FLEXIBLE CIRCUITS – THE NEXT 100 YEARS

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ABSTRACT
The printed circuit was one of the most important inventions of the 20th century. The Great Telecommunication Revolution that began in the 19th century was the catalyst for this invention and many others. The telegraph sent digital data, the telephone sent analog voice, and the new wireless sent both. The world was shrinking as technology connected cities and countries. Discrete point-to-point wiring was already being pushed beyond limits by wireless hardware, but the telephone exchange had the greatest density requirements. Although the telephone is a rather simple, low-density device, the PBX, or exchange station, required the placement of hundreds of wires into an area that could be reached by the telephone operator. The first patented circuit was designed to solve the PBX problem in the early 1900's. And the first circuit was flexible.

Electronic technology was rapidly evolving and the printed circuit was to play a key role as enabler and problem solver. The first quarter century of printed circuit development centered on flex as well it should. The pioneers understood the value of 3-dimensional interconnects and that the replacement for flexible wires should also be flexible.

Flexible circuitry continues to be the enabler of the "impossible" and the technology that solves extraordinary problems. The disk drive with its 500-million flex cycle requirement could not operate with any other technology, at least not affordably. Perhaps the flat panel display, now replacing the bulky, lead-laden CRT, would be impractical without the flex interconnect. And where would the high-density package be without thin, agile flex? This paper will explore the unique attributes of flex, the unusual materials, and the advanced processes. Then we'll look into the future. Flex will celebrate its first centennial in the year 2003. But the next hundred years will be much more interesting. We will wear circuits, too. So relax, flex your mind and get ready for a flexible journey.

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

JOURNEY
You are about to enter the future. But don't bring baggage from the past. The future is acutely dependent on technology and so we must focus on the human/machine interface. Electronics, and its eventual replacement, is the point of convergence. We will start at a point in time that is comfortable and familiar before moving into the distant future - for better or for worse!

All of you know what a circuit board is. It is typically a thick, rigid and *green-all-over* board. The "board" descriptor in Printed Circuit Board defines an important characteristic - modulus or stiffness.

What might happen if we could invent a circuit technology that produced a thin, light, electronically dense but also pliant product? What if this futuristic invention could be bent, rolled and flexed into complex shapes that could fit into or onto any housing? What if our future science could make the substrate and conductors so compliant and yielding that we could flex the circuit a billion times and still have a reliable system. This would truly be an amazing break-through that would free the design, enable unheard of new products and open up possibilities not yet dreamed of. Would we not have a "bionic" signal pathway that mimicked our own peripheral nervous system that might connect silicon "brains" to our own organic ones?

Let's pause for a moment and ponder what could be done with a technology that would deliver a paper-thin sheet or a long roll of circuitry that was light, electronically powerful, ultra-thin, extremely strong, easily shaped into volume-efficient configurations and so compliant that Surface Mount Technology (SMT) assemblies never experienced problems with thermomechanical fatigue once common with rigid boards. Our thin polymer substrate and directly-applied conductors would enable micro-via formation and ultra-fine pitch production that would be combined for very dense multilayer constructions. If only such a wonder was possible, we would have the magic circuit that could be the smallest, largest, thinnest, densest, simplest or most complex electronic circuit imaginable. And with all these attributes, it would also be a dynamic interconnect that would bring *motion to electronics*. This invention would truly be the freedom circuit/interconnect and the superior solution needed for our technology-dominated future.

We could now build ultra-fast memory drives, low cost printers, multi-functional watches, two-way pagers, integrated and roll-up keyboards, advanced multi-chip carriers and wafer-level chip scale packages, small and reliable automotive assemblies, complex and incredibly powerful volume-efficient avionics “black box” electronics and maybe even a space station power and signal array. If only we could pull off this incredible feat, certainly there would be a major impact on the entire electronics industry and it would be nothing short of a revolution

