

The First 105 Years of Flexible Circuitry

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ABSTRACT

It's thin, light, flexible, rigid, cheap, expensive, big, small, old, but new! Flex is the "grand enabler" that allows a multitude of industries to build ten's of thousands of neat and valuable products. Without flex, forget about transportation, satellites, communications, the Internet, many medical products, computers, flat panel displays, iPods and just about every cool electronic product. Flexible circuitry is one of the most fascinating technologies because it's an enigma - a contradiction and a paradox. Flex holds world records for the biggest and smallest, for the cheapest and most expensive circuits. But flex comes in many flavors and they are very different. This fast-paced overview will start with the amazing birth of flex in 1902, where you will meet the father of the PCB - a true visionary. We'll quickly travel through the 20th century and then explore advanced flex circuit technology. Finally, we'll look at modern applications using an assortment of teardown photos including phones, cameras and an iPod. Flex is everywhere, but is mostly invisible, or too far away to be seen. So join in as we uncover and discover "Flex Inside".

Keywords: circuit history, flexible circuit, flex-based package, telecommunications.

THE FIRST TECH REVOLUTION

Our technology journey could begin in the 19th century - the age of the Industrial Revolution, when high tech centered around marvels of mechanical engineering. The 1800's had delivered a plethora of valuable and practical mechanical breakthroughs like the Singer sewing machines, rotary clothes washers, Otis elevators, Pullman sleeping cars, Diesel engines, and zippers. But electricity was just starting to be harnessed as we approached the next century. So we'll start our journey by welcoming in the new 20th century that holds so much promise from science and technology. While mechanical inventions will continue unabated, **the 20th century will increasingly focus on the electron.**

We begin by celebrating the New Year - 1900 - and begin to anticipate the exciting things that are surely ahead in this **Century of Progress**. The Morse Telegraph System celebrated its 50th birthday. The Western Union Company has already been in business for a half-century, continuing to expand, as telecommunications becomes the big deal all over the world. Alexander Graham Bell has made telephonic communication an essential communication link between people everywhere and more continental cables are being installed to connect the

world. And just when it was hard to image anything that could top the telephone - wireless explodes onto the scene. Marconi has transmitted messages across the Atlantic to open up the airwaves. Telecommunications is already the most important technical revolution of the 20th century and there is no end in sight. The new **"age of electronics"**, launched in the early 20th century, is poised to continue making breakthroughs for more than the next 100-years. True electronics has entered the technical landscape as the electronic vacuum tube is introduced in the early 1900's. The Fleming Diode (Fleming Valve) and De Forest Audion (triode amplifier; first active device) will enable unimaginable inventions in the future, including the electronic computer. But for now, these electronic components will boost wireless broadcasting to propel us into **The Information Age**. Figure 1 shows the three technologies of early telecom (top-left is W1PHD at a Marconi Station).



Figure 1 – Early Telecom; Telegraph – Telephone - Wireless

Information age industries are rapidly expanding and creating enormous needs for electrical interconnections - mass-produced "wiring". The telephone systems, with hundreds of phone exchange lines, required manual switching platforms, or PBX consoles, to allow operators to make quick line connections. The increasingly complex radio circuits also need a solution to replace slow, error-prone hand wiring, so that the technology can become more widespread and far-reaching - and eventually portable. The electronics industry desperately needs an interconnect invention - a breakthrough. This breakthrough will later be called **circuitry**; a mass-produced and efficient means of connecting electronic components together to eliminate point-to-point wiring.

The year was 1902 when the first patents on “printed” wiring were filed. The circuit invention was initially aimed at solving the telephone exchange interconnection needs. The first circuit methods would produce conductive metal patterns on *flexible* dielectric substrate. Metal foil was first cut or stamped out into conductor patterns. The copper or brass traces were adhesively bonded to thin, pliable dielectric.

