Smoke, mirrors, and manufacturable displays

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Abstract

The ultimate display is not an ultra-high resolution, 3-D, holographic projection of arbitrary size. Instead, it is, simply, one that is good enough for the job at hand and, most important, one that can actually be manufactured.

This paper discusses the slow pace of evolution in display manufacturing, and the current status of global display manufacturing infrastructure. The >20 year typical development cycles of today's new display technologies are actually an improvement over what came before, but still are far slower than is commonly recognized. The author contends that the ultimate display technology is one that can actually be manufactured, and one that can be made to march to the beat of Moore's Law and to innovate on 18 month cycles. The emerging microdisplay technologies which use silicon CMOS backplanes appear best equipped to rise to the challenge of Moore's Law.

Why has it been so difficult for new display technologies to reach mass commercial volumes? Ultimately, the author contends that it is the lack of "killer applications" that has slowed display development. For example, the CRT was 'good enough' until the computing revolution demanded the laptop LCD display. Emerging "killer applications" for displays are discussed: pointing to strong demand for small "pocket" projectors and versatile autostereoscopic 3D displays.

Background

The researchers in high-end display technologies have been largely ineffective in taking their wonderful new display technologies from the laboratory *en-masse* to the world. In contrast, the last two decades have seen immense progress in electronics as integrated circuits, computers & software, have been tremendously effective at being able to move their laboratory innovations into mass production. The march of Moore's Law has not been as transformative to the display industry.

Of course, real progress has been made.

The shining point for display innovation is today's global move from cathode-ray-tube (CRT) to liquid crystal display (LCD), and the accelerating adoption of video projection systems (see Figure 1).

The vast majority of work in the "ultimate" display technology development is centered around the initial demo. The assumptions of the manufacturability of the demo go deep and are pervasive. Efforts around commercialization beyond the promising demo generally hit tremendous obstacles and die out after a few years. Typically, the work is then re-invented by another group a few years (or a decade) later, this group is generally unaware of previous abandoned effort, and specifically doesn't know why it failed. This scenario is particularly common in the area of 3D display.

Figure1: a flat panel LCD display is compared with a bulkier CRT

Some innovators in display technology often show something genuinely new and exciting in their initial demo. This is excellent and to be encouraged. Large area display, interactive displays, 3D and holographic displays, tactile feedback displays, displays in thin air, and so forth, inspire us.

> The *smoke and mirrors* are the manufacturable parts of these cutting-edge display demos.

If it only were all *smoke and mirrors*. The hard part of a manufacturable solution is the cost: bandwidth, video encoding, circuit design and yield, inspection costs, display uniformity, lifetime, reliability, contrast and image quality. They all take their toll. These are not simple, parsable tasks, but rather like a bowl of spaghetti: pull on one strand of spaghetti and everything else in the bowl moves as all the noodles are tangled together.

High-end 3D display technology is usually either:

a) very high end and very very few units
b) a fad when it reaches mass production

Of course, There are some companies that have created some novel 3D display technologies that have had real staying power, for example the 25 year history of StereoGraphics (San Rafael, CA) in making shutter glasses and other stereographic 3D displays. There are other examples of this kind of success, but they are the exceptions.

The author contends that the focus on the ultimate display should be on the manufacturing pipeline. The main question is then:

> How do companies and universities leverage the manufacturing capacity that already exists to allow them to get from demo to product more quickly?

The Pipeline

What is the current typical pipeline in going from the first demo to a product? There is much discussion in the literature, at research conferences, and the ilk, of the manufacturability of some of the nascent display technologies. Often the number of masks or steps in the manufacturing process is discussed – indicating that the new technology will be cents-per-square-inch - as a function of materials costs and lower number of process steps. What tends not to be emphasized is the enormous investment in process tuning to perfect the display technology that always seems to be required.

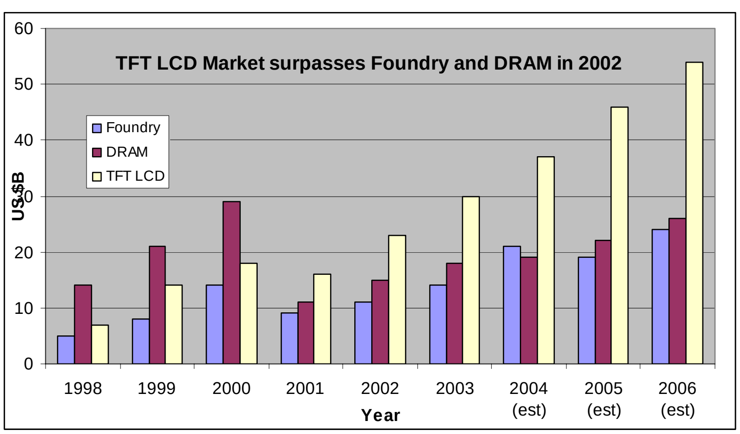
A typical path involves leveraging existing manufacturing infrastructure to allow more rapid development. The current flat panel display (FPD) market is described in Figure 2.