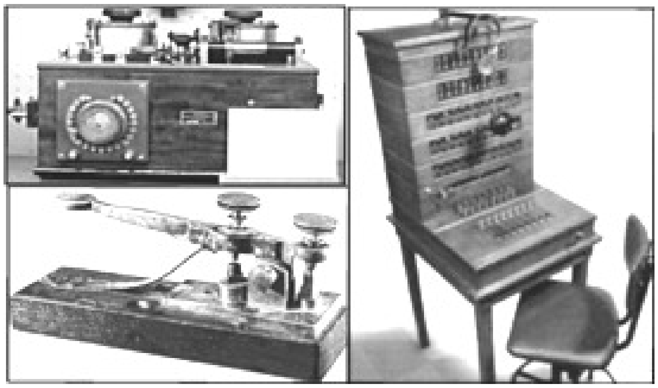

Figure 1 – Early Telecom; Telegraph – Telephone - Wireless

THE ONE HUNDRED YEAR REVOLUTION

Revolutions can happen quickly. Revolutions in electronics may take a period of months although a full decade is often required to feel the complete impact. How long will it take for our magic circuit revolution now that we realize the importance of our bendable 3D circuit board concept? Let’s first look at some early revolutions in electronics for guidance.

The year was 1900 when the Morse telegraph key celebrated its 50th birthday. The Western Union Company had been in business for a half-century. Alexander Graham Bell had thoroughly proven telephonic communication and the telephone and telegraph were essential communication links in countries throughout the world. In a more spectacular installment in the dynamic electronics age, Marconi had transmitted messages across the Atlantic, but it would still be a few years before Fleming perfected the vacuum tube, the first diode (the Fleming Valve), and Lee De Forest built the triode Audion (amplifier) to more fully enable wireless broadcasting. By 1901 we were well into the *Information Age*.

Just a short year later, the embryonic electronics industry consisting of telegraph, telephone and radio, was off to a strong start as we began to march bravely into the 20th century. These information age industries were rapidly expanding and creating immense needs for interconnections - mass-produced interconnections. The telephone systems, with hundreds of phone exchange lines, required manual switching units, or PBX consoles, to allow operators to make line connections. The increasingly complex radio circuits needed a solution to replace slow, high error hand wiring to allow that technology to become more wide-spread and far-reaching and eventually portable. The electronics industry demanded the invention that would later be called circuitry - a mass-producible and efficient means of connecting electronic components together.

The following year saw the invention and patenting of "printed” wiring. This invention was aimed at solving the telephone exchange interconnection needs. The first circuit process produced conductive metal patterns on 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 interconnect density would be of increasing importance and he therefore designed his circuits with conductors on both sides. He also recognized that inter-layer connections were critical and added access holes to permit the top and bottom conductors to be selectively connected together. Although the connections were basic, 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 Hanson’s circuit invention from the patent drawings.

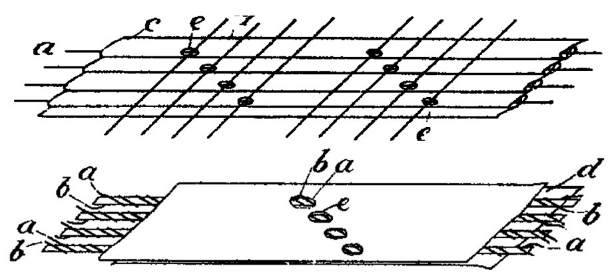

Figure 2 - First Flex - 1903

Several other circuitry ideas emerged over the next decade as the *information-driven* electronics age continued to expand at an exciting rate. Radio soon became the most important driver for printed circuitry. 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 and motivating 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 strongly motivated to answer the challenge. But please note that virtually all of these interconnects and circuits of the first quarter of the Age of Electronics were FLEXIBLE! Figure 3 shows some old flex.

Flexible circuitry was certainly ahead of its time. The flex revolution had come nearly 50 years too early to be noticed by modern technologists. Never-the-less, flexible circuitry had already done its part to enable the fledgling electronics of the Information Age. Flex was the turn-of-the-century answer to Faster-Smaller-Cheaper. Unfortunately, large radio vacuum tubes, heavy coils and clunky transformers forced the industry to take a step backward and move to thick, heavy and rigid circuit boards to support the burdensome weight of the interim electromechanical devices. Light and thin flex was temporarily sidelined while history waited for the next revolution - Solid State Electronics. So if you haven't heard enough about flex, maybe it's just because you came on the scene too late. Or is there another issue? Could it be that flex has an identity problem?