Albert Hanson, the real father of circuitry, had already realized that high-density interconnects would be of increasing importance and he therefore designed his circuits with conductors on both sides. He also recognized that inter-conductor connections were critical and thus added access holes to permit the top and bottom conductors to be selectively joined. Although the connections were simple crimped and twisted conductors, his turn-of-the-century invention clearly described double-sided through-hole circuitry. Since Hanson sought to build the most practical and versatile interconnect systems, he chose materials that could be shaped and configured to best serve applications. Figure 2 shows Albert Hanson, the land surveyor, photographer, maverick, and inventor.



Figure 2 - Albert Hanson (Courtesy of the Hanson family)

But Hanson showed even greater insight when he patented multiple layer circuitry to achieve the even high conductor density for future products. Hanson must have had incredible vision to realize that circuitry should be flexible, include double-sided through-hole connections and have multilayers. While better patterning and interconnect processes would take decades to develop and perfect, the basic flex circuit concepts that we use today, were defined in the Hanson patents. Figure 3 figures are from Hanson patents filed in Germany and Britain in 1902 and 1903. They clearly show double-sided and multilayer circuit concepts. These relatively modern ideas are 105-years old.

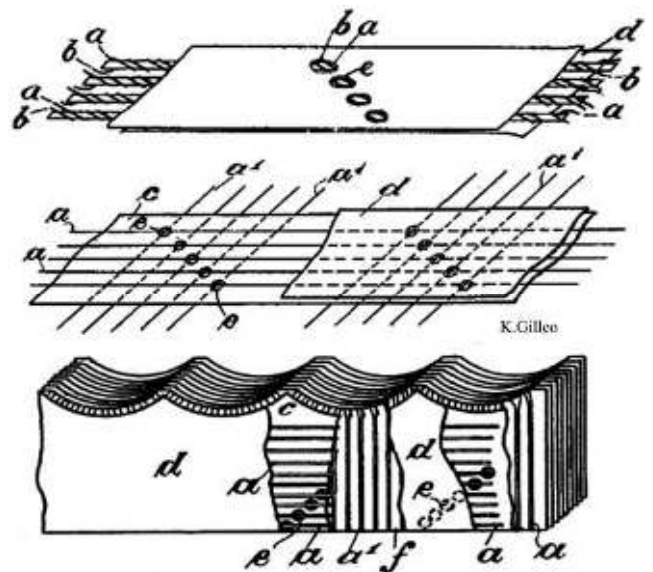


Figure 3 - Figures from First Flex Circuit Patents

THE EARLY AGE OF FLEX

Many other circuitry ideas emerged over the ensuing decades as the *information-driven electronics age* continued to expand at an exhilarating pace. Radio later became the most important driver for printed circuitry that evolved into additive and subtractive processes. Wireless was capturing the attention of the world. By the end of the second decade of our 20th century, radio had been introduced to most of the major countries. Ships now carried the Marconi Radio System and the wireless was saving lives while inspiring the world to embrace *the new electronics*. The Titanic told the world of its tragedy on a Marconi Wireless. Visionary pioneers could see the immense market for mass-produced circuits and were being highly motivated to respond to the challenge. But we should note that virtually all of these interconnects and circuits developed during the first quarter of the Age of Electronics, were FLEXIBLE! Figure 4 shows “old flex” that pioneered some of the modern principles.

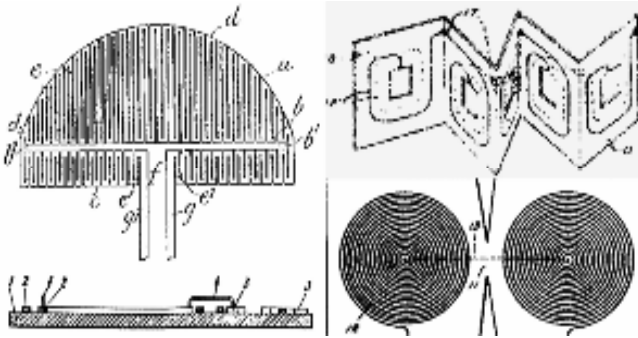


Figure 4 - Flex from 1903 – 1925

While early flex was the right answer in 1902, it was very far ahead of its time. Amazingly, 105-year old flex is the right solution for today's challenge of *Faster-Smaller-Cheaper*. But it would take other technology revolutions, particularly solid-state electronics, to allow flex to evolve into the modern interconnect, packaging and circuitry technology that it is today.

