The birth and early childhood of active matrix – A personal memoir

T. Peter Brody*

Abstract — The genesis and evolution of the concept of active matrix and its reduction to practice at Westinghouse Labs in the early '70s is recounted from a personal viewpoint by the author, who was manager of the thin-film projects at the time. The story is continued beyond Westinghouse's abandonment of the project to the formation in 1981 of Panelvision, the first AMLCD company, and ends in 1985 when Panelvision was sold and Japanese companies assumed their present dominant position in the market. A postscript expresses views of the author on the future of active-matrix displays.

Keywords — *Flat-panel displays, active matrix, thin-film transistor, CdSe, a-Si, history.*

1 Introduction

The title suggested for this article was "The Birth of the AMLCD," but I prefer the more general term, since active matrix, as originally conceived, was intended to be a generic display-addressing technology, not restricted to driving liquid-crystal screens. Although at present the main application of the active-matrix principle is to LCDs, the original work demonstrated its applicability to high-voltage electroluminescent displays as well as liquid crystals, and stressed the universality of the principle. In confirmation of this expectation, we now see work on non-LC active-matrix combinations, such as AM-TFEL, AM-VF, AM-PDLC, AM-EP, and several others.

I believe that the strength of the active-matrix principle is precisely its near-universal applicability. Thus, if the nematic liquid crystal is replaced in the future by a superior electro-optic fluid (or solid), it will almost certainly still be addressed by an active-matrix circuit.

In this commemorative article, I will trace the evolution of this technology from its conceptual roots to the point where first commercial AMLCD products began to appear on the market and, simultaneously, the U.S. handed over its leadership to Japan. I will, however, append a postscript to this history, expressing some strongly held views about where the future lies — or should lie.

2 Early work on thin-film transistors

The birthplace of solid-state electronics is customarily taken to be Bell Laboratories, where in 1949 Shockley and his co-workers first demonstrated the point-contact transistor, followed shortly afterwards by the junction and the junction field-effect transistor. While there is no doubt that the semiconductor industry was launched on licenses granted by Bell Labs, on their transistor technology, it is of interest to note that as early as 1934 a patent was awarded to a German inventor, Oscar Heil, for a thin-film transistor using a tellurium film![1] This was clearly a "premature" birth, since there is no evidence that Heil's device ever found a practical application, but there is no question that it would have worked: the patent clearly describes all the essentials of a thin-film FET and its operation. In light of the explosive growth of an active-matrix-based display industry, one might claim that solid-state electronics was born as early as 1934, but due to a historical accident, initially took a very different path.

The historical accident consisted of some failed experiments at Bell Labs by Shockley's group, who tried to fabricate a TFT using germanium. This device did not work, due to a large density of surface traps in the evaporated Ge film which prevented any useful conductivity modulation. This failure led Bell Labs to abandon any further work on TFTs, and it was not until the early 60s that others resumed investigation of such devices.

3 The rise of the integrated circuit

In the 50s, discrete bipolar transistors were manufactured in a great variety of shapes, sizes, and performance, at steadily diminishing cost, displacing most vacuum tubes and initiating the age of digital systems. Modern computers began to emerge and semiconductor logic circuits soon became large and complex. The problem of mounting and interconnecting a large number of discrete devices then arose and gave rise to the idea of forming many of these devices on a single substrate, interconnecting them *in situ*.

At this time, bipolar junction devices were exclusively used in computer circuits, but many semiconductor workers realized that for the future logic circuits, device performance was less important than fabrication simplicity, yield, and real estate occupied on the wafer. The resulting search for a simpler, more compact switching device then led to the idea of the MOSFET, and simultaneously, to the thin-film version of the same device: the TFT.

*Fellow, SID.

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The author is with Active-Matrix Associates, 5823 Kentucky Ave., Pittsburgh, PA 15232; telephone 412/362-4471, fax 412/441-2932, e-mail: pbrody@ivory.lm.com.

In the late 50s and early 60s, many laboratories were doing research both on MOSFETs and TFTs; however, with the bulk of the effort going into MOS. Major laboratories working on both types of devices included RCA, GE, Hughes, IBM, Raytheon, Zenith, Philips, and Westinghouse, as well as several universities. Japanese semiconductor laboratories concentrated on the MOSFET – I am not aware of any TFT papers published by them in this period. By the mid-1960s the MOS emerged as a clear winner and most of these laboratories dropped work on TFTs, with only RCA and Westinghouse continuing any significant effort beyond that date. RCA dropped out in the early 70s, leaving Westinghouse alone in possession of a deserted field.

4 Early TFT work at Westinghouse

We started working on TFTs also in the early 60s, encouraged by reports on thin-film tunneling devices and the RCA papers on CdS TFTs. However, in 1962, Westinghouse also established an Integrated Circuit Division and the division people turned out to be quite hostile to our work. Their slogan at that time was "bipolars forever." As early as 1963 they told us that if our TFTs did not make it that year as candidates for digital networks, we might as well forget about them, as they clearly would be of no use to anybody. Famous last words!

How did the TFT effort survive in this adverse environment? Two things helped: first, my own conviction that thin-film electronics would become important if the right uses for it could be found, and second, that we managed to obtain some government contracts and even some other divisional support for our work, despite the opposition of the IC division. Much of this work in the mid-60s was perhaps not of first-order importance, but served to keep the TFT effort alive, *e.g.*, the construction of a high-frequency InAs TFT.[2]

Finally, in 1967 we hit some "paydirt." My colleague, Derrick Page, and I designed a vacuum deposition system in which TFTs could be fabricated in a single pumpdown cycle, eliminating atmospheric interface contamination which was a major cause of nonreproducibility. We decided to investigate tellurium films in this system, following the RCA group who had reported good results with this material. We found Te TFTs very easy to make, and because of the high carrier mobility (around 800 cm^2/V-s), they were capable of quite high-frequency performance: 60-MHz cutoff frequencies were obtained in comparatively crude devices patterned by simple stencil masks.

One day, Page had the idea of trying to make a Te TFT on a strip of paper instead of the usual glass substrate! To my amazement, the TFT worked on the very first try, and soon thereafter we made TFTs on a wide range of flexible substrates, including Mylar, polyethylene, and anodized supermarket aluminum foil. TFTs on anodized Al foil worked particularly well, as the substrate acted as an excellent heat sink. For example, we used a single, 0.030 in. wide by 0.0005 in. long TFT as an audio amplifier and obtained almost 0.5 W of audio output from it. We also built multistage amplifiers, logic circuits, and oscillators with these devices.[3,4] In the latter paper, published in 1968, we postulated the use of TFT matrices for display addressing, predating the better known Lechner speculations[5] by 3 years.

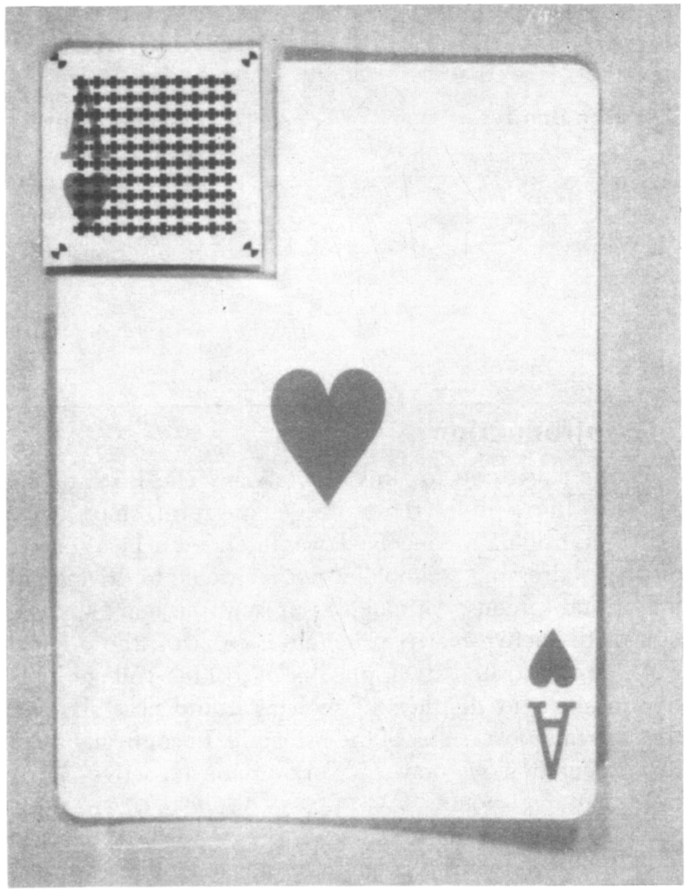

FIGURE 1 — Thin-film transistors on a playing card (1967).

The flexible TFTs could be bent into a 1/16-in. radius without damage and still functioned in this mode. They could also be cut in half, with both halves remaining operational. (In view of recent extensive press coverage of some flexible but very low-mobility polymer TFTs, our work, done over a quarter century ago, is worth recalling.) Figures 1 and 2 illustrate aspects of this work: Fig. 1 shows a 10×10 array of TFTs deposited on one corner of a playing card; Fig. 2 shows the "paper TFT" characteristics (a) after deposition and (b) after 1000 hours of operation. Note the unchanged characteristics!