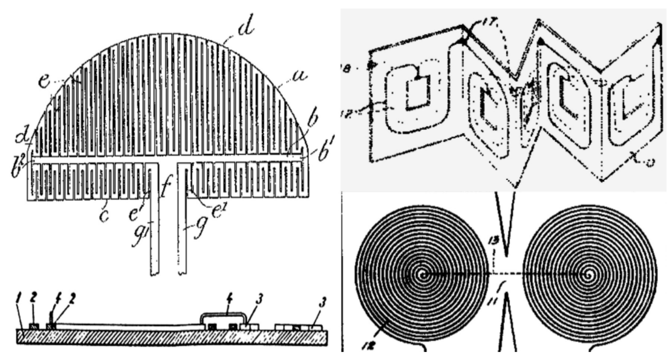

Figure 3 - Flex from 1903 – 1925

FLEX WHAT?

Does flexible circuitry have an identity problem? Most certainly! Show nearly someone a hard board and they recognize it as a circuit board although the layman may add, "computer board". But show someone a flexible circuit and they're apt to say, "cable?". I had the opportunity to do a flex circuit seminar at a large RCA facility a number of years ago with an audience of dozens of engineers. At the end of the talk, most of them rushed up to a table with a variety of real, but garden variety flex circuits. The reason for the excitement was that no one in this large and highly regarded electronics company had ever seen a flex circuit, even though all were using them in everyday products like cars, calculators and telephones. Flex, the enabling technology, had more than a problem, it had (and still has) a genuine identity crisis.

Years later, flex is still a relatively unknown and misunderstood technology even though every professional uses the product in computers, phones or pagers and most of us benefit from flex in medical devices, cars, cameras and so on. What is behind the paradox of the world's most important interconnect solution remaining so well hidden? Why is it hard to even describe flexible circuitry and why do modern studies and articles still call flex a "board"?

One answer to flex circuitry's ambiguity may surprise you. The very essence of flex, its incredible versatility, makes it hard to pin down and "pigeon hole" it as a product. Flex, even when conforming to agreed-upon standards, is a NON-STANDARD product. The ability to assume an infinity of forms, shapes and constructions, makes it difficult even for the flexible circuit industry to define itself. In fact, does the flex circuit industry really know who it is? Maybe UFO should stand for Unidentifiable Flexible Object, or is this being too *rigid*? Try the following trivia circuit quiz and judge for yourself.

Ask an avionics circuit designer to describe the lowest cost circuit and he may suggest a "print and punch" rigid board from Asia. Tell him that it is flexible circuitry and he will give a *where-are-you-coming-from* look. But the answer is flex, Polymer Thick Film (PTF) flex, made by applying ink onto pennies-a-foot polyester film using high-speed screen printers. It is quite intentional that calculators use flex for cost reduction instead of flexibility. Now ask the calculator maker to guess what is the most expensive circuit and he is unlikely to correctly surmise that it is flex - incredibly complex military flex. Let's make the questions easier. We'll ask for a guess about the world's smallest mass-produced circuitry. The astute engineer may possibly guess flex as used in hearing aids if he has even heard of flex. There is no doubt that flex wins the smallest circuit contest. It may be a flex watch, hearing aid or micro-disk drive, but its flex (see Figure 4).

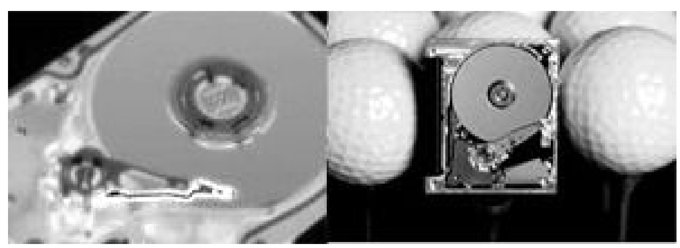

Figure 4 – Smallest Flex? IBM MicroDrive

Let's try one more. Ask about the industry's largest circuit and most will answer "those big mainframe computer boards". Flex, with its ability to be produced in long rolls, has always been the length champion. Years ago, the record was about 50 ft for storage tank "electronic dip sticks". Today, the crown probably goes to the 34,000 mm long flex circuits for the International Space Station. Ironically, the company [Sheldahl] that built *Space Flex* built ECHO satellites 30 years earlier using metallized flexible film with a process akin to the modern adhesiveless flex processes. In fact, was ECHO a flex circuit since it was meant to handle radio signals? So you can see that it is in the very "genes" of flex to be different - so different as to be unrecognizable by family members. Is it any wonder that flex struggles with identity?