FAST FORWARD TO MODERN FLEX

Flexible circuitry is the lightest, thinnest and highest density system in our PCB tool-kit. So why does flex always seem to be the forgotten orphan of printed circuits? Well, flex is hidden away while it enables all kinds of technologies that seem to get all the credit. Perhaps we should borrow from the Intel playbook and adopt the slogan, "Flex Inside" since that's where it typically is hidden. Flex spans an incredibly wide range of cost and complexity making it useful for almost any product. Screen printed and ink-jetted Polymer Thick Film (PTF) flex brings low cost circuit/keyboards to everything from computers to calculators. Printed carbon ink on thin polyester film, while performance-limited, is the low-cost winner. But flex also provides extreme density multilayer systems for military and avionics, but at a few orders of magnitude more cost than many other forms. Flex comes in all sizes and shapes, too, so it can be configured into optimal 3D format. Flex would easily win most categories if Guinness ran a PCB contest; smallest, biggest, thinnest, and so forth. The biggest flex (using a very liberal definition of flex circuits) was made in Northfield, MN and was the world's first communications satellite. ECHO I, shown in Figure 5, was launched nearly 50-years ago. Looks like a giant balloon and not a flex circuit? Well, the ECHO consisted of adhesiveless conductor (aluminum) on polyester that bounced back radio signals while circling the earth. Sounds like a really big RFID tag. But the fact is that aluminum on polyester has been used to make RFID circuits, so the 5-mil Mylar with vacuum-coated aluminum used in the ECHO satellite could be used today, if it hadn't all burned up on reentry. And today, flex is still made on polyester, and other plastic films, and it still uses aluminum, copper, and several other conductors, a tribute to the richness and diversity of the flexible circuitry technology.



Figure 5 - Fattest Flex? ECHO Satellite (NASA)

But a true circuit enthusiast may want to have irrefutable evidence of the biggest circuit that has a genuine conductor pattern. Although "electronic dipsticks" have been made with flex, at least 50 feet long, the Space Flex appears to be the winner for the world's longest circuit. The International Space Station solar cell arrays are connected with copper on polyimide - actually DuPont's Kapton® that was specially treated to resist solar wind damage (see Figure 6). The giant flex circuits, produced in Minnesota, were folded up accordion style, and the entire array was later unfolded high above the earth. And the space flex is still up there - working just fine under the most extreme conditions. This is one of the few flex circuits that is not hidden away inside. The beautiful flex is the most visible component of the space station.

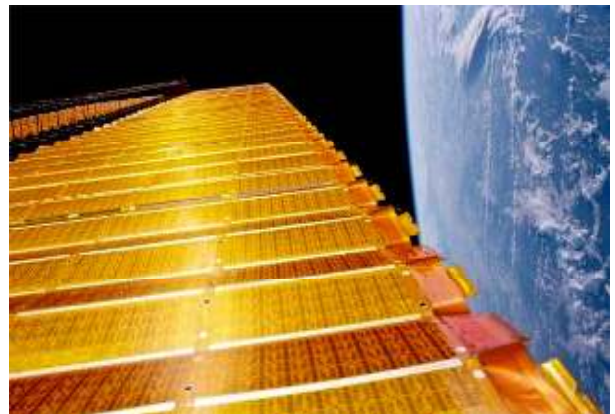


Figure 6 – Longest Flex? International Space Station

And while we're on the topic of aerospace, it's good to know that flex has flown in just about every NASA mission, including those that sent the Rovers to Mars. Figure 7 shows *Rover Flex* courtesy of DuPont who supplied the materials. This is only one of several flex circuits used in the Rovers. Circuits were manufactured by Pioneer Circuits, one of the foremost fabricators of *space flex* [other examples to be shown in slides].



