boards. The initial prototypes showed promise but due to the availability of competitive technology Boeing ceased support after two years. At this point Commtech decided to form a new company called Coloray (President Charles "Chuck" Anthony) to exploit the SRI FED technology, with an investment of $3 million (the maximum allowed by Commtech's charter). The company elected to acquire a pilot production facility and intended to find partners to finance putting the plant into operation. In the business climate at the time this strategy proved unsuccessful and Coloray after some adventures was finally dissolved. Some key members of the staff joined another display company, Silicon Video Corporation (SVC), which subsequently became Candescent Technologies.

However, they could not find any backers for the next stage of the research program: the building of a pilot production line. It took them ten years to build prototypes, but by this time, a better-funded program at LETI had moved ahead of the SRI group to solve some key technological problems connected with manufacturing FEDs. At this time, the well funded program at LETI had moved ahead of the SRI group to solve some key technological problems connected with manufacturing FEDs.

Silicon Emitters vs. Molybdenum Microtips

Many different technologies have been investigated to overcome the real and imagined problems with the Spindt technology, Silicon based devices being the most prominent due to the availabilty of silicon fab lines for integrated circuits. One approach to FEDs was to use a p-n junction in a semiconductor device "biased into avalanche" as a low voltage "cold" electron source.

> In such a device electrons in the depletion layer, either existing or generated by impact ionization within the same layer, gain energy from the high field in such a region; and, if the junction is sufficiently shallow, many of them can acquire the necessary kinetic energy to reach the surface and win the surface work function, thus escaping into vacuum.[14]

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[12] Jules D. Levine, "Field Emitter Displays," presentation made at the Flat Panel Display Processing and Research Tutorial and Symposium, San Jose Convention Center, June 21-22, 1995. Dr. Levine was an employee of Texas Instruments.

[13] C.A. Spindt, K.R. Shoulders, and L.N. Heynick, U.S. Patents 3,755,704(1973); 3,789,471 (1973); 3,812,559 (1974).

[14] Iannazzo, p. 302.

In 1969, Williams and Simon published a paper on getting field emission from forward biased silicon p-n junctions. This work set off a series of experiments on using silicon instead of molybdenum as cold cathodes.

In 1981, Henry F. Gray and George J. Campisi of the Naval Research Laboratory (NRL) patented a method for fabricating an array of silicon microtips.[15] The process involved thermal oxidation of silicon followed by patterning of the oxide and selective etching to form silicon tips. The silicon tips could act as cold cathodes for a FED.

In December 1986, Gray, Campisi, and Richard Greene demonstrated a silicon field emitter array (FEA) that was fabricated on a five-inch diameter silicon wafer at the International Electron Devices Meeting but did not formally published their results.[16] At this time, Gray and his colleagues were more interested in demonstrating the benefits of using FEAs as switching devices (like transistors) or amplifiers than as displays, but the possibility of using them for displays was held out as an additional potential benefit.

The arguments that Gray made in favor of FEAs was that they might permit faster switching speeds than semiconductors and that they had a greater probability of surviving extreme conditions such as those experienced in war or natural disasters. FEAs could be made in either a vertical or a planar structure. They could be constructed using a variety of materials: silicon, gallium arsenide, molybdenum, nickel, platinum, iridium and conducting carbides. The devices did not require an extreme vacuum to operate but there were problems of getting uniformity in FEAs that had to be overcome before they could be used in commercial displays.[17]

After 1988, Gray became a major supporter of federal funding for further research on FEDs and FEAs. Government funding of subsequent research on FEAs was motivated primarily by the desire of the government to replace thermionic cathodes in microwave amplifier tubes. As it turns out, the operating parameters required for microwave tubes are much more demanding than those for display applications.[18]

In September 1995, Gray and David S.Y. Hsu announced a new process, using chemical beam deposition techniques to fabricate thin-film-edge field emitters. Instead of using molybdenum or silicon cones, as before, the new process created vertical free-standing platinum/lithium/platinum triangular shaped wedges with very sharp tips.[19]

Research on silicon emitters continues, but -- to our knowledge -- apart from Micron’s (now defunct?) use silicon emitters for camcorder displays, there are no major investments in this technology for the purpose of fabricating displays.

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[15] Henry F. Gray and G.J. Campisi, US Patent 4,964,946 (1990).
[16] Dennis Pidge, "Feature: Vacuum Microelectronics: The New Frontier," *Japan Economic Newswire*, July 4, 1989.
[17] "Vacuum Electronics Could Find Use in HDTV Technology," *ASAP*, v. 31, No. 8 (August 1989), p. 33.
[18] Email correspondence from Dev Palmer, July 15, 1999.
[19] "Advanced Electronics for New Display Panels," *Electronic Materials Technology News*, v. 9, No.9 (September 1995).

The Work of Robert Meyer and His Colleagues at LETI

In 1983, Robert Meyer of LETI began a program of research on fabricating arrays of Spindt cathodes using molybdenum tips. By 1988, the LETI research program had born fruit. Meyer patented a method for fabricating an array of molybdenum microtips with a lateral resistive layer. The lateral resistive layer helped to prevent arcing between the cathode and anode and therefore to improve the performance and prolong the life of the FED. It also evened out the electron emissions from the individual arrays across the display. The LETI researchers were able to demonstrate that FEDs fabricated with lateral resistive layers could be manufactured with the desired uniformities and had the expected lifespans needed for commercial displays.