Despite these results, which received wide international publicity, our TFT programs were still threatened by the inputs of the IC division who kept telling laboratory management that we were just wasting company money. Once again we had to come up with an idea to keep the work alive, and were given just 3 months to do this.

Once again, we survived – death threats are a valuable spur to invention! Based on our flexible-transistor capability, we devised a continuous fabrication process which used reels of anodized Al foil as substrates. Devices and circuits

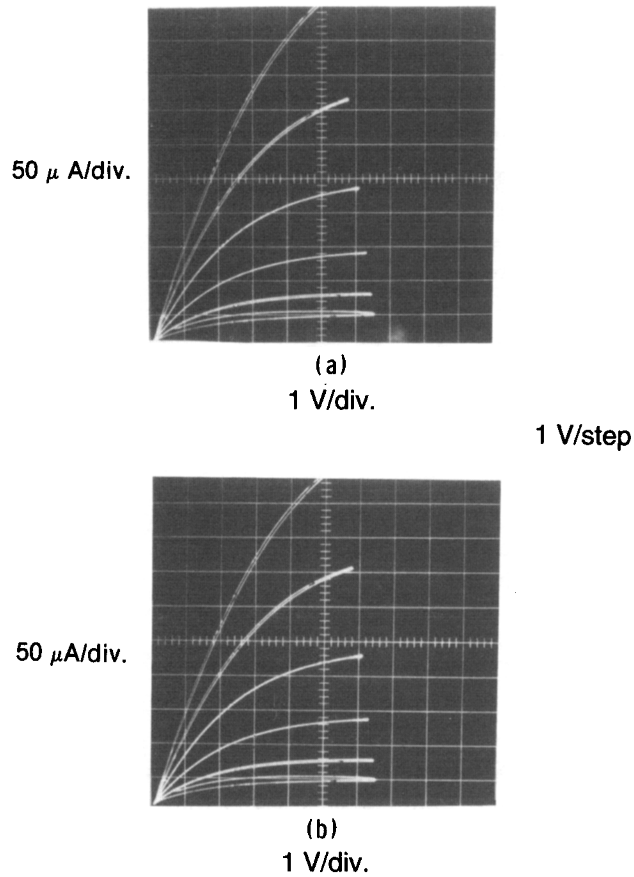

FIGURE 2 — Characteristics of a "paper TFT" (1967-1968).

could be fabricated in a single vacuum cycle on successive positions of the reel, which at the end of the fabrication cycle looked like exposed frames of 35-mm photographs (Figs. 3 and 4). With this idea and some demonstration circuits, we made the round of a number of Westinghouse

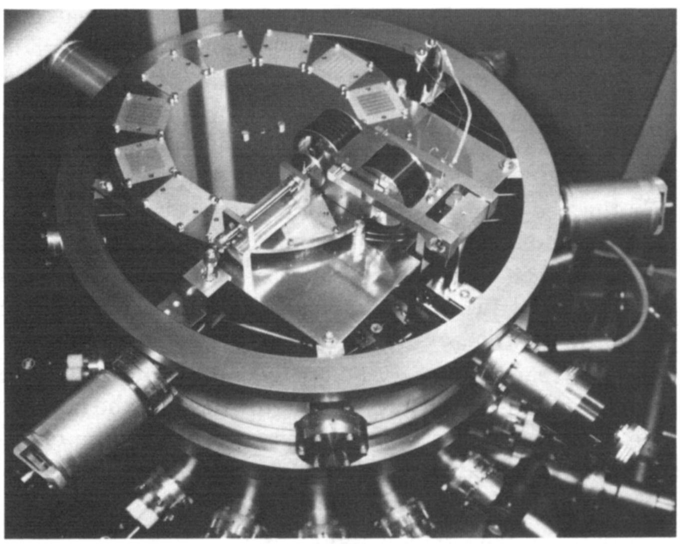

FIGURE 3 — 12-station rotary mask wheel for fabricating TFT arrays and circuits in a single 18" vacuum system (1968).

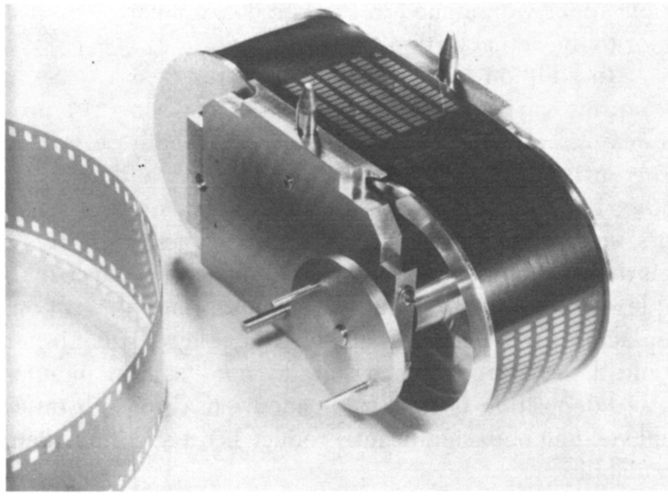

FIGURE 4 — Substrate tape carrier with aligning pins and indexing drive.

manufacturing divisions with the proposal that our technology would allow them to make custom circuits for themselves. The tactic worked and we quickly picked up enough support to continue – and even expand – our TFT work.

What undoubtedly helped our survival at this time was the (for us) lucky demise of the Westinghouse Integrated Circuits Division. They were forced out of business in 1968 and were thus no longer able to agitate against the TFT work. In retrospect I believe that, paradoxically, this was the real turning point in our fortunes. We now had the support of several profit center divisions and our chief divisional critic disappeared from the scene; thus our position improved markedly. Although in industrial research the norm is that the operating divisions support the short-term, product-oriented development work, while the central laboratory, with corporate funding, engages in the more speculative programs, we found the situation just reversed: the divisions were in our case more farsighted than central laboratory management.

Having learned the correct survival strategy, we continued to pursue and obtain additional divisional support and built up a highly capable group oriented entirely towards the exploitation of our TFT capability. The section grew into a department called "Thin Film Devices" and I became its manager. Thus, in the late 60's, when every other semiconductor laboratory and company gave up on TFTs as being of no use to anybody, we found a number of very useful applications – developments sufficiently promising to be supported by short-term-oriented divisions with quarterly profit responsibilities.

All this took place before we started on any TFT display applications, but the seeds of active matrix were already present in a creative and well-motivated group of workers who had to prove to a skeptical world that indeed, TFTs were of *some* use and perhaps quite important, even though where the breakthrough would occur was not yet clear. A few examples will suffice to illustrate the range of ideas and applications we pursued in the late 60s and early 70s, just prior to the actual birth of active matrix.

In addition to Te, we started working with CdSe, a promising candidate. Our criterion in choosing TFT programs was to discover applications not readily served by conventional semiconductor components and circuits, either because of performance requirements or other factors, such as cost or availability. Among such applications was the development of a 400-V high-input-impedance multiplexer circuit with a 120-dB common-mode rejection, replacing high-cost mercury-wetted relays. This circuit could then be fabricated by the division itself on an automated deposition system, using anodized Al-foil substrates and yielding both significantly reduced cost and immediate availability.

Other interesting and innovative developments at this time were an aircraft power-control circuit which for the first time combined logic and power devices in a single integrated network (long before the semiconductor industry produced such circuits), and applications of our ability to build both high-voltage and high-power TFTs, such as an Al-foil-based 15-A, 200-V TFT – certainly the first high-power FET ever built. At the same time, we developed suitable encapsulation techniques for the TFTs, such that the devices had zero drift after 1000 hours of constant dc bias operation – a very significant achievement, and one that gives the lie to the oft-repeated allegations of CdSe TFT instability. We also by this time had a fully reproducible fabrication process, and design rules which allowed us to predict device performance accurately.

Although these examples are seemingly far removed from the eventual display use of the TFT, this breakthrough would not have occurred had it not been embedded in a successful "intrapreneurial" operation, which was ahead of its time in its technology and also in its relationship to its parent corporation. We were convinced that one day TFTs would come into their own – the only question was: could we keep going long enough to find where that would be? The only other group that could have made the breakthrough to active matrix was Paul Weimer's group at the RCA Labs. In the early and mid-60s they were in a leadership position and indeed, formulated ideas similar to ours. But they did not have the staying power; towards the end of the decade, RCA Lab management, tired of seeing the TFT as a permanent also-ran against the MOSFET, put the group out of existence just when we began to think seriously about the display application.

Although 25 years after the event, in light of the spectacular success of the active-matrix principle, many people claim that they had a significant share in its invention, the fact is that – apart from the Westinghouse and RCA groups – no other company or researcher was within striking distance of actually building and demonstrating operating active-matrix displays. Sure, the concepts were around (as was that of a world-champion chess computer), but in order to reduce a paper concept to actuality required the existence of a strong, well-equipped and well-supported group, an extremely "pigheaded" leader, and several years of additional search for funding, the receipt of which could only be ensured by showing considerable past achievements and evident capability for the new tasks. There was no other such group in existence either in the U.S. or in Japan at this time. These are blunt statements, but they need to be made in view of the well-known truth, "success has many fathers, but failure is an orphan."