Figure 7 - Most Distant Flex? - Mars Rover

FLEX IS EVERYWHERE

We've covered outer space, so let's look at inner space. Flex is critical to medical electronics, an expanding field with converging technologies. Futuristic medicine now includes electronics, photonics, biology, physics, chemistry, and MEMS (MicroElectroMechanical Systems). Flex is also beginning to play a vital role in bionics, especially in sight restoration where flex connects retinal sensors to electronic hardware. Several companies are developing sight restoration technology and most use very thin and pliable flex as interconnects. Figure 8 shows a concept from Second Sight.

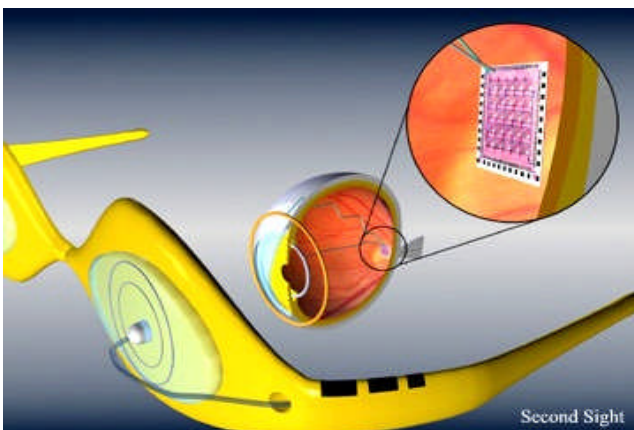


Figure 8 - Second Sight Vision Bionics Concept

Flex is used in pacemakers, hearing aids, sensors, monitors, drug delivery, attachable electrodes, and within much of the medical equipment in use today. Figure 9 shows a montage of flex-containing health and medical products. These flex-enabled products (not to scale) are: (1) a PTF electrode, (2) hearing aids (3M), (3) pacemaker circuit, (4) DNA analyzer, (5) wearable oxygen-sensing spectrophotometer made with PTF; conductive adhesives are used for SMD assembly.