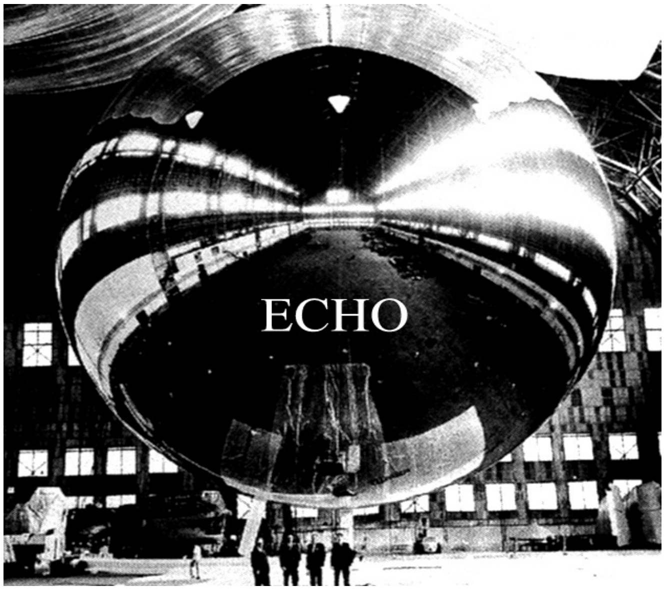

Figure 5 - Biggest Flex? ECHO satellite (NASA)

Now we'll move on to packaging and check out the rumored revolution. What is this brand new, *said-to-be-hot* technology, thing called *chip carriers* all about? Many are now convinced that there is really a Packaging Revolution afoot and we must ask if there is *room* for flexible circuitry. A few years ago, IBM and Motorola began the advance into area array packaging and the Ompac® was added to the lexicon along with BGA. Well, if packages are getting smaller, lighter and denser, isn't this what flex is good for? So why are they using rigid circuit boards for BGAs, you may ask.

Figure 6 – Highest Flex? International Space Station

More recently, some area array packaging engineers moved designs to a flexible circuit platform. IBM's TBGA is built on a thin flex circuit bonded to metal allowing extremely good heat dissipation. But, what does the "T" stand for? "Tape", of course. One more point scored against identity. While "Tape" Ball Grid Arrays are made with rather nice flexible circuits, the industry seems determined to avoid the rather elegant term "flex". Why isn't it a Flex-BGA or FBGA? Doesn't Amkor have a *FleX*-BGA? Looking a little further, we see other BGAs without a rigid board. Take apart Tessera's μBGA chip carrier and inside is a really nifty flex circuit. In fact, it is the compliancy of the flex circuit that makes this CSP work. So why isn't it a flex-micro-BGA, or Flex-CSP or something that denotes its flex heritage? Well, let's just call them flex-based packages (see Figure 7).