5 "Large-scale display integration"

In early 1968 we had already demonstrated our "flexible" transistors and built some higher voltage devices (>100 V). My own thin-film group was originally part of the same department that in the early 60s had worked on electroluminescence and actually built a rudimentary EL display of discrete devices in which every EL element was controlled by a dedicated ferroelectric switch. Going through some old departmental files, I encountered the EL-FE reports and decided to see whether we could turn an EL nightlight on and off with one of our high-voltage TFTs. Our attempt worked the first time and I would say that this was the seminal event in the genesis of our active-matrix concepts – nothing to do with liquid crystals at this time.

Soon afterwards we had a 14-segment EL character controlled by a set of high-voltage TFTs and with Page I designed a circuit for a TFT-EL display, which – this was 1968, remember – already contained its own integrated row and column drivers! I therefore get rather impatient with the poly-Si people who, 20 years later, announce integrated drivers as a great discovery of their own, made possible only by polysilicon technology.[6]

In reflecting on the flat-panel display problem I started to read the literature and was amazed to find the huge number of attempts made over the previous 20 years to develop a viable technology. What particularly struck me was the number and variety of electro-optical materials and phenomena that had been proposed and worked on – all promising at the outset, but none of them reaching maturity. It seemed to me that most of the attention had been given to the electro-optical materials and their physics, but remarkably little to the problem of addressing them and distributing the picture information to the pixels.

The existence of the EL-FE display scheme stimulated my thinking: it embodied the idea of having a control element associated with each picture element, which became one of the key ideas of the active-matrix scheme. The purpose was clear: in ordinary, non-active matrix addressing the problem of crosstalk always arose, growing with the number of rows and columns to be addressed. It had to be eliminated for a viable flat-panel-display technology. The provision of a control element for each pixel allows us to control that element independently of all others.

Another important motivator was my realization that all existing implementations and concepts for flat-panel displays were electronic hybrids, with the (usually matrix addressed) display panel using a certain electro-optic phenomenon such as gas-discharge, dc or ac electroluminescence, light-emitting diode, incandescent filament, electrochromics, electrophoretic suspensions, etc., but the addressing of the display rows and columns was performed by a totally different electronic system, usually discrete line and column drivers or later, multi-output integrated circuits which had to be separately mounted and then interconnected with the display.

I felt an "esthetic" aversion to all these schemes and decided that this messy external interconnection step of thousands of terminations had to be eliminated for any sensible and economically viable flat-display system. At this stage I began to formulate our display philosophy, which could be summarized as "Solve the addressing problem and the materials will fall into place." Two factors thus came together in a fortunate combination: my definition of the problem and the availability of our, by that time, very well-developed TFT capability, which was in search of a significant application. Looking at silicon chip integration, I felt that a larger-scale version of similar principles was needed and could be developed through the use of TFTs. At that time I coined the name "Large Scale Display Integration," which we used until the modern term, "active matrix," was introduced in our 1975 paper.[7]

Our model of what was needed began to look much like a coarse-scale version of a DRAM and, indeed, we made this reference in our first publication reporting on an operational AMLCD. But that was in 1973 and I must cover the intervening years of struggle and near-surrender to the opposing forces of "law and order." We had the right ideas and the capability to carry them into practice, but for the time being we had no support and furious opposition from all sides.

Our semiconductor experts said: "We have problems in making a 1/8-in. chip and you want to build a 6-in. integrated circuit with your primitive technology? You should be locked up in an asylum, not given money." Our cathode-ray-tube experts said: "Who needs a flat panel? The CRT is so good, nothing will ever replace it, and besides, you don't stand a chance of building a manufacturable flat display, lots of people have tried and failed, why try again?" Laboratory management said: "We let you get away with TFTs so far because you managed to get divisional support, but we are certainly not going to fund such a crazy project." Fortunately, after my repeated pleading, they added: "Well, if you have really set your heart on it, why don't you try to get some government support? We will not take such a risk, but Uncle Sam might." This turned out to be our salvation – though not straightaway!

In this period, I received valuable encouragement from Prof. D. Gabor (inventor of holography and an old friend), to whom I had written about our work with TFTs. In a 1968 letter he responded: *"I have no doubt that your new developments open the way for a new era of transistor technology, beyond what has been achieved by silicon microcircuitry. One may well ask though what is there beyond it? Can we not build any circuitry with existing integrated elements, and is there any point in carrying integration beyond it? I can see at the moment two lines of potential applications of your large and cheap active networks: 1. Scanning circuits... if we ever approach solid-state television devices, we may have to think of 250,000 elements, each capable of switching a common supply of energy in proportion to a signal which it receives once in a scanning period. I consider all attempts so far made as prohibitively expensive".*[8]

Gabor's support for our ideas was gratifying and made me even more convinced that we were on the right track. This belief in turn enabled me to battle on for something like 3 years in my search for funding, while, of course, the department had to survive that long to benefit from it.

In the 1968-1971 period, we were mainly thinking in terms of an AM-EL display, and tried to get funding for such a display program from a large number of government and military agencies. Liquid-crystal technology was then in its infancy: dynamic scattering was the only optical effect known and field effects had not been discovered yet. While money-hunting, we refined our thinking about the display problem. I now said that the function of an addressing matrix should really be that of separating the task of addressing (or scanning) the picture elements from that of supplying power to the display material. In Gabor's words, one should provide "an array of elements capable of switching a common supply of energy in proportion to a signal which they receive once in a scanning period."

This formulation leads at once to the concept of a large-area dynamic memory as the appropriate circuit representation of the display matrix. One could write into this memory at high speed, irrespective of the response characteristics of the display medium, and the setting of the memory element in turn would determine the supply of energy to the display pixel.

From this formulation and our general approach it is evident that I intended the active-matrix principle to become a universal addressing scheme, solving this key problem in general, instead of just a way of removing the multiplexing limitation from liquid-crystal displays. As it happens, for liquid crystals, the small amount of energy stored in the memory elements is in itself enough to power the pixel, and this leads to the particularly simple elementary circuit which we published in 1973 – and which is still being used 23 years later (Fig. 5)! For emissive displays, or other types of materials for which the energy stored in the memory cell is insufficient to turn on its associated pixel, we need more complex but still easily realizable designs, such as the one we used in our AM-EL work (and which is also used today, Fig. 6). Both types of circuits, however, embody the same basic principle.

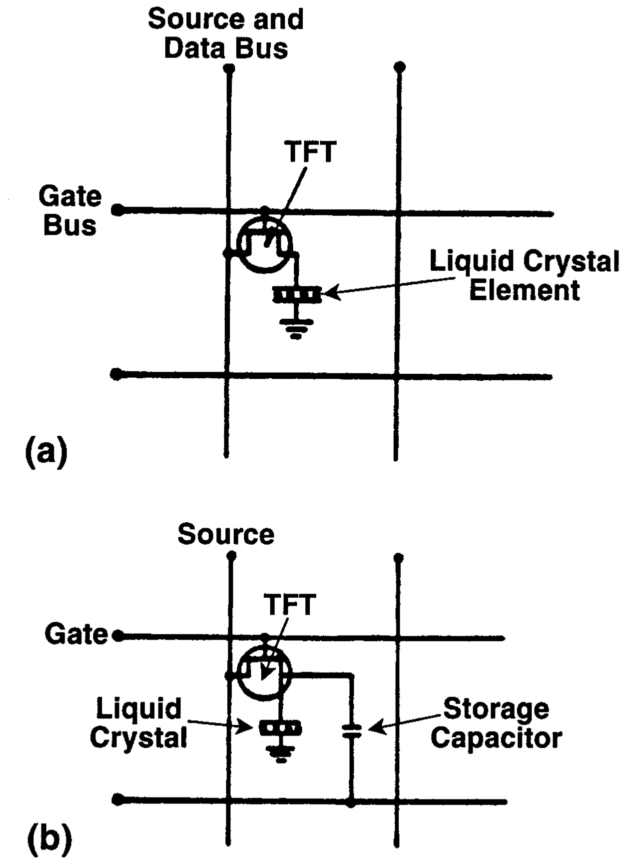

FIGURE 5 — Design for elemental matrix circuits of first AMLCD (1971).

6 1971 – Work starts at last

From our early and simple experiments and ideas formulated in 1968, it took us 3 whole years to obtain government support – Westinghouse was still not interested, and of course we had the additional problem of keeping the department alive and financed with other programs during this period. At this time I was responsible for a department of around 15 professionals and the same number of technicians, so it is evident that keeping them all gainfully occupied was a major task in an environment where our very existence as a "Thin Film Devices" group was an anachronism.

By 1971, liquid-crystal technology had emerged as an alternative target for active-matrix addressing and in this year we finally managed to obtain two small contracts, one from the Air Force for the construction of a 6 × 6 in. AMLCD and one from the Army for an AM-EL display of the same size and resolution. The Air Force contract provided all of $60,000 of support, which even those days was not a lot of money! The Army was a little more generous.

In those days there was no specialized equipment available for active-matrix fabrication, so we had to design our own. We retained the concept of trying to complete all deposition steps in a single pumpdown cycle, since we found that this was key to device stability and reproducibility. I designed a variable-aperture matrix stencil mask, consisting of two overlapping identical stencils with square apertures, which could be shifted in their relative position in both the *X* and *Y* directions, thus having the ability of generating identical rectangular apertures of varying sizes and aspect ratios at all matrix points – in this case, an array of 120 × 120 = 14,400 points. The two stencils forming the desired apertures could then be further shifted as a single unit in both *X* and *Y* directions. The principle of the *XX-YY* mask is illustrated in Fig. 7.