However, using emitters with a base diameter of one micron, approximately 80V was needed to switch the emitters. This was much higher than the voltage needed to switch pixels in liquid crystal displays. Therefore, integrated circuit drivers for LETI's FEDs would be very expensive and the device itself would not be portable because of its high power requirements.

Tom Holzel of Raytheon was following Meyer's work and recommended in 1988 that Raytheon Corporation invest in FEDs. Raytheon decided to license the patents that SRI had obtained on the basis of the work of Spindt and his colleagues. A venture capital company named Commtech International had purchased the patents from SRI in 1985. However, Commtech and Raytheon could not work out a deal. Commtech would not assume any of the risk in commercializing the SRI technologies. Raytheon decided to work on its own. The Commtech technology was sold to Coloray (see below).[20]

Meyer tried to sell LETI's technology to Raytheon in 1988, asking $25 million for it. Raytheon opted not to take this offer, so the technology was sold instead in 1992 to Jean Luc Grand Clement, a former executive of Motorola in France who had already been involved in three previous startup firms, including, most notably, a firm called European Silicon Structures (ES2). After selling his interest in ES2, Grand Clement began working with Apple Computer's venture capital fund for Europe. His primary responsibility was to review opportunities for investment in Europe. He took some Apple people to meet with the people at LETI who were working on FEDs in October 1991.

PixTech

Apple was not interested in manufacturing displays, but Grand Clement was intrigued. He put together a short proposal for venture capital financing of a new display company called PixTech. A VC firm called Advent International became one of his earliest investors. Advent was convinced that PixTech would be able to produce FEDs using the LETI patents without infringing the patents owned by SRI. PixTech raised capital in incremental amounts: starting at $3 million from Advent in late 1991 and then rising to $10, $22 and $35 million from other investors. Over half of the funds came from U.S.

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[20] Interview with Tom Holzel, June 25, 1996.

investors.[21] Pixel International was formed as a French company in June 1992; PixTech, Inc., was formed as a U.S. corporation in 1993.

Using these funds Grand Clement purchased exclusive rights to all 16 of the patents that were owned by LETI in early 1992. He convinced Raytheon to become a partner of PixTech so that it would then have access to LETI's patents. Tom Holzel moved from Raytheon to become Vice President for Marketing and Sales of PixTech in July 1995. Motorola, Texas Instruments, and Futaba also joined the PixTech alliance for the same reason. TI pulled out in March 1996 when it abandoned its efforts to manufacture FEDs.

All knowledge and patents in the PixTech alliance are held in common. Everything is shared, but only within the partnership. The partners meet quarterly and request help on specific problems. They split up tasks and then report back on their progress at subsequent meetings. The meetings are rotated to various locations convenient for the partners.[22]

PixTech set up an R&D facility in Montpellier, not too far from LETI in Grenoble. The equipment in their pilot production plant in Montpellier was "off the shelf" -- a small amount of the equipment was custom developed within the PixTech alliance. The plant used a conventional semiconductor photolithography process, with an MRS 2 micron stepper. They also used a Holtronics holographic mask system at LETI for photolithography of microtip emitter holes. The facility was leased from IBM France. Production of FEDs commenced in November 1995 and the first samples of monochromatic (green) FEDs produced by Futaba were sold in December of that year. These displays were 5.2 inch diagonal, 1/4 VGA displays with 70 foot Lamberts (fLs) of brightness.[23] PixTech opened an R&D facility in Santa Clara, California, in February 1996.

The displays made initially by PixTech used Mo cathodes 1.2 microns tall. There were 2,000 emitters per pixel. The anode voltage was 350V; the gate voltage was 80V. Grey scale was obtained by varying the gate voltage by about 30V. The phosphors used on the anode of the Futaba monochromatic displays were ZnO:Zn phosphors, just like those used in fluorescent tubes.

Production yields in the first half of 1996 were erratic. There were problems with the lithography equipment. PixTech's approach involved the use of high-voltage drivers for the cathode combined with low anode voltages. The high cathode voltages created problems of arcing and expensive drivers while the low anode voltages meant that PixTech FEDs could not be as bright as CRTs (which relied on high-voltage phosphors) unless better low-voltage phosphors could be developed.

The first markets that PixTech targeted were avionics, medical devices, and motor vehicles. These markets were interested in smaller displays, in the 4 to 8.5 inch diagonal

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[21] Interviews with PixTech executives on June 25, 1996.
[22] Interview with Jean Luc Grand Clement on June 25, 1996.
[23] Robert Young, "Leader of the Pack?" *The Clock*, October 1997.

range. Customers in these markets needed very bright displays that were readable from wider angles than were available with LCDs.