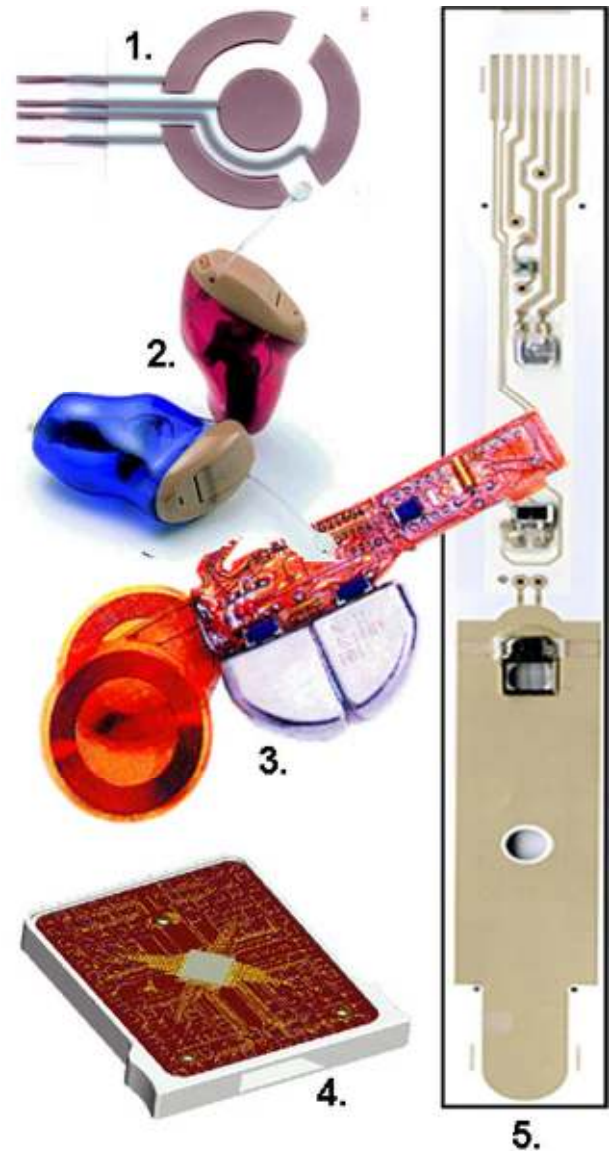


Figure 9 - Medical Flex

Before moving on to consumer electronics, it is worth noting that flex, the first integrated chip carrier, is playing an increasingly important role in electronic packaging. Way

back in the 1960's, flex was used to interconnect chips to PCBs. The beginning was Flip Chip Strip Flex, first made in Northfield, MN. This was followed by the GE invention, Minimod, now known as Tape Automated Bonding (TAB) that is still very popular today. Flex packaging has greatly evolved, thanks to innovators, like IBM and Tessera, into the highly-efficient Chip Scale Package (CSP) that can be assembled using SMT. But the μ BGA, and other area array flex modules, were only the beginning. Today's flex packaging supports multiple chips using dozens of designs. One of the most fascinating concepts is the folded, "origami" concept introduced by Tessera that is shown in Figure 10 - the last line (4th) of the figures. The 1st line in Figure 10 shows Flip Chip Strip Flex that used IBM flip chip technology, line 2 shows TAB, and line 3 shows Tessera's μ BGA that can be viewed as a form of TAB where the outer leads are fanned in and then bumped.

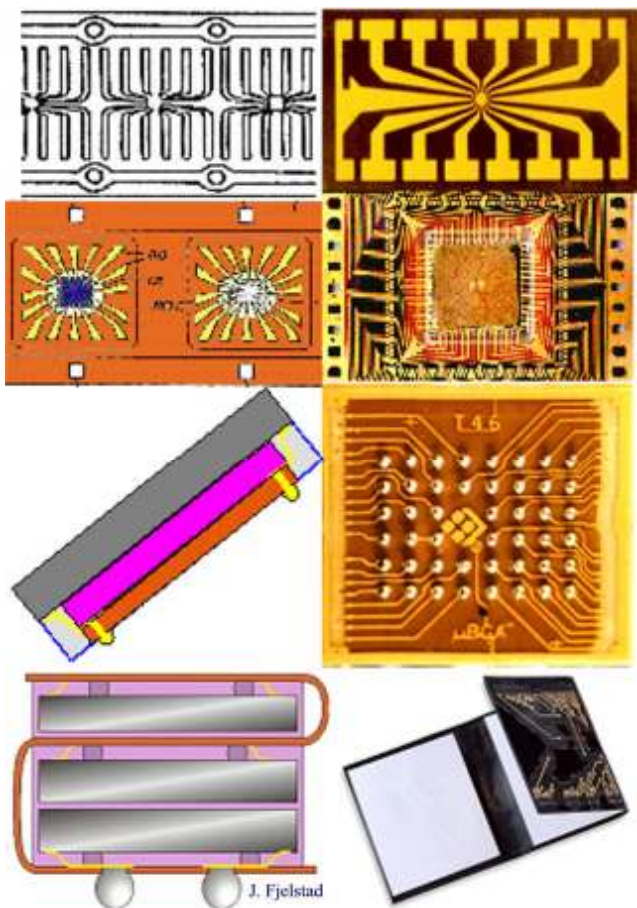


Figure 10 – 40 Years of Flex-Based Packages

FLEX FOR DISPLAYS

Just about every flat panel display (FPD) is connected using flexible circuitry and this is an expanding market as the CRT is replaced by this newer technology. What's more, the