With it, we could synthesize all the busbar, semiconductor, and insulator patterns needed to form a complete active-matrix circuit, and we could do this both for the simple, single-TFT matrix used for the liquid-crystal display and the significantly more complex layout needed for the EL display. All the apparatus needed was inside a single 18-in.-diameter laboratory vacuum system and could be operated from the outside by feedthroughs which engaged the *X-Y* shifting mechanisms of the variable mask. All four displacements of the mask were controllable to an accuracy of 0.0001 in. with attached dial gauges. A design for an AM

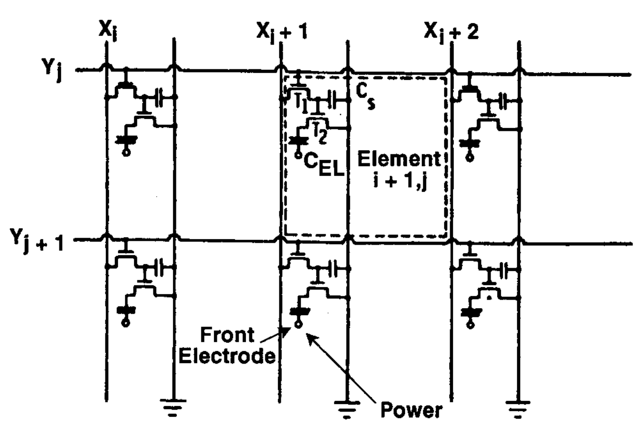

FIGURE 6 — Elemental AM-EL circuit (1972).

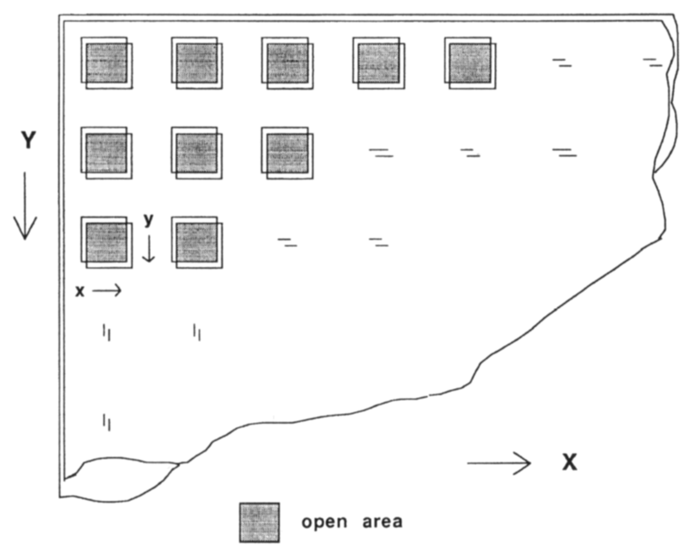

FIGURE 7 — Principle of *XX-YY* double mask.

circuit was thus reduced to a series of dial-gauge settings, specification of the material to be deposited for each setting, its deposition rate and thickness, controlled by an oscillating-quartz-crystal monitor. This was before the time such monitors were commercially available, so we had to make our own.

However, the process also involved evaporating all materials: metal, semiconductor and insulator, through the same mask. Again, the "experts" told us that this would lead to unacceptable cross-contamination, but the process worked and by early 1972 my co-worker Fang Luo produced operating active-matrix circuits with this primitive setup. We now had to learn the art of liquid-crystal alignment, filling, and sealing. After some failed approaches, I decided to use the then recently published oblique SiO evaporation method of Janning.[9] This worked, and within a short time thereafter we had our first operating AMLCDs. This was reported in our 1973 paper,[10] which also emphasized the long-term importance of integrated row and column drivers. In fact, I stated that AMLCDs would not become economic until such fully integrated active matrices could be produced. I still believe this today.

One of the first things we did with our TFT-LC panels was to put them in a projector and project a much enlarged image on the screen. This seemed such an obvious thing to do that we did not even think of patenting it! Today, there are hundreds of patents covering this area, with many people claiming that they had invented this particular use of AMLCDs. For the record: *we did it in 1973.*

Soon after receiving the two active-matrix contracts, we received a third one from the Navy, to develop a floating-gate memory TFT, similar to today's MNOS devices, which we then intended to use in a display with memory. Thus, after 3 years of penury, we had the support of all three Service branches. But our problems were not over: the battle now shifted to the defense of our defense contracts. Such contracts were normally reviewed by government committees staffed by industry experts in the various fields. In our case, the committee was called the Advisory Group on Electron Devices (AGED), and was staffed exclusively by semiconductor-industry executives.

Soon after we were awarded the first two contracts, they came before the AGED committee, which was incensed to discover that, several years after TFTs were officially declared dead by the semiconductor industry, some agencies had the audacity to support programs which involved using these forbidden devices! They wasted no time in attacking our contracts as a "waste of government funds," and managed to kill our Air Force contract after just 1 year. It is ironic to note that in this 1 year we built operating AMLCDs together with the necessary drive electronics, and thereby laid the foundations of today's AMLCD industry, yet the AGED people, driven by their prejudices, terminated one of the most successful research programs the Air Force had.

The Army AM-EL program was allowed to continue for the time being, but was under intense scrutiny and would not have survived if Elliott Schlam, our contract officer, had not been a man of exceptional courage who risked his own career in continuing to support us. Of course, we had to deliver under this contract, which we did handsomely. I cannot resist mentioning here that Dr. George Heilmeier (often credited with the origination of today's AMLCD technology on the strength of his early work on dynamic scattering) was at this time a high official in the Defense Department, and in that position adamantly *opposed* work on TFTs, as he "knew" from his RCA experience that these devices did not work! I remember several heated encounters with him at AGED meetings, where I was called upon to defend our contracts. As I said, success has many fathers . . .

The loss of our Air Force contract, successful though the work was, intensified company pressure on us again, and we were subjected to a 6-month-long "un-Westinghouse activities" investigation, which we barely survived. That we did survive was due to the fact that all our technical programs were progressing well, and by 1973 we also had an AM-EL display working[11] (Fig. 8).

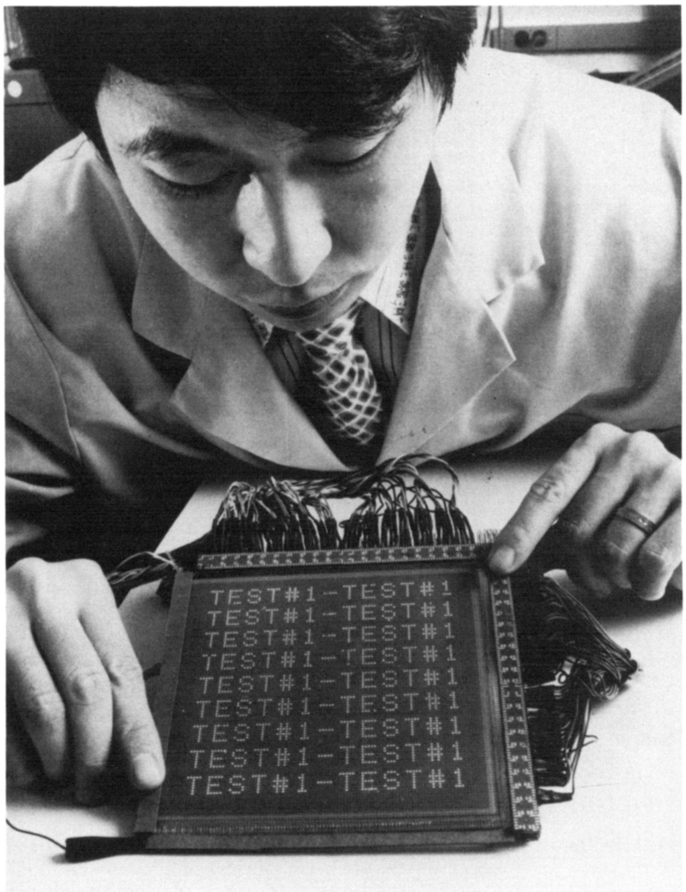

FIGURE 8 — 120 × 120 pixel AM-EL display (1973).