The decision of Texas Instruments to end its work on FEDs in March 1996 was a blow to the alliance. TI's marketing manager for flat panel products said there was "…too much R&D going into liquid crystal technology based on the revenue streams being generated for the technology not to have made some significant improvements."[24] The decline in prices for TFT LCD displays that followed the ramp up of Samsung's first major factory also influenced TI's decision. Nevertheless, PixTech and its remaining partners persisted. For example, PixTech concluded a deal with Nichia Chemical of Japan in March 1996 to develop new low-voltage phosphors (to make brighter displays).[25]

PixTech hired Richard Rodriguez away from IBM in April 1996 to improve yields. He had previously directed an IBM plant in Corbeil, France. Rodriguez became Executive VP and Chief Operating Officer in March 1997.[26]

In May 1996, PixTech unveiled a 10.5-inch FED color display at the annual meeting of the Society for Information Display in San Diego, California. It also showed an advanced 6-inch color display with a brightness of 100fL and 160 degrees viewing angle. There was also a brighter 5.2 inch monochrome display with a brightness of 200fL at this show.

In September 1996, PixTech signed a marketing agreement with an unnamed Japanese manufacturer. It later announced that the Japanese firm involved in this agreement, Sumitomo Corporation, would be the exclusive distributor of PixTech products in Japan.[27]

In November 1996, PixTech announced that it had concluded a memorandum of understanding with Unipac Corporation in Taiwan to use Unipac's high-volume TFT LCD manufacturing facility for the production of FEDs on a contract basis. In January 1997, UMC, Unipac's parent firm, said that it would purchase 1.1 million shares of PixTech for $5 million of PixTech's. PixTech would sign a display foundry agreement with Unipac in June 1997.[28] Also in January, PixTech was given a "Display of the Year" award from *Information Display* magazine for its 5.2-in. monochrome display.

In April 1997, PixTech announced that it would lead a consortium of European companies to develop FED technology under a $3 million grant from the European Union. They would work with SAES Getters and Rhone-Poulenc to develop getters and low voltage phosphors respectively. PixTech also received a zero-interest loan of $2

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[24] Andrew MacLellan, "TI Scraps Display Plan," *Electronic News*, April 1, 1996, p. 1.
[25] "Nichia, Pixtech in Display Deal," *Electronic Materials Technology News*, April 1, 1996.
[26] "PixTech Promotes Richard Rodriguez to Executive V.P. and Chief Operating Officer: Yves Morel to Chief Financial Officer," *PR Newswire*, March 18, 1997.
[27] "PixTech Announces Fourth Quarter and Year-End 1997 Results," *PR Newswire*, February 12, 1998.
[28] "PixTech Sings Display Foundry Agreement with Taiwan-Based Unipac," *PR Newswire*, June 3, 1997.

million from the French government to develop FED displays for multimedia applications.[29]

Dieter Mezger replaced Jean Luc Grand Clement as President of PixTech in March 1998. Mezger had previously worked for Texas Instruments and VLSI Technology. Grand Clement retained his position as Chairman and CEO of the firm.[30] In the second quarter of 1998, Zoll Medical Corporation introduced a portable defibrillator that incorporated an FED. During this same period, the first FEDs came off the production line at Unipac.[31]

PixTech purchased Micron Display for $16.8 million of 7.1 million shares of PixTech stock in March 1999. Micron would own 30 percent of PixTech's equity as a result and, as part of the deal, Micron would transfer $4.35 million in cash and an unspecified amount in liabilities to PixTech. PixTech said that it would use the Micron display facility in Boise, Idaho, for the codevelopment of 15-inch displays with a major unnamed Japanese company. David Cathey, formerly Vice President and General Manager of Micron Display, would become an observer on the PixTech board of directors.[32]

With the purchase of Micron, it was now theoretically possible for PixTech and its partners to fabricate a wide range of sizes of FEDs for a variety of potential applications. The combination of government research subsidies with private venture capital financing was enough to get PixTech started, but it took a careful strategy of alliances and partnerships to take the firm to the brink of successful commercialization. We shall see below that a similar pattern emerged for PixTech's main rival, Candescent.

Pixtech's Partners: Raytheon, Texas Instruments, Futaba, and Motorola

Raytheon

As discussed above, Raytheon's interest in FEDs started in 1988 with Tom Holzel's recommendations to invest in the new technology. Raytheon is primarily a supplier of products using advanced technologies to the U.S. Department of Defense. Like most other defense contractors, Raytheon began looking for new dual-use technologies to get into in the late 1980s as the Cold War wound down. Raytheon focused its efforts in this area on high brightness FEDs for military avionics applications. It did not produce displays for civilian applications.

Texas Instruments

Texas Instruments, along with Raytheon and Futaba, was one of the three initial partners in the PixTech alliance. TI's initial interest in FEDs stemmed from its desire to have an alternative to TFT LCDs for notebook computers. In 1990, TI was paying around $1500 per display for TFT LCDs. When PixTech board members suggested that equivalent

[29] "PixTech Announces Second Quarter 1997 Results," *PR Newswire*, July 23, 1997; "PixTech to Lead $3.0 Million FED Development Contract," *PR Newswire*, April 3, 1997.
[30] "PixTech Announces New President: Deter Mezger, Electronics Industry Veteran, Joins Effective Today," *PR Newswire*, March 25, 1998.
[31] "PixTech Announces Second Quarter 1998 Results," *PR Newswire*, July 24, 1998.
[32] "Micron to Sell Display Division to PixTech," *Semiconductor Business News*, March 22, 1999; David Lieberman, "Micron to Sell Display Unit to PixTech," *EE Times*, March 25, 1999.