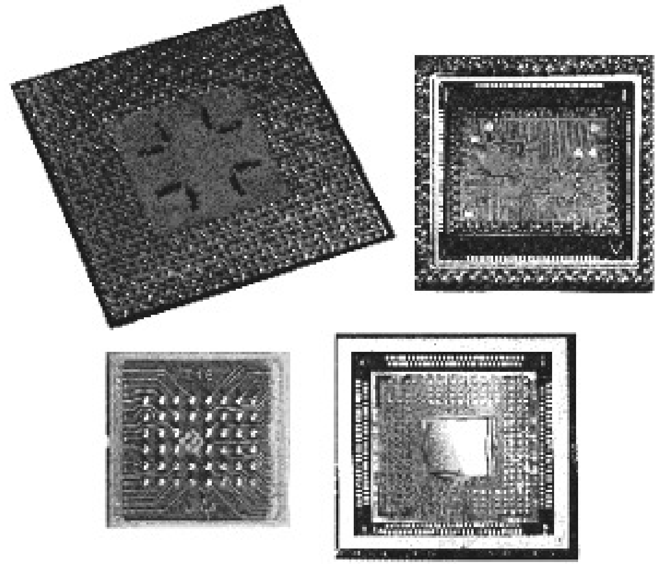

Figure 7 – Densest Flex? TBGA and μBGA = Flex-BGA

Before leaving the flex packaging area, let's investigate the recent package designs used for the Intel Pentium chips for portables. It's called a TCP, but it has that flex circuit look. Okay, what does the "T" stand for? By now, you know that it's that "tape" moniker rearing its ugly head again. Yes, the thin, compliant chip platform for Pentiums is a Tape Carrier Package...a flex circuit with an alias. By the way, that "new" name, Tape Carrier Package, was coined in 1974. But once again, flex is solving problems, this time for the world's largest IC company, but being forced to work under an assumed name. Also examine the "new" embedded chip modules, aka chip-down-first, (reminiscent of the old GE MCMs?) and look for flex. Hint: flex can be produced *in situ*.

But wait, those with a good memory will say, that TCP thing is really TAB. Oh! What's TAB? TAB stands for Tape Automated Bonding. And what's a TAB? Well, it's just one more neat flex circuit invented in the 1960's as an efficient means of connecting dense chips to not-so-dense circuit boards. Since marketing gurus like to add pizzazz and perk up products with buzz names, we must continue to wonder why such a great name as FLEX has been replaced with a rather low tech and unappealing term as "tape" like in tapeworm and duct tape. Maybe "flex" sounds too much like "sex" and it has a politically incorrect feel. Or the tape industry has better PR. Figure 8 shows TAB and the new TAB, the μBGA.

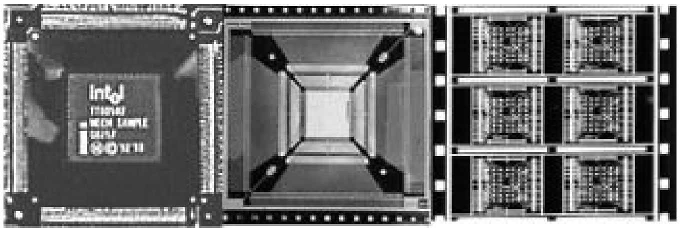

Figure 8 - TCP and TAB = Flex Chip Carrier

Let's ask one more question. What would happen if we used the flex features of the flex-based packages? We would get a 3D package like the one in Figure 9.

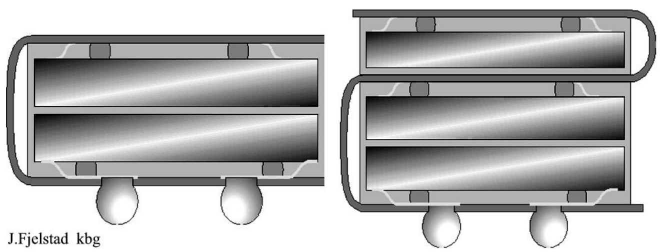

Figure 9 – Tessera 3D Flex-Based Package

Hopefully, you can now understand why "flex" is rather unknown and poorly understood. Its very versatility expands the product range over so large an area, and with so many attributes, that no single image can be conjured up to generically identify the product. Even color is different for the various products, ranging from clear to white to yellow to amber to brown.

Now let's try a more consolidating definition of flex. We might say that *flex is a thin, signal carrying, highly integratable circuit-interconnect system that is capable of being shaped in 3-dimensional space or able to withstand long-duration continuous dynamic motion with high reliability*. In a more poetic vein, we could say that *flex is thin and translucent, with gleaming conduits carrying power and messages, linking the worlds of technology together. Supple and yielding, curving and soaring from point to juncture like a carefree bird, flex interconnects in a magical and boundless way. Flex with subtle strength and the ability to assume an infinity of shapes, brings solutions for today and tomorrow by adding the dimension that others forgot. Flexible circuits now gently cradles masterpieces carved from silicon to bring the world of microprocessing to the human interface. Flex is the past, present and future of interconnectability.*

Having failed at a hard definition of flex as so often happens in describing superficially simple, but conceptually complex entities, let us try to anticipate the role of flex in the ***Second Century of Electronics*** now underway. Imagine a time when ICs have achieved atomic-scale dimensions and billions of *speed-of-light* quantum devices are squeezed into a single monolith. We will also add photonics as the preferred signal messengers promised by those who gaze more distant.