7 Display programs in high gear (for a short while)

By 1974 we had demonstrated an AM-EL panel capable of showing off-the-air video – the first active-matrix TV screen

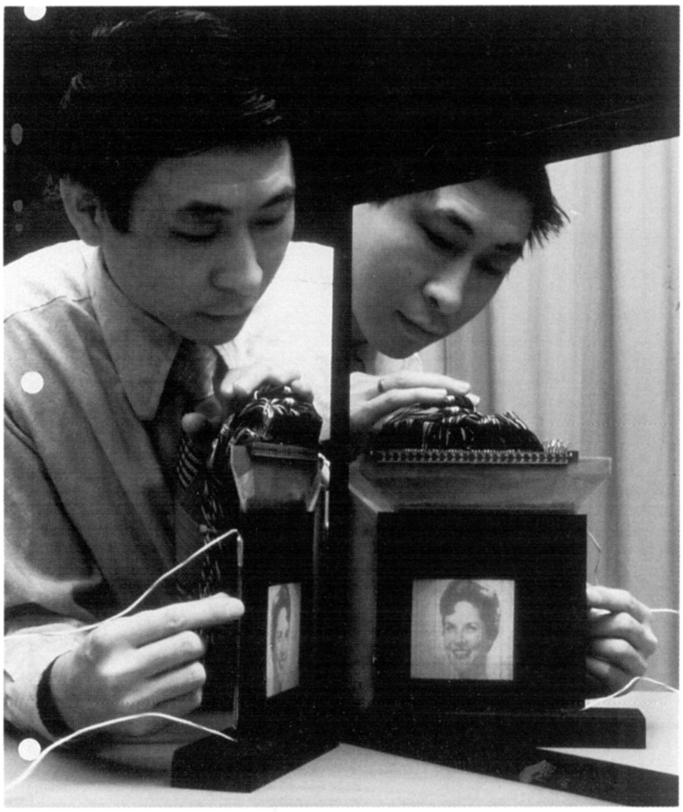

FIGURE 9 — 120 × 120 pixel AM-EL TV display (1974).

ever built. This helped us to get some recognition at last and even some company support! Figure 9 shows one of our early TV panels. We would have liked to continue the AMLCD work also, but our contract was cancelled due to the wisdom of the AGED committee, and so Westinghouse felt that we should concentrate on the AM-EL display, which still had significant government support. We also continued the work on the memory panel.

The Westinghouse Electron Tube Division now started to supplement our government funding by quite substantial divisional funds, which allowed us to go from the early 20-lines/in. display to 30 and eventually to 70 lines/in. We were also able to begin work on the row and column scanners and built a 64 × 64 element AM-EL memory display with our Navy funding. Figure 10 shows two different types of scanner circuits: a 7 × 112 demultiplexing switch[12] and a 256-bit four-phase dynamic shift-register. We encountered no significant problems in any of this work. In this period, the Army also began testing our devices and displays, and gave a favorable report on their stability.[13] We also reported on an AM-EL display with nonvolatile memory, utilizing the floating gate TFTs developed under our Navy contract.[14]

This happy and creative period did not last long: in 1976 Westinghouse closed down a large portion of its Electron Tube Division, which brought about a large cut in company funding. As partial compensation, we obtained a sizable manufacturing methods contract from the Army and a renewal of our AMLCD funding, this time from the Navy. We had concentrated most of our effort on the display programs now, but with our non-display support also dwindling we were in trouble once again – despite the spectacular success of our display work which by this time had received national and international recognition.

8 The end of the road at Westinghouse

I was confident that we would extricate ourselves from this hole also: the manufacturing program went well, we had designed and constructed a large vacuum deposition system in which we could make eight complete active-matrix circuits in each vacuum cycle – entirely under computer control and without any manual handling of the substrates from start to finish. Figure 11 shows this system and Fig. 12 shows a finished product of this system. Simultaneously, we built

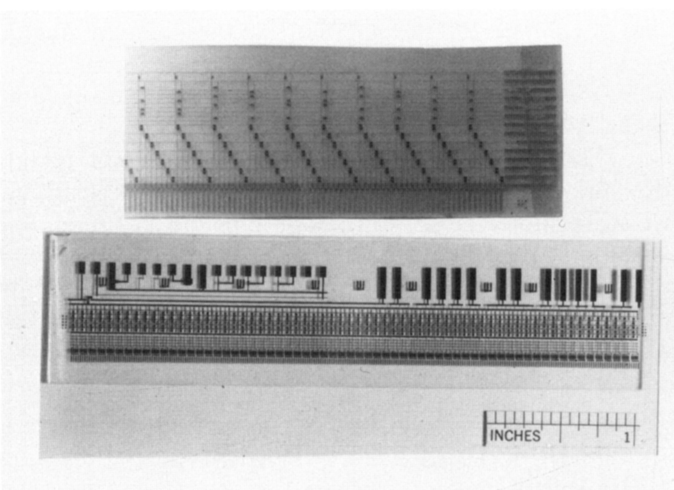

FIGURE 10 — 7 × 112 demultiplexing switch and 256-bit dynamic shiftregister for column and row drivers (1976).

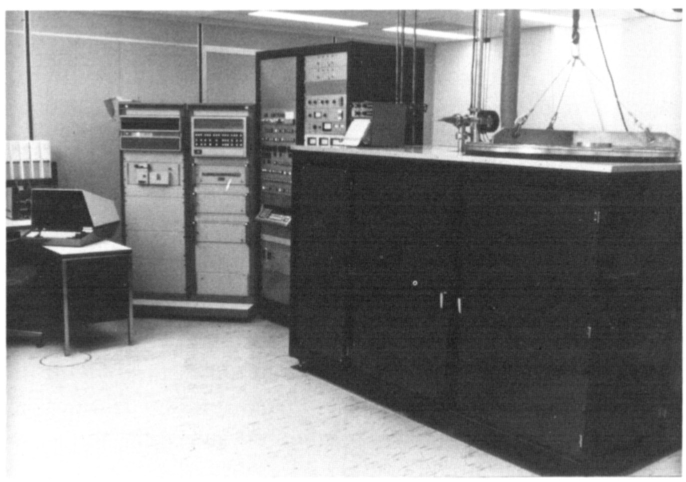

FIGURE 11 — Computer-controlled deposition system for TFT circuits (1977).

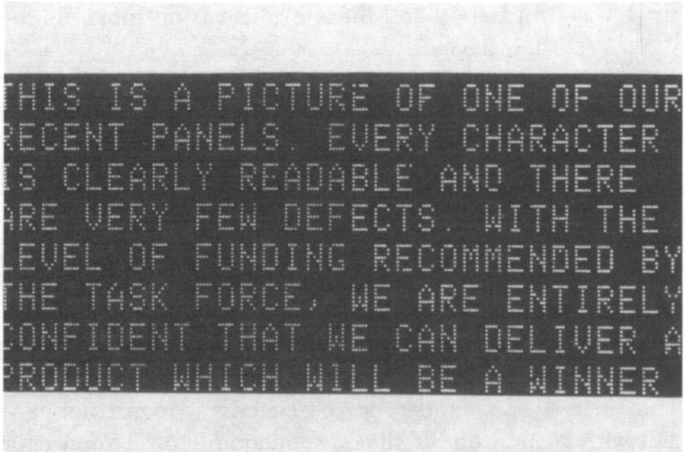

FIGURE 12 — 8 × 32 character alphanumeric AM-EL panel produced on automated deposition system (1978).

and demonstrated an AMLCD TV panel[15] and a high-performance AM-EL video panel. Figure 13 shows the AMLCD panel image projected on a screen and Fig. 14 shows the AM-EL TV panel.*

But it was not to be. Soon after losing much of our support from the Tube Division, Westinghouse underwent some high-level management changes with a disastrous effect on our project. Our former chief supporter, the Business Unit Manager, a very able computer scientist, was promoted and his place was taken by a manager with an accounting background. This manager was very unhappy with the high-risk project he inherited and went to work trying to get rid of it. Because of the large Army contract we had at the time this was not a straightforward task: many review committee meetings had to be held (with foregone conclusions), and it took him about 2 years to shut the project down. At the end of the contract period the project was

*This TV panel is still operational today – so much for CdSe instability!

FIGURE 13 — 4 × 4 ft. projected image of an AMLCD video panel (1977).

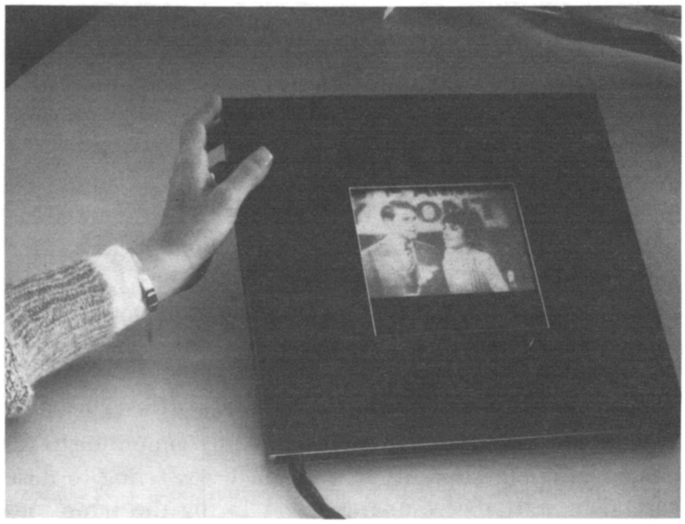

FIGURE 14 — AM-EL video panel with frame-freeze capability (1977).

cancelled, to the dismay of the Army that was counting on Westinghouse to start manufacturing the displays.

I was informed that Westinghouse decided to terminate the program because it did not meet the ROI objectives set in corporate guidelines for the risk class of our project (the highest, of course): a computer analysis showed that the best return the Division could expect was 13.2% while the hurdle was set at 13.4%! I will refrain from commenting on this analysis, but clearly Westinghouse at that time had no stomach for risk-taking. Of course, underlying their decision was also the fact that even in 1978, 7 years after we started our active-matrix work, there were still no apparent followers elsewhere of this technology, leaving the corporation very uncomfortable about being out of step with everyone. Such are the penalties of being too early.