FEDs would eventually cost around $500 per unit, TI got interested in FEDs. The FED project at TI was put under the control of the analog IC division of the firm that was responsible for digital signal processors (DSPs). There was no long term budget for the project. It was reviewed on a year-by-year basis. TI built an R&D laboratory, and PixTech transferred its proprietary technology to the lab, but apparently the lab had difficulties using the PixTech technologies to build FED prototypes. In October 1995, a new manager, Bruce Gnade, was brought in to direct the project. Gnade later went on to become the head of the High Definition Systems (HDS) Program at DARPA. By the end of 1995, the price of 12.1-inch TFT LCDs had descended to less than $500, so TI management decided to pull the plug on the FED program early in 1996.[33]

Futaba

Futaba, like Raytheon and Texas Instruments, was one of the three initial partners in the PixTech alliance. Futaba had experience with manufacturing monochrome vacuum fluorescent displays (VFDs) for small devices like watches and was interested in scaling up its work on VFDs. VFDs use low-voltage phosphors, so the fit with PixTech's FED technology was good. Futaba was the first member of the PixTech alliance to produce a commercial FED. As mentioned above, this was a 5.2-inch diagonal, 1/4 VGA display with 70 foot Lamberts (fLs) of brightness. Production began in November 1995 and the first units were sold in December 1995.

One of Futaba's contributions to the development of FED technology was its work on "getters." A getter is a chemical substance that is introduced into the cavity between the FED anode and cathode to reduce cathode current fluctuations caused by residual gases in the cavity. Good getter technology, in short, in necessary to obtain uniformity in performance and to prolong the expected lifetime of the display.[34]

Futaba demonstrated prototypes of color FEDs at a number of international conferences after 1997, but had not introduced any of these displays to the marketplace as of mid 1999.

Motorola

In 1993, Motorola set up a corporate R&D facility to do research on FEDs. In 1995, the company set up the Flat Panel Display Division of the Automotive Energy Components Sector (AECS). A six-inch glass wafer pilot production line was built in Chandler, Arizona, in 1996. Later that year, construction of a second-generation 275,000 square-foot facility was begun in Tempe, Arizona. In 1998, construction was completed. The new plant was capable of producing up to 10,000 units per month. It was designed to produce multiple displays on 37cm by 47cm glass substrates, a standard size for second generation TFT LCD plants. Motorola worked with the following suppliers:

Nikon -- for production steppers
MRS -- for development steppers
Lam Research -- for dry etch equipment

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[33] Interview with Francis Courreges of PixTech in Montpellier, France, on December 20, 1996.
[34] See http://www.futaba-na.com/fed/fedappnote.html.

Ulvac -- for vacuum technology
Balzers -- for sputtering equipment

Problems of ramping up production occurred soon after the completion of the plant. The main problems had to do with sealing the glass tubes, getting the right spacers to get uniform distances between the anode and the cathode, and discovering the right getters for dealing with residual gases in the cavity.[35]

In May 1999, the manager of the Flat Panel Display Division of Motorola, Pete Shinyeda, said that Motorola would delay the ramp up of its FED production facility in order to solve some basic technology problems. Shinyeda said that the main problem was the limited lifetime of color displays (the firm was unable to achieve its goal of a 3,000-hour lifetime). On May 10, Motorola announced that it laid off 120 of its 200 employees at the Tempe site and that the staff would be pared down to a "small research team."[36]

Micron Display
Commtech International sold the 14 SRI patents to Coloray Display Corporation of Fremont, California, in 1989.

Micron Display Technology, Inc. (MDT) was formed in January 17, 1992 as a subsidiary of Micron Technology, Inc. On the day of its founding, MDT purchased a small stake in Coloray, but apparently it was not enough to keep Coloray afloat. In 1992, Coloray filed for bankruptcy under Chapter 11. It was purchased after reorganization by Scriptel Holding in April 1994. Scriptel was a pen-based digitizer company headquartered in Columbus, Ohio.[37] Coloray closed its doors for good in ______.

MDT secured a DARPA contract for development of FEDs in 1993. It demonstrated 0.7-inch prototypes in 1994. MDT developed a new manufacturing technology for FEDs involving chemical mechanical polishing (CMP) of the cathode substrate. CMP makes it possible to manufacture cold cathode arrays precisely and reliably without the need for lithography.