Global FPD market (US$ B) *src: PIDA*	2002	2003	2004	2005 (Est)	2006 (Est)	% 2004
TFT LCD	20.38	29.4	36.33	43.02	47.23	**71%**
Projection	4.06	4.61	5.56	6.62	7.07	**11%**
TN/STN LCD	4.3	4.13	4.12	3.83	3.45	**8%**
PDP	1.37	2.19	3.55	5.43	7.99	**7%**
OLED	0.08	0.2	0.48	0.92	1.82	**1%**
VFD	0.62	0.61	0.58	0.56	0.55	**1%**
LED display	0.64	0.71	0.76	0.79	0.81	**1%**
Total	**31.45**	**41.85**	**51.37**	**61.19**	**68.95**	

Figure 2: Shows the relative market size of competing flat panel display technologies (FPD). Note the domination of LCD technology in the categories of TFT LCD, TN/STN LCD, and Front Projection. The vast majority of display manufacturing capacity is in LCD fabrication.[1]

86% of the global flat panel display (FPD) revenue came from LCD in 2004. The breakdown is as follows: 71% in TFT LCD, with an additional 8% in LCD, plus 11% in front projection of which >60% uses LCD technology. Thus, the global flat panel display manufacturing is dominated by LCD.

The TFT-LCD industry is enormous. It alone has revenues that are now double the size of the DRAM market or the Silicon Foundry market (see Figure 3). If one were wishing to make the ultimate display – and get it out into wide usage - it would be good to somehow leverage one of the mature manufacturing infrastructures of the world.



[1] CRT manufacturing capacity not included as part of flat panel display category.

Figure 3: graph showing the growth the TFT-LCD industry relative to DRAM and Foundry. TFT-LCD industry is now twice the size of the other markets.

The display industry uses much of the same essential infrastructure as the micro-electronics industry, but the micro-electronics industry is measurably more accomplished. While the micro-electronics industry has doubled the speed of our computers every 18 months for the past 40 years vastly increasing our communication and computing abilities, the display industry has only moved from CRT to LCD. [2]

Historically it takes much longer than anticipated for a display technology to reach maturity (see Figure 4).

	early entrant	PREDICTED high volume sales	ACTUAL high volume sales
CRT	Braun (1897)	15 years (1910)	50 years (1950s)
LCD-TV	RCA (1968)	10 years (1978)	35 years (2003)
DLP (MEMs)	TI (1978)	10 years (1988)	>20 years (~2000)
LCOS	IBM, Hughes (1980s)	10 years (1990s)	20 years (2005)

Figure 4: Depicts the predicted and actual approximate entries of new display technologies into high volume production. Only in the case of Texas Instruments (TI) did the early entrant see technology development through to high volume sales. Also note that with a 20 year development timeline, any early or fundamental patents are in public domain.[3]

Why does it take so long?

Since the human visual system is very picky, artifacts and non-uniformities can detract enormously from the value of a display. The specifications for image quality and reliability are also difficult to attain and increase materials costs, development time, and manufacturing costs. However, the same could be said for doubling the transistor density every 18 months, also an issue of materials development, process complexity, quality and reliability.

What are the real reasons that display development seems to take longer than typical IC development?

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[2] To be fair – the printing industry has seen remarkable change over the last 50 years: Kodak, Polaroid instant photography, home movies, home slide projection, digital cameras, inexpensive ink-jet printing and so forth - are all truly remarkable innovations.

[3] Note: Digital Light Processing (DLP) is a micro-electro-mechanical (MEMs) technology. Liquid crystal on silicon (LCOS) is a microdisplay technology involving liquid crystals on top of CMOS Silicon substrates. Initial demonstrations of first LCOS system date to the 1960s by RCA.