I was told by laboratory management that I was held in high regard as a scientist, and was welcome to choose another area of work which would (hopefully) be of more use to the corporation than my active-matrix displays. However, having spent 15 years of my career promoting thin-film electronics, I was not prepared to abandon it, as I was by that time totally convinced that active matrix would soon emerge as the dominant flat-panel technology and I wanted to remain involved in it. I therefore resigned and set about trying to raise money for an AMLCD company of my own.

9 A 2-year hiatus

Finding the necessary money proved to be much more difficult than I had imagined. Again, our principal problem was being too far ahead. Venture capitalists don't like to back innovators: despite their reputation as risk-takers they much prefer to invest in a well-tenanted field. They said, "Pioneers end up with arrows in their backs."

Another drawback was that Westinghouse had cancelled our program, even though that gave venture capitalists their opportunity to invest in our technology. "If it is so good, why did Westinghouse give up on it?" they asked, and I had to supply an analysis of "Why?" – a longish essay with quotes from a Harvard Business Review article entitled "Why Big Companies Are Not Innovators" and an account of a newspaper interview with Vladimir Zworykin, the inventor of the TV tube, who also worked for Westinghouse in his time. He recounted the story of the first demonstration of his tube to Westinghouse management, where at the end he was told, "This is very nice, Vlady, but what can we do with it? You are a bright guy, so why don't you work on something useful instead?" Ironic how history repeats itself.

Yet another obstacle was the same semiconductor "establishment" that tried to kill my projects within Westinghouse and then tried through the AGED committee to kill our government support. Now when I was trying to raise capital to start my company, I was facing the same foes again. One example of this will suffice: During my fund-raising trips I traveled to California, home of high-tech venture capital, made a presentation to a well-known venture capitalist (one of the original investors of Apple), and gave him a demonstration of our video panel. He was very impressed, and said, "I didn't know such things were possible." Unfortunately, he then continued, "I am very interested, but I am not a technical man. This looks like a semiconductor device, so let me talk to some of my semiconductor industry friends and get their opinion."

My heart sank at this, since I knew exactly what would follow. The venture capitalist talked to a famous semiconductor executive (one of the founders of Intel), who responded thus: "This guy is using thin-film transistors. We played around with those many years ago, but the industry has gone in a different direction, so these devices are now obsolete, no one is using them. I wouldn't touch this with a 10-ft. pole, if I were you." This is absolutely true! The venture capitalist of course turned me down, but this was just one of the 80 or more refusals I encountered during my search for money.

Early on during this technically fallow period, soon after I left Westinghouse, I received an invitation from several Japanese companies to visit them and give talks on active-matrix technology. I spent 2 very pleasant weeks in Japan during "cherry-blossom time" in 1979, and met altogether with seven different companies, all showing great interest in active matrix.

I was impressed by the thoroughness with which the companies prepared for my visit, in some cases presenting me with very detailed questionnaires about our process. My conclusion at the time was that, while the interest was obviously great, progress in Japan to this time had been quite small and sporadic. Several of the companies I visited had attempted to duplicate some of our results, but had not been too successful – at least, that is what I was told. An amusing incident: during one laboratory visit, I was asked to tell my hosts why their TFTs were not working. I said that I would have to look at the devices and their characteristics before I could be of any help, but the response was that this work was proprietary and therefore it was not possible for me to test their devices!

I came back from Japan feeling that I had better hurry up getting started, since the Japanese companies were obviously planning to put major resources into active-matrix research, and would soon catch up with our state of the art if we remained inactive. This was a concern that I could not share with potential investors, as they would see it as a negative factor and be still less inclined to fund me. My forebodings turned out to be only too well justified a few years later.

A significant technical event occurred while I was in the midst of the money-raising activity: a group at Dundee University in Scotland reported success in constructing a TFT with an amorphous-silicon semiconductor.[16] Soon after its publication, articles began to appear in engineering magazines like *Electronics* to the effect that at long last, the right material for active-matrix TFTs had been found, avoiding the problems of CdSe such as instability, nonstoichiometry, and non-reproducibility, which had forced Westinghouse to stop the project!

There was of course no evidence for these assertions, which had been suggested by the Dundee group in search of funding. On the contrary, we had developed fully stable and highly reproducible devices years ago – I would have been foolish to try to start a business whose basis was the TFT if we did not have the necessary device technology. At this time (1979) we had done exhaustive life testing and stress testing and had test circuits running continuously, without degradation, for several years. I have one of these, built in 1974, which is still running today!

Despite our published and demonstrated results, great damage was done to the reputation of CdSe by these stories and I was not in a position to defend it. After all, Westinghouse did give up from an uncontested leadership position, and even though the reasons for this were purely business-related, it was a plausible rumor to plant – in the excellent cause of raising money – that the reason was the "bad CdSe" material. I believe that it was at this time that the Japanese workers, who *did* have problems with CdSe, switched over to a-Si, on the assumption that this was just like single-crystal silicon, a well-known and well-charted territory. I will return to this subject in my postscript.

For well over a year after my visit to Japan I was still without resources, having been turned down not only by scores of venture capitalists but also by companies like Boeing, ITT, Control Data, General Electric, IBM, Motorola, General Motors, Hewlett-Packard, Bendix, Sperry, NCR, Beckman, Bell-Northern, General Dynamics, Honeywell, Texas Instruments (rejection letter signed by Dr. G. Heilmeier), Tektronix, Thomson, Sanyo, Eaton, Standard Oil, Schlumberger, Xerox, TRW, National Semiconductor, Bausch and Lomb, SINTRA, Apple, Rockwell, Siemens, Exxon, MATRA, Mead, Mitsubishi, Matsushita, Corning, and others. But finally, after the 80-odd failed attempts, late in 1980 I found a venture capitalist who was prepared to take us on, on condition that a large industrial corporation could be brought in as a co-investor. Our luck held this time, and we found this co-investor. Following a prolonged negotiation between the three parties, we ended up with a small minority holding of stock, giving the investors immediate control of the company.

10 The birth of Panelvision

Despite our loss of control, this was a triumph, and Panelvision was born during the first days of 1981. We bought a lot of Westinghouse equipment no longer needed by them, including the computer-controlled deposition system, found an empty warehouse in a good location, and began the arduous business of building the company from the ground up, starting with putting down drains. Building a high-tech company in a field that we ourselves created was of course a fantastic dream come true, but one also replete with nightmares.

After we received our first financing, I persuaded several of my engineers and technicians to join me. I also made an advantageous deal with Westinghouse, securing exclusive licenses on the active-matrix patents and technology, as well as the right to purchase surplus TFT equipment they no longer needed, since they were totally abandoning thin-film device technology.

Within 6 months of moving into our new location we had the computer-controlled deposition system installed and working in a temporary clean area. By the end of this year (1981), we were getting TFTs with excellent characteristics and had designed and received a complete stencil-mask set for our first proposed product, the Panelvision "Minigraphic" AMLCD, consisting of 128 rows and 192 columns, capable of displaying 512 alphanumeric characters and graphics over an area of 2.56 × 3.84 in. Progress in our first year was so encouraging that our investors asked me to write a follow-up business plan, on which we raised $4 million by early 1982 – a big stepup from our initial $1.6 million financing. But, simultaneously, we ran into major problems.

We used metal stencil masks to define all circuit levels in the matrix. This worked fine with the variable aperture masks we used in our early work and also worked in our computer-controlled deposition system where we used separate masks for each level. But we could not make the masks ourselves: for these we were dependent on a single outside source – not by choice, but because we could not find another company willing to commit itself to timely deliveries. In one instance, for example, we were quoted an 8-month delivery on the first level mask, and we needed seven masks for the complete circuit!

At Westinghouse we received excellent masks from our source. However, 3 years had passed and even though the maker assured us that he could match our designs, the first mask set delivered in mid-1981 was faulty. Individual mask levels were usable, but there was a runout error between the masks. We could make good devices with this set, but not complete circuits. A second attempt by the mask supplier was better – almost (but not quite) perfect. It was soon after the delivery of this set that I wrote our second business plan, on the assumption that the third set would be "on the nose."

Alas, the third set was worse than the second and I now recognized that we were in big trouble. Coincidentally, the mask suppliers admitted that one of their key technicians had left the company and it was apparently on his skills that the quality of our masks depended. They said they would try yet again, but I decided that relying on this one small company, with now very questionable skills, was too risky and that we had to switch our process, midstream, to one based on photolithography.

This was a heavy blow and could not have come at a worse time. We had just raised a large amount of money on my assumption that we would soon have operating circuits emerging from our automated deposition equipment, and now I had to make the admission that the stencil-mask process would not work without a significant development effort we could not fund. In consequence, we had to go back almost to "square one" with our manufacturing technology and start all over again with photolithography – about which I had major reservations.

I have often been asked why we had committed ourselves to the stencil-mask process without having an alternative fabrication process developed and ready. This is an important question and I will answer it here.

First, there were several good technical reasons. Stencil masks worked very well for us so far, therefore we felt no need for alternatives. Our Westinghouse funds, always limited, were just sufficient to develop the stencil-mask process, and I could see no justification for pursuing another, radically different process. The ability to deposit all the levels of an active-matrix circuit in one pumpdown cycle was an essential element in our success, avoiding contamination of the critical semiconductor-insulator interface. The stencil-mask system allowed us to implement this principle in a very simple manner.