> The process begins with the deposition of the tips, which are then covered by a dielectric layer, which in turn is covered by the conductive film that will constitute the FED's gate. All you see at this point is a planar film having many bumps, the bumps having been created by the buried tips.
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> The trick involved is that chemical-mechanical polishing removes material much faster at the bumps than anywhere else. As the bumps are polished down, the surface becomes flat, the polishing nearly stops. The polishing is self limiting because the removal rate is dependent on the local pressure

[35] Interview with Tom Credelle, David Pearson, and Pete Shinyeda at the Tempe facility of Motorola, on March 27, 1997.
[36] "Moto Cutting Back Display Operations," *EETimes*, May 10, 1999.
[37] John Carey and Robert D. Hof, "Meet Silicon Valley's New Screen Hopeful," *Business Week*, February 3, 1992, p. 32; Katherin Derbyshire, "Beyond AMLCDs: Field Emission Displays," *Solid State Technologies*, November 1994, 55-65.

> between the polishing pad and the conductive layer. A wet chemical etch is then used to remove the insulator surrounding the tips.[38]

The process was patented in ____.

Micron also developed some new spacer technology for both high and low voltage FED applications.[39]

At the end of 1996, MDT began to produce .55-inch diagonal monochrome FEDs for military viewfinders and thermal imagers. Kaiser Opto-Electronics purchased MDT's FEDs for head-mounted displays under a contract with DARPA.[40] These displays are used on rifles and other hand-held weapons. They can detect both movement and heat. Another application of these displays was for firefighting: they were used on devices to detect hot spots in burning buildings.

A new 50,000 square foot facility in Micron's hometown, Boise, Idaho, with 30,000 square feet of clean room became operational early in 1997.[41] This new facility was initially designed to produce 12-inch displays for the Abrams M-1 tank commander station. David Cathey, president of MDT, said that the CMP technology would permit MDT to scale up to displays as large as 17 inches. GVC Corporation of Taiwan invested $4.5 million in MDT around this time.[42]

After struggling for two years to manufacture large-area FEDs at the Boise facility, Micron Technology decided instead to sell it to PixTech in exchange for an equity stake in the latter firm. PixTech would use the facility to produce large-area FEDs for televisions and workstations.

Candescent

With the sale of Micron Display to PixTech in March 1999, Candescent Technologies Corporation became the main competitor to the firms in the PixTech alliance. Candescent Technology Corporation grew out of Paul Lovoi's idea of using multi-layer ceramic material as an enabling element for flat CRTs. Earlier efforts at Source Technology had involved the use of etchable glass as a grid above a toaster wire cathode to fabricate a monochromatic tube, but Source was unable to solve fragility and focusing problems, even with thick self-supporting face and backplates. Lovoi, co-founder and president of InTA, a metal ceramic research and development company, proposed that recent developments in multi-layer and zero-shrink ceramics could solve both the electrical and mechanical problems connected with flat CRTs.

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[38] Vic Comello, "Can FED 'Davids' Vanquish the AMLCD 'Goliaths'?" *R&D Magazine*, December 1996, p. ; see also http://www.micron.com/mdt/tech/tech.htm.
[39] See http://www.micron.com/mdt/tech/spacer.htm.
[40] "Micron Display Technology, Inc., Announces Early FED Prototype," *Business Wire*, April 27, 1994.
[41] Lieberman, op cit.
[42] Jack Robertson, "FED Program Expands -- Micron Display Plans to Develop Larger Panels in an Effort to Enter the Volume Computer Market," *Electronic Buyers' News*, September 8, 1997.

Lovoi, Darryl Wilburn and Lowell Nobel approached Marko Slusarczuk at DARPA in 1989 with a request for $1 million to fund development of a flat CRT based this multi-layer ceramic technology and using a hot-wire cathode. He expressed considerable interest, but such a project did not fit with the work of any of the three founders' companies.

Robert Pressley had just sold his previous startup, XMR, a manufacturer of industrial excimer lasers, to Amoco Corporation. Pressley was approached by Lovoi, Wilburn, and Nobel to form a new company called Silicon Video Corporation (SVC) to develop flat CRTs. Pressley had a background in flat CRTs, having worked on the idea when he was employed at the RCA Sarnoff Labs in Princeton, New Jersey. Pressley, along with Capform Ventures, decided to invest $400,000 in the new company. Slusarczuk negotiated a contract with SVC to build a flat CRT using funds from the Army.

Pressley recruited Robert Duboc from Coloray, Ted Fahlen, VP of R&D at XMR, and Chris Spindt, son of Capp Spindt with a newly minted Ph.D. from Stanford, to work at SVC. These individuals built a prototype hot cathode display with 80 lines per inch that operated on 10 watts of power.

A second round of financing was secured from Hewlett-Packard and Carl Berg, a Silicon Valley venture capitalist and real estate executive. The role of Hewlett-Packard here was crucial. Richard Hackborn at H-P had backed the relationship with SVC because he felt that HP should be a dominant player in displays. Displays would be very important to the future of the company, he thought. Hackborn had led the successful program at H-P to partner with Canon on the development and manufacturing of ink-jet printers. He wanted to do something novel in displays, while avoiding the expense and difficulty of setting up a TFT LCD plant. His philosophy was "if the enemy has superior forces and occupies the high ground, do something more novel than stage a direct uphill attack."[43]