increasing size and resolution of displays for HDTVs adds more flex. Flex is ideal for glass or plastic displays since a 3D interconnection is typically required. The connection to the electrodes on glass, typically made with indium tin oxide (ITO) on most FPDs, requires a very compliant and fine-pitch cable to enable the anisotropic conductive adhesive (ACA) connection. ACA, consisting of dielectric adhesive that contains tiny conductive spheres, requires high coplanarity at the interface. Flex, because of thinness and compliancy, has become the *de facto* standard. Soldering is not an option here because of heat-sensitivity and incompatibility. But there is a 3rd valuable flex attribute that can be used, and it's the ability to incorporate the driver chips directly into the flex cable by means of TAB technology. The display driver chips can be directly interconnected to the flex circuit so that the cable is the 3D link, circuit and package. The ability of flex to combine many features into one product makes it the only good choice for many applications, like FPDs. Figure 11 shows flex display circuits with TAB-bonded driver chips from a large TV. Flex cables are used on two sides to input vertical and horizontal signals.



Figure 11 - Flex for FPD HDTV (Gilleo teardown)

MOBILE CONSUMER ELECTRONICS

If it's electronic and portable, it probably has a *flex inside*. And if it folds, twists, or rotates during use, the chances are better than 99% that flex is the dynamic link. Most cell phones now have a fold-out, open-up, or slide-out design, and flex is the enabling technology. While wires might seem like a consideration, their poor fatigue resistance generally precludes such use. Flex is unsurpassed in dynamic applications and has set endurance records exceeding 1-billion flex cycles. Let's now look inside of several personal electronics products to discover flex. Since flex is incredibly thin, light, and dense, we might expect to find it inside of the

“impossibly small” **Nano iPod**. And sure enough, flex is performing a variety of functions inside of this top-selling Apple product. Figure 12 shows an iPod teardown.



Figure 12 - iPod

How about a modern mobile phone with a camera? Yes, flex is used to connect the “clamshell” components and camera unit as seen in Figure 13 - a top-of-the-line Sony Ericsson phone. Note that SMDs are soldered to the flex. The termination on the right was connected to the color flat panel display. The camera circuit is shown in the lower section of Figure 13.

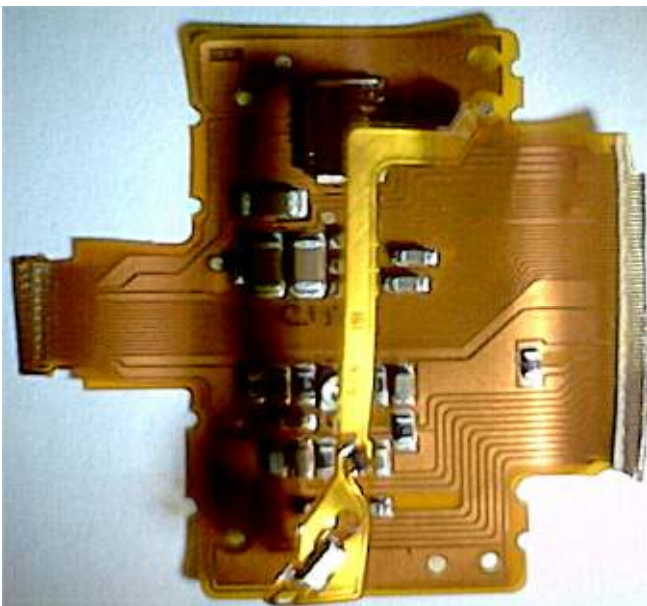


Figure 13 - Sony-Ericsson Phone (Gilleo teardown)

Flex circuitry ends up inside just about every level of cellular phone, including the lowest priced. In fact, the cost of the phone

and amount of flex don't seem to be related as is seen in Figures 14A and 14B, a low-end AT&T /LG phone.