The stencil-mask process provided an extremely attractive manufacturing technique as well: depositing the successive layers of the circuit in the same vacuum system in rapid succession seemed an ideal candidate for eventual mass production. It was an almost exact analog of a multicolor printing press, with stencil masks in place of printing plates. All we needed was good masks, and no need for resist spinning, baking, photo-exposure, development, rinsing, ashing, *etc.*, and the need to repeat this tedious sequence for each successive level of the circuit. Furthermore, we could see no way of using photolithography without exposing the semiconductor surface to contamination, which we knew was a root cause of nonreproducibility.

Finally, we were the first in the AMLCD field to reach manufacturing. Before us, there was no manufacturing technology for active-matrix circuits. It seemed an unacceptable risk to try to develop a photolithography-based

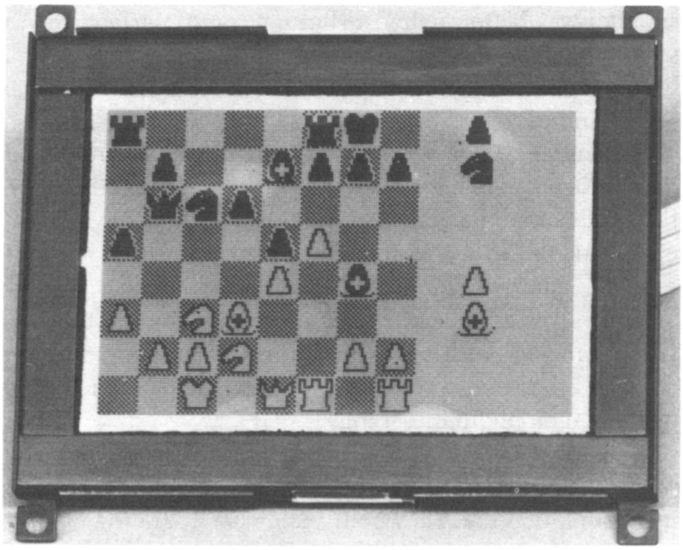

FIGURE 15 — Panelvision "Minigraphic" AMLCD panel (1983).

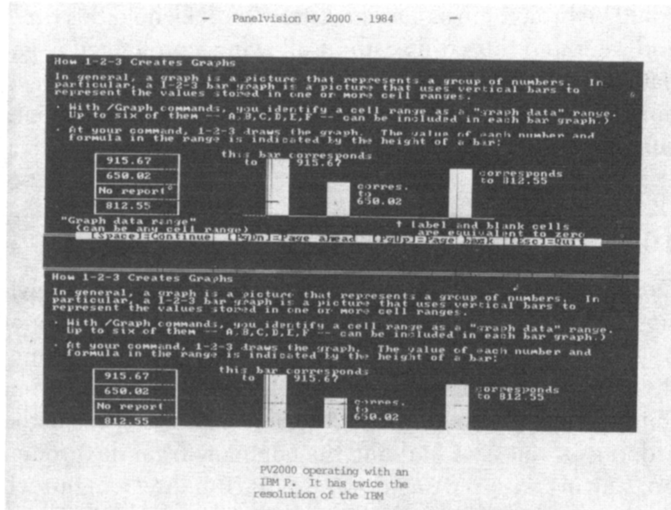

FIGURE 16 — Panelvision developmental "PV-2000" 400 × 640 pixel AMLCD panel with alphanumeric display (1984).

process, when all our experience at Westinghouse had been with stencil masks.

There were also some "political" reasons. At Westinghouse, I knew that our days were numbered when we lost our funding from the Tube Division. It would have been the kiss of certain death for us even to hint at that stage that we needed an alternative to stencil masks. As it turned out, we kept the project alive just long enough to take it outside in a reasonable shape, and (eventually) find investors.

At Panelvision, the problem of "swapping horses in midstream" appeared equally unacceptable: a sure way of undermining our investors' confidence, so we had to persevere with our stencil masks. The fact that we were eventually forced to change our process precipitated exactly the crisis of confidence I was trying to avoid. The lead investor was furious and immediately deposed me from the presidency, appointing our very recently hired marketing manager as the new president!

Panelvision never recovered from this setback. It took us the best part of 2 years to develop a reliable, contamination-free photolithographic process, and in these two years the display world changed drastically. As expected, Japanese companies started to invest major funds in active-matrix development, while we in turn needed to raise additional funds to keep our company going for this period. This became ever more difficult when the technical press was full of Japanese achievements and reports on their intent to dominate this field.

Towards the end of 1983 we had our new process working, and shortly thereafter we began fabricating our first product, the "Minigraphic" panel (Fig. 15). The product was announced early in 1984 and attracted great press and customer attention. We were still the first in the market with a working AMLCD product, but by this time the Japanese were close on our heels. Our yields were low and the panels had defects, but they worked well and survived all our and our customers' life and environmental tests. We were selling them as fast as we could make them.

By the fall of 1984 we had 80 customers evaluating our prototypes, with some of them beginning to design the panels into their products. We also started to develop a much larger panel, the "PV-2000," a 640 × 400-pixel 80-lpi 9.5-in. diagonal display; within a few months we had these operating also (Figs. 16 and 17). We demonstrated these units to all the computer companies, and they were very excited, asking us when we could start delivering large quantities, say 100,000 panels! But when we pointed out that we were a tiny company that would need significant investment to expand its manufacturing plant, and invited them to invest in Panelvision, they all said: "We don't invest in component manufacturing, we just buy them, so find your money somewhere else and come back when you have adequate capacity to give us a quote."

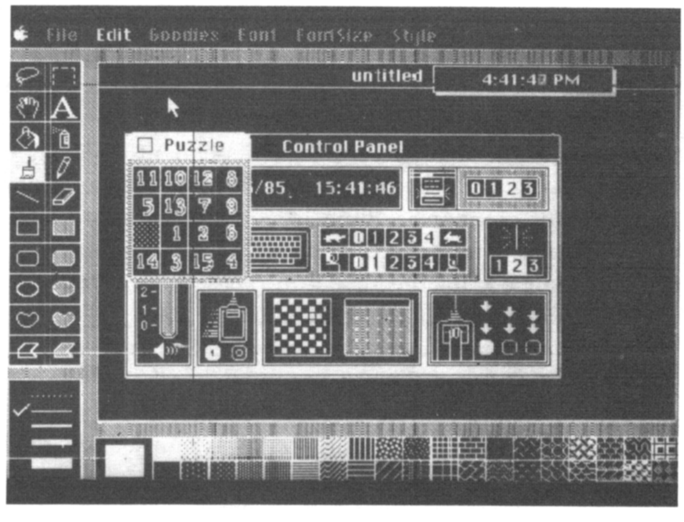

FIGURE 17 — PV-2000 panel in graphic mode.

This never happened. By this time the Japanese were aggressively promoting their AMLCD capability, investing heavily in manufacturing facilities and dominating press attention. Four years earlier, I had great difficulty in raising money for an AMLCD company because there was nobody else in this business – now, paradoxically, the problem was just the opposite: there were too many large companies (all Japanese) entering the business and frightening U.S. investors who could not visualize Panelvision being able to compete with these giant corporations, even though it was still ahead technically at the time.

My obstinacy was of no avail in this situation, as I was no longer in control of my own fortunes. I did write another business plan and we carried it around to about 70(!) potential investors: large companies and venture capitalists, but nobody would step up this time, while our original investors wanted to get out. We still had lots of eager customers and significant size repeat orders but not enough capacity to break even, so Panelvision was put on the block in 1985 and its assets – equipment, people, and knowhow – were sold to Litton Industries.

The fate of Panelvision was sealed by the computer industry's refusal to invest in it: 10 years later, this same industry is totally dependent for its AMLCD supplies on its Japanese competitors. There is a lot of national agonizing about this situation but no solutions have been found. This does not say much for the foresight of an industry that prides itself on foreseeing the future, but as far as the birth and childhood of active matrix is concerned, this is the end of that story.

11 Postscript

While I am gratified by the dramatic worldwide acceptance and exploitation of the active-matrix principle, I must admit to some major regrets and reservations about the way the industry has developed and is still developing.

First and foremost, of course, I am dismayed by the fact that the USA, where the active-matrix display was invented and first fully developed, not only allowed its large technological lead to vanish, but is today trailing not only Japan, but Europe, Korea, and Taiwan as well, putting the mighty U.S. out of medal contention – in fact, barely in the race at all! This is almost incredible in a high-technology field whose market volume is expected eventually to rival, if not surpass, that of the semiconductor industry.

I can find no explanation for this situation other than the shortsightedness of the U.S. computer industry. Traditionally, U.S. computer manufacturers were design and assembly houses, buying their components from outside suppliers. As far as monitors were concerned, when desktop computers became commodities, CRT manufacturers had a great overcapacity and were delighted at the new markets that had developed for their tubes.

This was fortunate for the U.S. computer makers who in consequence could get their monitors at rock bottom prices. But what they overlooked was that AMLCDs represent a totally different economic situation. AMLCDs were developed in Japan not by the CRT manufacturers, but by corporations with heavy involvement in the semiconductor and computer industries, and were explicitly intended to put them ahead of their U.S. competitors rather than become their display suppliers.