When it became clear in 1992 that LCD power consumption was coming down and that hot cathodes would not be efficiency competitive with LCDs for portable notebooks, SVC shifted its efforts toward implementing cold cathodes. After extensive modeling and experience with ceramics and electron beam focusing, it became apparent that a truly competitive thin cathode ray tube must have the following attributes:

1. The display must operate at a high anode voltage, both the efficiency and lifetime of phosphors increase rapidly with voltage. It should not generate x-rays, so the voltage should be no more than 6 to 8 KV. The existing P22 CRT phosphors are adequate, they took twenty years to optimize in the beginning of color television and any new and better ones are unlikely in any reasonable time. (This conclusion came out of Pressley's experience with phosphors at RCA Sarnoff Labs.)
2. The front and back glass should be supported with thin, weakly conductive ceramic walls spaced between the pixels. The ceramic thermal expansion must match the glass, the electrical resistivity must be high enough to minimize leakage

[43] Email correspondence from Robert Pressley, August 19, 1999.

from the anode, but must be low enough to avoid any space charge buildup. (This came out of Lovoi's ceramics experience.)

3. The switching voltage on the Spindt type emitters must be 10 volts or less to minimize switching losses. (This was based on Fahlen's modeling.) This, in turn, required gate diameters to be about 0.1 microns using standard molybdenum Spindt emitters, or a tip coating of some very low work function material on 1.0 micron diameter emitters. The small diameter approach recognized that these emitters had to be made without any high-resolution semiconductor lithography. (This conclusion was based on Spindt's modeling.)
4. Field emission is noisy. For a satisfactory display, there should be a large number of emitters for each pixel. At the desired resolution of about 100 lines per inch, the small gate approach gave room for some 3000 emitters. This gave a statistical reduction in the inherent noise to a satisfactory level. (Spindt modeling)
5. The emitted electrons come off the tip with a lateral velocity and must be focused to obtain satisfactory performance with a high voltage display. This can be done with an additional electrode on the cathode surface. (Spindt modeling)
6. The structure must incorporate a vertical resistor behind each emitter to limit runaway emission and resultant damage. (Spindt and Fahlen planning).
7. The thin structure must be evacuated, sealed, and gettered to have a long life. (Duboc ideas and structures)

A cold cathode tube appeared to be feasible if a low cost way could be found to make the sub-micron gates. SVC made this gate project their highest priority. A variety of approaches based upon ion tracking in insulators demonstrated the possibility making these sub-micron Spindt emitters without expensive steppers. A specific procedure using ion tracking invented by John Macaulay was shown to work. The rest of the requirements then required more perspiration than invention and Silicon Video proposed to HP that this display could meet all of HP's notebook requirements.

After reviewing the results of the FED work at SVC, Hackborn convinced HP to provide additional funding to SVC. Not only did HP provide money, it also gave SVC technical help from HP Labs and helped SVC later to obtain more financing from venture capitalists.

While the molybdenum tips are sufficient for a competitive display, any reduction of the tip work function improves the overall system efficiency. There were occasional reports of "negative work function" in some forms of diamond emitters, but a larger problem was how to measure and or determine the work function of various materials and coatings.

Lincoln Labs had suggested that DARPA fund a theoretical analysis of cold cathode emitters for displays. DARPA asked Silicon Video to supervise this and compare and evaluate all known approaches to building FEDs as an extension of SVC's first DARPA grant. Duboc led this evaluation and after some six months, SVC determined that the best direction was to proceed with the molybdenum tip approach as none of the diamond type surfaces were yet reproducible or had any definable path to low cost, large area displays.

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SVC continued to require equity investment and approached, among many others, J.H. Whitney. Harry Marshall, a general partner at the venture capital firm of J.H. Whitney, did not convince Whitney to invest, but left Whitney to become an investor in SVC in 1992. Prior to working at J.H. Whitney, where he was a principal in 15 technology start-ups, Marshall was a senior partner at Hambrecht and Quist, a well-established Silicon Valley investment firm. In 1993, Marshall came on board as President and CEO of SVC.[44] He led the fund raising for the C and later rounds of financing.

In May 1994, Advanced Technology Materials Inc. (ATMI) and SVC received a $1.1 million award from DARPA for optimizing methods for building FEDs using diamond microtips. It was hoped that the depositing of thin films of diamond materials on cold cathodes would lower power consumption. This work resulted in significant intellectual property, but still no manufacturable diamond coated tips, due to the difficulties of working with the diamond materials.

In the spring of 1994, Compaq Computers invested in SVC.[45] Wyse technology of Taiwan also invested $1.8 million in March 1994.[46]

In September 1994, SVC leased a disk drive manufacturing facility in south San Jose previously occupied by Dastek and started to install a display fabrication line based on 4" semiconductor fabrication equipment. In October 1994, SVC received a $22 million grant from the Technology Reinvestment Program (TRP) administered by DARPA to further develop its FEDs. The TRP funded about a third of the total of $67.2 million SVC received, which also included matching funds from the State of California and private investments.[47]

By January 1995, the San Jose plant was ready to begin producing prototype FEDs on 4-inch glass circles. In March, 1995, the first prototypes were actually produced, but these displays were not "sealed tubes." It was not until June that the first sealed tubes came off the line. SVC first showed its 3-inch prototype display publicly at Display Works in San Jose in January 1996.