Possible reasons that display development is slow compared to IC development	
Reason	**Viability**
Large area Display tougher than IC feature size shrink?	NOT LIKELY: Uniformity is more difficult to attain over a larger area, but the cleanliness and purity requirements should be more difiicult in attaining feature size reduction.
IC guys are smarter?	POSSIBLY
Display tech is harder?	NOT LIKELY
Organic vs. Inorganic	NOT LIKELY: Organic materials are often used in displays and organic materials can have reliability limitiations, ICs also have had reliability problems to overcome even with the use of inorganic materials. It's unclear why one barrier would be greater than the other.
Analog or digital	NOT LIKELY: Most ICs are pure digital and optimized for rail-to-rail operation. Thus, uniformity may be easier to maintain. Digital display is atypical, liquid crystals tend to be voltage modulated (not rail to rail - aka analog) and thus uniformity can be difficult to attain (shading correction circuitry is typically used to compensate for non-uniformities). However, the DLP is all-digital and still took 20+ years to develop.
Investment?	NOT LIKELY: Billions and billions of dollars in each area
No Killer Application!	LIKELY!!!!: The CRT was just fine, until the move the laptops required the LCD.

Figure 5: Possible reasons that display development takes so much longer than IC development.

Many reasons presented in Figure 5 can be dismissed in the right-hand column, however the one that seems the most difficult to dismiss is the lack of need. Perhaps, for all that we say that we want better quality displays - it's not actually true. The CRT was just fine for most purposes until the advent of portable computers demanded LCD displays. As these improved, they eventually took over (nearly) all computer displays. Without the 'killer app' of the laptop, we'd still be sitting in front of CRTs at the office.

Starting in the 1980s, the Japanese government and high-tech sectors promoted HDTV because they wanted to sell more televisions, and stay at the forefront of TV technology. This faltered because content was mediocre and because one couldn't really tell the content was HD from a standard distance, on a standard size CRT. Larger CRTs (>36") diagonal were an option, but they were unlikely to fit through a standard 36" door. There was little need for the big-screen TV before HDTV because the blown-up "standard" resolution TV signal had poor quality. Advances in electronics have enabled the HDTV signal and have improved standard signal fidelity, and so, with more pixels, the large-screen image looks very good. Today, HDTV is enabling the migration to big-screen TVs. Now, with the killer app emerging, the market needs displays to match.

While the actual time from early entrant to high volume sales is declining (~50 years for the CRT to ~20 years for LCOS). This development time is still is much longer than is typically funded in a business unit or standalone company. It's difficult for a business to stay in business if it takes 20 years to start making serious money. In addition, by the time the display technology reaches high volume sales, the fundamental patents have expired and gone into the public domain. Trade secrets perhaps offer a better barrier to entry.

What is the ultimate display then?

Let us define some criteria.

1. People should be able to see it -> thus many copies should exist. A demo in the lab seen by only a few *cognoscenti* isn't so far removed from a tree in the forest falling un heard...

2. Thus, this display should be manufacturable in the near term. To achieve this, the current manufacturing infrastructure should be leveraged. Ideally, we can learn something from the IC people and leverage Moore's Law.

3. It should look *really* good.

4. It should solve a real problem, have a "killer application"

Let us divide the world up into kinds of displays: little, medium, and big. Little displays are in your cell phone. Medium sized displays are monitors and laptop screens, and big displays are, for example, theatre projectors.

"LITTLE" displays

Little displays have problems with power consumption, small display size, small display resolution, fragility, brightness, and cost. The emerging "killer application" is likely reading full screens of email on cell phones and previewing larger-size digital camera pictures. Some options for creation of a large image with a small portable display:

1. A screen that stretches out, folds out, rolls out, or projects onto something (the wall or something that rolls out, unfolds or stretches).

2. A spray gun in the phone or camera that sprays a display on the wall. The phone can then beam the information to the sprayed-on display. Ideally the display will disappear later, without damaging the environment.

3. Ultimately mental images and telepathy would alleviate the need for a physical display, but the information would need to be somehow beamed to the visual cortex (this is also an option medium and big displays).

Now, let us apply the other criteria, mainly that of relatively near-term manufacturability. There is only one technology on our list that is currently manufactured in large volume, and is starting to leverage Moore's law. This is microdisplay technology. While some progress is being made with displays on flexible substrates; display technologies take an enormously long time to get to mass-production. Thus I contend that the pocket projector (a low-cost microdisplay-based projector which can fit in a pocket and runs on batteries and LEDS) is the ultimate display in the near-future for this category. To be sure there are some issues to be worked out, high brightness being a major one, but perhaps with a screen that can roll-up and also rejecting ambient light, as is common for rear-projection screens, could be a winner.