Why would the Japanese computer companies, having invested billions of dollars to move ahead of their U.S. competitors, suddenly elect to become charitable institutions and look after the negligent U.S. computer industry's display needs before satisfying their own? Not a very probable scenario! The alternative of financing potential U.S. suppliers does not seem to occur to U.S. companies even today, or else is dismissed with the comforting excuse, "It is too late now to build up a viable U.S. AMLCD industry (though apparently not too late for Korea, Europe or Taiwan!), so let's wait for a successor technology that is superior, and *then* we will invest."

This sounds like a parody, but is in fact exactly what is being said today. This "successor technology" is supposed to be the field-emitter display (it has actually been around for 30 years) and so there is now a pathetic and (in my opinion) totally deluded flow of investment into FED companies, which will peter out in a few years when it becomes obvious that they have no chance of competing with active-matrix displays.*

So much for the U.S. display scene – but I am also critical of the Japanese approach. My position is fairly well known from previous publications[17,18] and presentations, but I will summarize it here once again, since I believe it to be of critical importance for the future of active-matrix displays if they are to fulfill the market expectations placed on them.

It will be recalled that our original active-matrix designs included integrated row and column drivers, and the cost advantages of such a structure were emphasized from the start. It is estimated that currently the cost of separate silicon chip drivers, their mounting and interconnection with the matrix rows and columns, represents 50% of the total manufacturing cost, and this percentage is likely to increase with size and resolution.

By the choice of a-Si, the Japanese industry and their followers elsewhere have deprived themselves of the ability to realize this concept, since the carrier mobility of a-Si is too low to be usable for the high-speed column drivers and also imposes a severe limitation on the row drivers, which have to supply significant current to the pixel storage capacitors. Not only does the need for separately mounted IC chip drivers increase the cost by a large factor, but obviously the reliability of the whole system is compromised by the need for many thousands of interconnections. "Chip-on-glass," supposedly the next step in AMLCD driver attach-

*Texas Instruments recently came to realize this and abandoned its FED effort.

ment, shifts the interconnection problem elsewhere but does not eliminate it.

Thus, more than 20 years since my original formulation of active-matrix principles, the AMLCD industry is facing exactly the same problem that I proposed to solve in 1971. Due to the enormous and unfounded prejudices against CdSe – with which these problems can be readily solved – the industry abandoned its best resource for creating a truly integrated display. But setting aside the driver-integration problem as if it did not really matter, is only one of my criticisms of the Japanese approach. There are at least two other major factors, probably as important as driver integration, which militate against the use of a-Si instead of the high-mobility CdSe.

The first of these factors is the combination of manufacturability, yield, and equipment cost, all critical for cost reduction of a component which, although it has very high performance, costs far more than it should. Through the substitution of CdSe for a-Si, here are some eminently practical ways of cost reduction:

1. Because of the very high carrier mobility (3–400 cm^2/V-s, 484 has been measured in some devices), much looser design rules can be used: 15–20 μm instead of 2–3 μm, resulting in (a) much lower-cost, higher-throughput lithography (steppers are not needed, the entire glass area can be exposed in a single shot), (b) higher yields because of the much reduced tolerance requirements, no image stitching.

2. The very high mobility also provides much wider tolerances on device performance, since even a fourfold drop in mobility would give superior devices, while a 50% drop in a-Si mobility is disastrous.

3. CdSe deposition is much faster than a-Si: it takes a few seconds, hence higher throughput again; in equipment no more expensive than a-Si CVD systems. The same equipment will also deposit a passivation layer over the CdSe film, protecting the interface. Equipment cleaning is also much faster, providing a higher percentage of up-time.

Against the argument that turning to CdSe means throwing away everything that has been learned about AMLCD fabrication, I point out that most of the equipment at present used can remain in place, except for the replacement of the a-Si CVD reactor. The steppers can be traded in for full-area exposure systems costing one-quarter as much.

Finally – and this is the basis of my third criticism – AMLCDs are comparatively young, and it behooves us to look at their future. I maintain that by choosing a-Si as their TFT semiconductor the Japanese industry has erected a major barrier against future growth. The limitations of this material are clearly apparent, and will soon make themselves felt even in the simple development of larger and higher-resolution matrices – they do not have the switching speed and current carrying capability to go much further in this direction. This problem was analyzed, for example, by Lüder,[19] who has shown that even for the next generation of HDTV application, *i.e.*, a 1250 × 1920 × 3 matrix, a carrier mobility of around 6 cm^2/V-s is needed to charge the pixel storage capacitor in the available dwell time of 8 μs, *i.e.*, it cannot be done with a-Si.

Here I want to look further ahead than a linear extrapolation of present capability. With the choice of a-Si technology, the AMLCD industry has become the captive of the semiconductor industry, both in the sense that it was developed by engineers from that industry, and also that the equipment used and developed for matrix fabrication was directly derived and scaled up from semiconductor equipment. Because of the 2–3 μm, design rules and very close tolerances needed for a-Si TFTs, the equipment has become as complex and expensive as that used for IC fabrication. Thus, 50 cm and larger circuits have to be fabricated with equipment originally designed for submicron circuits – a serious manufacturing anomaly.

This was never my intention: I visualized the emergence of a manufacturing technology borrowing ideas from both the semiconductor and the circuit-board industries, but eventually lying much closer to the latter. This has not happened because of the factors discussed above, but could happen if CdSe is adopted. For example, advanced printing techniques are capable of printing and resolving 4-μm lines and gaps, and with appropriate development could be used for resist patterning of CdSe TFTs and matrices, but almost certainly not for a-Si. The development of a printing-related technology would of course produce a dramatic cost reduction in matrix fabrication.

Again, because of the demonstrated high-voltage capability of CdSe TFTs, which do not contain *p-n* junction regions liable to breakdown, a wide range of other materials requiring higher voltage drives, such as VF, EL, PDLC, PLZT, dipole suspensions, and others become eligible for active-matrix addressing. This feature further extends the future importance of CdSe.

Lastly, there has been a lot of talk recently of the "system-on-panel" or the "display becoming the device," by putting more electronic functions on the display glass itself. I claim to have anticipated these ideas as well in a paper published in 1980: *"...in a mature technology...our integrated flat color panel, the late child of a mature, multi-billion dollar industry, will have a 50 to 1 weight advantage over the shadowmask tube, as well as having much more 'brain,' both in the sense of containing or eliminating much of the electronics which is external to the CRT and also in the sense of allowing additional functions, limited only by the circuit designers' imagination, to be integrated into the screen."*[20] This sentence is taken from a chapter entitled, "The CRT, like the brontosaurus, will become extinct" – a phrase that has often been used since in popular technical literature. The chapter starts with the words, *"It will become extinct, in fact, for the same reasons; namely, too much bulk, very little brain!"* This was dismissed as utopian in 1980 – today no one doubts that it will indeed happen.

The point I wish to make here is that with CdSe, by virtue of a mobility which is only 40% lower than that of single crystal silicon, one can realize a large proportion of the enormous repertoire of MOSFET circuits and functions *on the display glass*, while with a-Si this is again out of the question. In the long run this could be an even more important advantage of CdSe than the ability to generate integrated drivers, since the drivers are just a small subset of such realizable circuits, while new types of circuits, specifically invented for image processing (for example) could be accommodated within each matrix element.

I will not speculate here further on these new possibilities, which will be realized only if the AMLCD industry is converted to the use of CdSe – now an unlikely, though not inconceivable event. To conclude this highly personal, but perhaps historically important account, I want to acknowledge the critical contributions of many members of my great Westinghouse team, with special mention of Derrick Page, Juris Asars, Fang-Chen Luo, Karl Yu, Paul Malmberg, Bob Stapleton, Joe Murphy, Leon Sienkiewicz, Ed Greeneich, Zoltan Szepesi, Willy Lehman, Bill Rogers, and Dave Davies.

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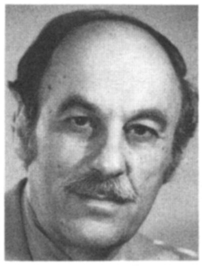

T. Peter Brody received his Ph. D. in theoretical physics from the University of London. From 1959 to 1979 he worked at the Westinghouse Research Laboratories in the fields of semiconductor device theory and experiment, pattern recognition and thin film technology. Over the period 1968 to 1979 he pioneered active-matrix display technology. His Thin Film Device Department built the world's first AMLCDs in 1972, the first AM-EL displays in 1973, and demonstrated real-time video on both types in 1974. He coined the term "active matrix" and introduced it into the literature in 1975. Dr. Brody left Westinghouse in 1979 and founded Panelvision Corporation, the world's first AMLCD company in 1981; it introduced the first AMLCDs into the U.S. market. Panelvision was acquired by Litton Systems in 1985, and, after a period of consulting, Dr. Brody started Magnascreen Corporation in 1988. He left Magnascreen in 1990, formed Active Matrix Associates and has recently been working on manufacturing-cost reduction of AMLCDs and color filters with DARPA support. Dr. Brody is a Fellow of the SID and recipient of the SID Karl Ferdinand Braun Prize, the Rank Prize (GB), and the Eduard Rhein Prize (Germany) for his pioneering work.