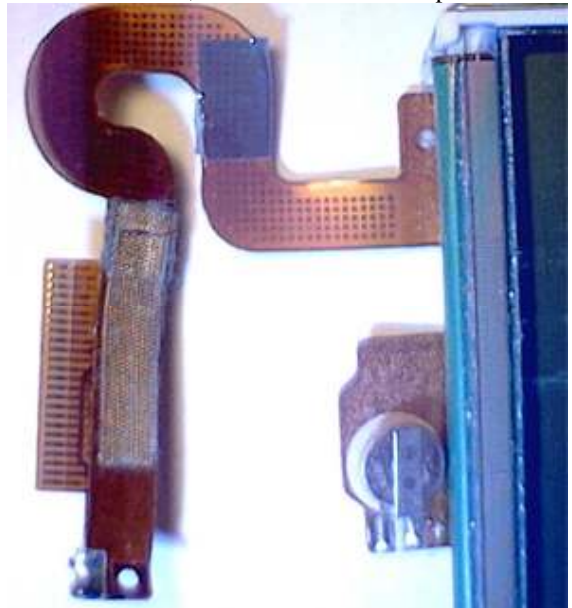


Figure 14A - LG Phone Hinge



Figure 14B - LG Phone Display Flex (Gilleo teardown)

Flex also makes an entry in many of the compact plug-in and add-on products as seen in Figure 15, a digital camera that can be tilted and rotated.

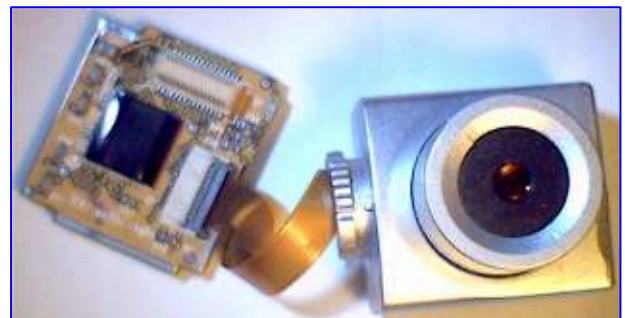


Figure 15 - Plug-In Camera

And for PDA fans, here's a teardown in Figure 16 of a Dell AXIM that suffered a hardboard burnout. Flex is used for the display interface, LED front panel lighting, and several switch functions. Flex can be wrapped around to provide side switches on both sides while providing a platform for component assembly. In all of these portable applications, flex provides numerous important features that are typically integrated in one flex solution. The ability to combine so many features into a single system makes flex the lowest cost system even when the cost per area of circuitry is higher than a rigid PCB. Installed cost is the right way to think about designs and manufacturing.