Lithography equipment for the plant was purchased from Dainippon Screen. SVC received assistance from the US Display Consortium (USDC) in purchasing holders, scribers, and markers, but the firm had some difficulty purchasing tracking equipment (Dainippon would not build them in the United States).

SVC continued working very closely with one of its major partners, Hewlett-Packard, to complete this FED tube technology and characterized it with a new name, "Thin CRT."

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[44] Julie Schmit, "Candescent Vies for Breakthrough: Start-Up Takes Risk on Screen Technology," *USA Today*, September 6, 1996, p. .

[45] "Silicon Video Awarded U.S. Flat Panel Display Funding: Hewlett-Packard and Others Reveal Alliance with Silicon Video," *Business Wire*, October 25, 1994.

[46] "Taiwan, US Join Hands to Develop Display Technology," *Financing*, March 26, 1994.

[47] "Silicon Video Awarded…"; "Flat Panel R&D: Taxpayers' Dollars Aiding Competitors?" *Defense Week*, September 5, 1995.

Unlike the PixTech FED, which required about 80V on the gate for switching pixels, the SVC display required only 10V. Instead of using emitters that were about 1 micron tall and gate holes with a 1-micron diameter (as in the PixTech design), the SVC device used emitters that were 0.2 microns tall with 0.15 micron gate diameters. Instead of using 200 emitters per pixel, the SVC device used >1,000 emitters per pixel. The anode voltage for the SVC device was around 5,000V as compared with 350V for the PixTech device. The gap between the anode and the cathode was 50 mils (as compared with the 4 mils of the PixTech device). This meant that there had to be a way of focusing the electrons emitted from the cathode before they reached the anode and that spacing between anode and cathode had to be highly uniform. SVC developed its own "spacer" technology using ceramic strips that were 2 mils thick and 50 mils tall. Using this distinctive design, it was possible for SVC to build a display that could use regular high-voltage (P22) CRT phosphors -- a real advantage because of their lower cost and longer expected lifetime as compared with the low-voltage phosphors used by PixTech.[48]

Manufacturing ThinCRT's in the San Jose plant initially involved 250 separate process steps and 80 different tools. About 80 percent of the tools were the same as those used in a TFT LCD plant. The faceplate (anode), spacers, and cathode were processed separately and then assembled. By June 1996, SVC was sealing about 15-20 tubes per week. One primary goal for the San Jose plant was to reduce the number of process steps from 250 to around 110 and increase the yield. SVC hired David Bergeron from IBM in January 1995 to be Vice President in charge of manufacturing technology. Bergeron brought with him extensive experience in semiconductor manufacturing. He had worked previously on the IBM-Siemens-Toshiba joint venture for DRAMs and on the joint venture between IBM and Motorola to make a microprocessor for Power PCs. Bergeron helped to formulate a "concurrent engineering" approach at SVC -- which meant that the firm would work on product and process technologies simultaneously.

A second fabrication line was installed in the San Jose plant to produce ThinCRT's on 32cm by 34cm glass plates (commonly called "mother glass" because more than one display could be produced on a single sheet of glass). SVC continued to use a stepperless lithographic process in order to increase throughput. After processing the mother glass, SVC would cut up the panel into smaller pieces for further processing as 5.3" diagonal engineering prototypes.[49] Accu-Fab Systems provided assembly equipment for the prototypes. These prototypes would be sold as engineering kits to companies interested in developing FEDs for final products.[50]

One goal for the second San Jose plant was to reduce the number of process steps from 250 to 110. SVC hired David Bergeron from IBM in January 1995 to be Vice President in charge of manufacturing technology. Bergeron brought with him extensive experience

[48] Interview materials; "New Design, AMLCD Tools SVC Cost Keys," *New Technology Week*, January 8, 1996; Andrew MacLellan, "CTC Eyes Notebook PC Display Role," *Electronic News*, August 5, 1996, p. 1.
[49] SVC discussed the prototype 5.3 inch displays at the annual meetings of SID, SPIE and IVMC in 1999.
[50] "Silicon Video Commits $40 Million to Speed Thin CRT to Notebook Computer Market: Flat Panel Display Venture Expands Facilities, Capabilities to Process Large-Area Glass Wafers," *PR Newswire*, May 14, 1996.

in semiconductor manufacturing. He had worked previously on the IBM-Siemens-Toshiba joint venture for DRAMs and on the joint venture between IBM and Motorola to make a microprocessor for Power PCs.[51] Bergeron helped to formulate a "concurrent engineering" approach at SVC -- which meant that the firm would work on product and process technologies simultaneously.

SVC Rounds of Financing

1st: 1990, $1 million from DARPA; $400,000 from Robert Pressley and Capform ventures.

2nd: 1992, unspecified amount from Hewlett-Packard and Carl Berg.