Even in the first decade of the next millennium, flex has begun to carry photons using flexible optical guides as it continues to be the "boundary breaker" in both the literal and figurative sense. Flex will continue to transport the products into the full-stereoscopic range, volumetric world that frees design from the constraints of two-dimensional thinking. It will become virtually impossible for designers to deal in flex without gliding into a world of new ideas that will be so welcomed in the future. The circuit *imagined* will become the circuit *engineered* and built. Perhaps the *small-when-folded*, 110 ft long deployable array space circuit, built to survive the severity of outer space, is an ideal example of the boundless nature of flex (Figure 6).

So what will the Future Flex look like? It will remain an easily shaped 3-dimensional system with even higher density and newly added light-piping capability. In the year 2000-Plus, we will march bravely forward along pathways in a new millennium. The term "electronics" will fall from common use. We will talk about mind processors and knowledge modules described earlier by the long-dead science fiction writers of the 20th century. They wrote the *Real Roadmaps*! Nearly all of the mind-assisting processors will be portable in every sense of the word and communications will be essentially wireless. Our standard personal tool kit will include an info-communicator/processor where all technologies have finally converged. Entertainment products will remain a mainstay industry, as they are today, but infinitely more incredible. The "engines" of the future will be extremely powerful yet small and light. And taking an idea from *space flex*, tiny portable products will be specially deployed for use such as are laptop computers, but the volumetric space transformation will be even more pronounced as pocket products fold out into full interface systems. Many products will be *worn* by the users, a trend established for pagers and now broadened with Motorola's first "wearable" cellular phone, the StarTAC. The human interface of audio, video, tactile and even direct nerve & brain-link, will require configurable spatial relationships that enable a unit to fit each user. Heads up displays will let us communicate with the processor and the world as we walk or are transported. A flexible headband will interface with our vision, hearing, voice and brain. In the future, you will be fitted for these products. Health "vitals" will be monitored by MEMS chips to keep your electronic medic up to date.

Looking inside and out of these products, we see a single flexible entity interconnecting a master chip to the necessary peripherals that must be spatially deployed. Flex has become the bionic nervous system for the synthetic auxiliary brain, and as with the human body, it must allow movement. We have reached the day in the sun for flex where the rigid board can only be viewed on a display when we call up a history file from the 20th century.

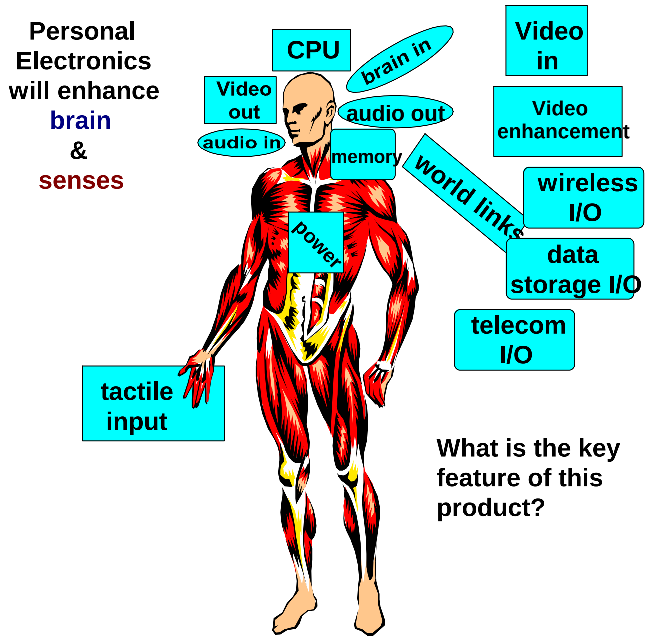

Figure 10- Flex Bionic Person - Model 2000-Plus

The Personal Electronics Products of Future

- **Wearable**
- **Fully Integrated**
- **Fully Interconnected**
- **Highly Reliable**
- **Fully FLEXIBLE**
- **Conclusion: "Flex Takes Over Future!"**

But wait, the wearable circuit is already here. Check out the US Army's wearable circuit program.

Figure 11 – Wearable Military Circuits & Electronics

CONCLUSIONS

Flex has been the key enabling interconnect technology for 100 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 new 3D stacks. Over the next 100 years, flex will solve unusual problems for products that have not even been dreamed of by the science fiction writers.

ACKNOWLEDGEMENT

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