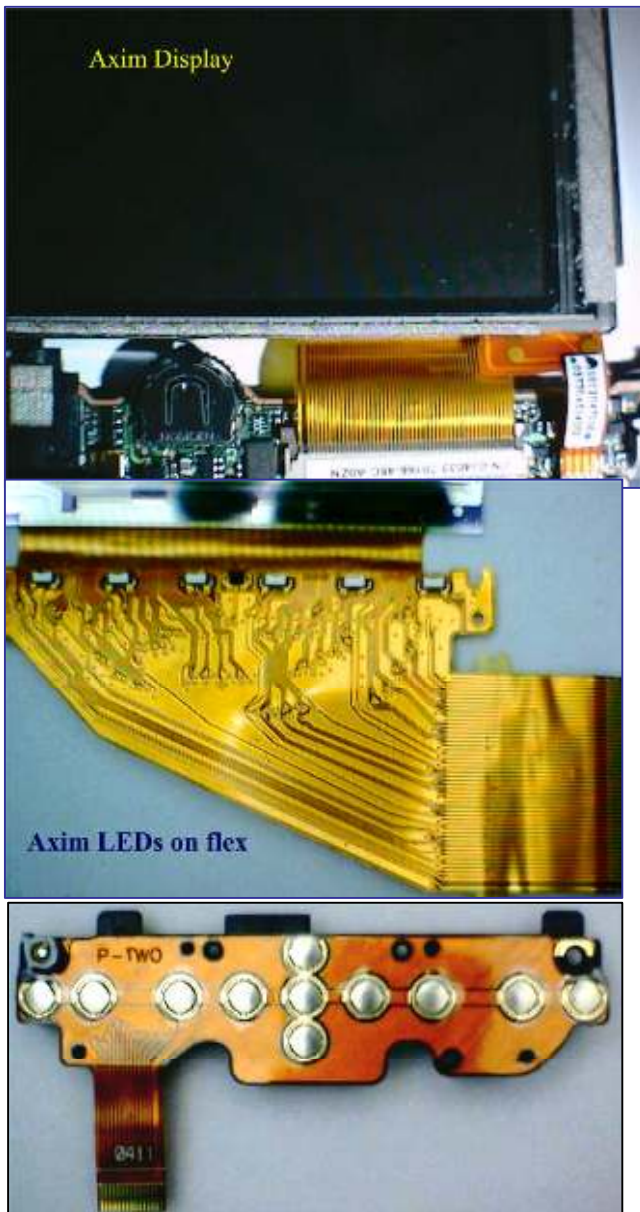


Figure 16 - Dell AXIM (Gilleo teardown)

FLEX SMORGASBOARD

The slide presentation will cover many more flex applications and we can't do justice to the wide applicability of flex in a short paper. But here's a final graphic of some popular flex circuits in Figure 17. Description is at the bottom of the page.

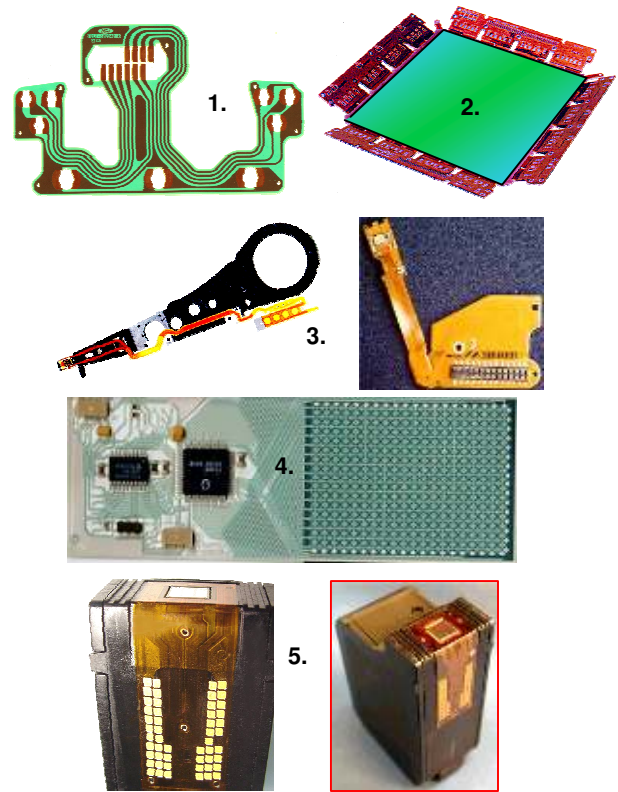


FIGURE 17 - FLEX IS EVERYWHERE

CONCLUSIONS

Flex has been the key enabling interconnection technology for 105 years. Extreme thinness, advanced dielectric without glass filler, and extraordinary flexural endurance, make flex the unique solution that makes our *push-the-envelope* technologies reality. The result is an incredibly wide range of applications from the smallest to the largest circuits. The high-density attributes also allow flex to be used in the premier component packages such as CSPs and newer 3D stacks. Over the next 105 years, flex will solve unusual problems for products that have not even been dreamed of by the science fiction writers.

Legend for Figure 17: (1) Ford instrument cluster; (2) F-16 Display; (3) Disk drive; (4) PTF mouse pad; (5) Ink jet flex "3D package & interconnect".