3rd: March 1994, $10 million: New Enterprise Associates & Affiliates and Sevin-Rosen Management; new investors owned 40% of the stock

4th: May, 1995, $17 million:

5th: May 1996; $55 million: Bankers Trust, Berger Associates, BKP Partners, Compaq Computers, Citicorp, Hewlett-Packard, J.P. Morgan Investment Management, New Enterprise Associates & Affiliates, and 21st Century Communication Partners

6th: May 1998: $125 million: sale of senior subordinated convertible debentures

other earlier investors:

Bayview Investors
Farmers Insurance and Affiliates
Oppenheimer & Affiliates
Sierra Venture Affiliates
Century Financial Partners, Inc.
John Govett & Co.
Leach Capital
Rock Rimmon Securities

On June 22, 1996, SVC changed its name to Candescent Technologies Corporation (CTC). The press release for the name change explains it as follows:

> The name, taken from the Latin word *candere*, "to shine, highlights the most prominent and appealing features of the company's novel Thin CRT display

[51] Interview with David Bergeron at CTC in San Jose on June 27, 1996.

> technology -- brightness and vibrant colors that are comparable to to the cathode ray tubes found in televisions and desktop computer monitors. "Candescent" was chosen to convey the ideas and innovation that are necessary to compete with liquid crystal displays (LCDs), the dominant display technology found in notebook computers today.[52]

The press release mentioned the CTC strategy of targeting the notebook display market in competition with TFT LCDs. This strategy was criticized by a number of observers as unrealistic, given the growing competition and declining prices of TFT LCDs, especially after the entry of Korean firms in 1995.[53] Nevertheless, senior managers of CTC continued to assert their intention to compete in notebook markets eventually on the basis of the expected superior performance of Thin CRTs for multimedia applications.

In May 1997, CTC and Schott Corporation announced a joint development and supply agreement under which Schott would establish a new high-volume glass processing facility to supply glass for Candescent's Thin CRT fabrication facility in San Jose. As part of the agreement, Schott purchased ___ percent of the equity of CTC for ___ dollars and CTC agreed to use Schott as its primary supplier of glass. The two firms agreed to co-develop glass processing and finishing technologies.[54]

On May 18, 1998, CTC announced that it had raised $125 million through the sale of "Senior Subordinated Convertible Notes." The seven percent notes were due in the year 2003 and were convertible into common stock at a conversion price of $13 per share. All of the money would be used in financing a high-volume manufacturing facility in San Jose. The new 340,000 square-feet production facility would cost around $400 million and would be capable of producing 12-15 inch displays on 59cm by 67cm glass substrates for notebook computers. It would not be completed until late 1999 or early 2000.[55]

In November 1998, CTC announced an agreement with Sony Corporation for joint development of a 14-inch diagonal FED by the year 2000. Both companies pledged to spend $50 million on this effort. Most of the work would be performed at CTC's plants. A team of six Sony engineers were sent to San Jose to begin the work, with some additional staff dedicated to the project in Japan.

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[52] "Silicon Video Changes Name to Candescent Technologies," Candescent press release dated July 22, 1996.

[53] See, for example, comments by David Mentley quoted in "CTC Eyes Notebook PC Display Role."

[54] "Candescent and Schott Partner to Establish Flat Panel Display Manufacturing Infrastructure in the United States," Candescent press release, May 14, 1997, accessed via the web at http://www.candescent.com/Candescent/pr05.html on June 9, 1997.

[55] "Candescent Raises $125 Million Toward Flat-Panel Display Manufacturing Plant," press release dated May 18, 1999, at http://www.candescent.com/Candescent/press/pr09.htm; Hank Hogan, " ." *Electronic Business*, December 1998; "Candescent Technologies to Make Flat-Panel Display," *Wall Street Journal*, November 19,1998; Jerry Ascierto, "Candescent Delays Plant, Replaces CEO," *Electronic News*, March 1, 1999, p. 1.

In short, by mid 1999 Candescent was the only viable competitor to PixTech and its allies in FEDs.

Conclusions

Key elements necessary for surviving the very difficult process of converting a new and promising technology into a commercial product are:

- access the right technologies at the right time
- adequate control over the necessary intellectual property
- a combination of strong management skills and technical excellence in senior managers
- access to patient capital during the period before products can be commercialized, and
- a convincing and viable strategy for managing product and process technologies so that key investors can remain patient.

PixTech and its partners and Candescent used rather different designs for products and pursued different marketing goals. PixTech opted for fast commercialization of high gate, low anode voltage FEDs, while Candescent opted for somewhat slower commercialization of low gate, high anode voltage devices. PixTech never explicitly targeted the notebook market, while Candescent did so from its very beginning.

PixTech was an international alliance from the start with its base in France but strong links to both Japanese and North American firms. Candescent had a more nationalistic focus, but did not limit itself to working only with other U.S. firms, even though a sizeable proportion of its R&D spending was financed by the Department of Defense.

The key similarity between the two firms was their ability to early combine government funding (from the French government in the case of PixTech; from the U.S. government in the case of Candescent) with venture capital to assure that they would be able later to move to high-volume production. Neither firm became a "hot house flower" dependent solely on government subsidies.

We do not know, of course, whether either firm will survive in the long run. Nevertheless, the history of the FED can provide useful lessons about competition in high technology industries in a globalizing world economy.

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