"MEDIUM" displays

Medium-sized displays have problems that include cost, fragility, brightness, resolution and the notion of immersion. Two killer applications stand out above the rest:

1. Gaming and effective immersive 3D display at low cost

2. TV and computer screens for the other 4 billion – the world's global middle class.

The solutions are separate. For gaming the new autostereographic 3D displays with eye tracking are probably the next thing. These systems are getting better, but 3D needs higher resolution and this challenge appears addressable in the near term.

For the world's global middle class, it's the lowest cost display technology that matters the most – there are approximately 4 billion people in the world today that can't afford to use computers and TVs designed for the first world. Those displays are too expensive and use too much power. Extremely low cost microdisplay projection systems can enable $50 projection TVs and $100 laptops in the near future. The technologies needed to make such displays are derivative of the technologies being used (and paid for) to enable the hot-selling microdisplay-based front- and rear-projection systems, and low-cost microdisplay based camcorder view finders. Such systems leverage existing manufacturing infrastructure and Moore's Law.

"BIG" displays

Big displays are traditionally what one thinks of when brainstorming about the ultimate display. We want huge 3D tactile feedback systems, but, better yet, would be a way to literally share our imaginations. Even the best display technology is limited by the content and our ability to truly distill our thoughts and visions from our crystal-clear mental images. Ideally we can find a way to directly share our mental images and thoughts as we begin to better understand brain science. In the meantime, the other systems well described by other papers in this issues will do quite nicely.

Conclusion

Lack of killer applications may be the reason that the display industry lags behind the IC industry in terms of development cycle time, and delivery of innovations to the populace.

To find the ultimate display, the author contends that we must find its killer application. In the table below possible killer applications for little, medium and big displays are outlined.

Display Size	Problems	Killer Applications	Solutions
Little	size, resolution, power consumption, brightness, cost, fragility	full-screens of email on cell phone, maps, picture previewing on digital cameras	"pocket projectors", with stretchable or roll out screens
Medium	cost, fragility, brightness, resolution	hundred dollar laptops; gaming	"pocket projectors", with stretchable or roll out screens, autostereographic 3D
Big	cost, 3D, interactive, tactile feedback	entertainment? Combat simulation, video gaming	expensive one-of-a-kind

Figure 6: Outline of Killer applications and solutions for various display sizes

A criteria for down selection of the solution space was near-term manufacturability as defined by ability to leverage the existing manufacturing infrastructure, and ability to follow Moore's Law scale improvement over time. There are two killer applications outlined in Figure 6 that I would especially like to call attention to.

1/ **Autostereographic 3D displays** are 3D video displays that require no glasses. Such displays can provide the immersive environment craved by gamers. Many prototype systems are currently entering the market, and are initially low resolution and expensive, but rapid improvement of these systems is possible leveraging existing infrastructure.

2/ **"Pocket Projectors"** are low-cost microdisplay-based projectors with LED lights sources that can fit in one's pocket and run on batteries. Such displays can enable full-screen reading of email on one's cell phone, and, when used in rear-projection-mode can enable tremendous display cost reduction making laptops affordable to the emerging world.[4] If the price is right, there are 4 billion possible new customers.

In short, the ultimate display is not an ultra-high resolution, 3-D, holographic projection of arbitrary size. Instead, it is, simply, one that is good enough for the job at hand and, most important, one that can actually be manufactured.

[4] http://laptop.media.mit.edu/

AUTHOR BIO

Dr. Jepsen is the principal at JOE, Inc (www.joeinc.tv). She has been active in many fields of display: from flat panel televisions, to holography, to laser displays and day-lighting. For the last decade she has focused on bringing liquid-crystal-on-silicon (LCOS) technology to maturity. She was most recently Director of Technology Development in Intel's Display Division. In 1995 Dr. Jepsen co-founded the MicroDisplay Corporation and served as its Chief Technology Officer through 2003.

Dr. Jepsen's principal technical contributions to LCOS are in liquid crystal mode development, LCOS panel drive scheme design, and head-mounted-display and optical engine architectural design. Her recent emphasis has been on single-panel LCOS systems, and her leadership in this area has brought her world-wide recognition as a top innovator in the industry.

Prior to entering the microdisplay field in the mid-90s, Dr. Jepsen contributed to several breakthroughs in diffractive optics and holographic display technology. Dr. Jepsen holds a PhD in Optics, BS in Electrical Engineering and BA req. in Studio Art all from Brown University. She also holds an MS from the MIT Media Lab. She can be reached at mlj@joeinc.tv