The Circuit Centennial

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ARTICLE TOOLS

1903 was an important milestone for technical innovation. The Wright Brothers demonstrated sustained flight at Kitty Hawk. Marconi proved that wireless communication across the Atlantic Ocean was practical. There were many other achievements, but these stand out. Yet there was an even more important technical event in 1903, and its ramifications have been profound. The invention about to be discussed is the grand enabling technology of almost everything else including flight and communications. Without this concept, all electronics including computers, cell phones, telephones, automobiles, electricity and tens of thousands of other products could not exist. In fact, if this pivotal invention were to suddenly disappear, the world---as we know it---would end, throwing us into catastrophic chaos.

The 19th Century Telecommunications Revolution

Dateline Dec. 31, 1899. The Morse telegraph key had celebrated its 50th birthday. Alexander Graham Bell had proven telephonic communication and the telephone and telegraph were now essential communication links in countries throughout the world. Marconi had already transmitted messages across space, but it would be a few years before Fleming would perfect the diode rectifier, and DeForest would build the triode amplifier to fully enable wireless broadcasting. We had already entered the Information Age.

Embryonic electronics, consisting of telegraph, telephone and radio, was off to a strong start as we entered the new century. All of these communication industries were rapidly expanding to create an immense need for circuitry. The telephone systems, with their hundreds of phone exchange lines, required manual switching units, or PBX consoles, to let operators make line connections. Increasingly complex radio circuits needed an alternative to tedious, error-prone hand wiring if the technology was to become widespread and far-reaching. The electronics industry sought circuit technology that could enable mass production and automated assembly.

The Invention of Circuitry

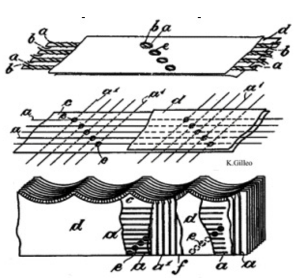

Figure 1. Hanson Patent Figures.

The year was 1903 when Albert Parker Hanson, of Berlin, filed his "Electrical Cables" patent in England (Ref.1). Hanson described several methods for forming conductors onto dielectric. The primary approach involved cutting or stamping out conductors. The copper or brass traces were then adhesively bonded to paraffined paper to form conductor patterns. He aimed to solve the telephone exchange problem. This appears to be the first publicly documented circuit invention*. Figure 1 shows the basic circuit, a double-sided construction, and multilayer circuit.
(*Hanson had filed for a German patent in 1902 that was not "published" until 1905, while the British office placed the Hanson patent into "public domain" in 1903 and granted it in 1904.)

Hanson was far ahead of his time, and his patent described amazing innovations including multilayer, typically considered to be modern. He had already realized that high density was crucial and his designs maximized this feature. He also added access holes to the substrate so that crimping and twisting could connect the top and bottom conductors. Hanson further stated that conductors could be formed in situ by electrodeposition or by applying metal powder in a suitable medium (conductive ink) and thus anticipated additive circuitry. It is remarkable that the very first circuit patent covered so many concepts generally credited to our own era.

Thomas Edison also offered circuit ideas in response to a query on how to replace wires in 1904. Edison's concepts included 1) selectively applying glue (natural polymer adhesive) and dusting the wet "ink" with conductive graphite or bronze powder, 2) patterning a dielectric with silver nitrate solution and reducing the salt to metal and 3) applying gold foil to the patterned adhesive (Ref. 2). Edison got busy with other inventions and never worked directly on circuits although he did invent the electrolytic copper foil process that is still used today.

Other ideas emerged over the next few decades as electronics continued to expand at an exciting pace. Radio soon became the important driver as it captured the attention of the world. The first public radio station, KQW (San Jose, CA) had gone on the air in 1912. By the end of the second decade of the 20th century, radio had been introduced to most of the major countries. Ships, including the Titanic, now carried the Marconi radio system and the wireless was saving lives. Soon, there would be a radio in every household creating an immense market for mass-produced circuits.

Subtractive or Additive?

The earliest circuit processes were based on additive, or build-up methods, where conductors were deposited onto dielectric. This is certainly the most straightforward approach. But, the commercial printing industry had long used subtractive etching techniques to make plates. Centuries ago, wood had been carved to form raised letters and graphics. Later, metal was cut and finally etching became the standard process for printing plates. Acid etching had been known for centuries since natural processes produced acid.

In 1913, Arthur Berry filed for a patent claiming a method of making circuits where unwanted metal was etched away [3]. He described the process of coating metal with a resist, prior to etching, as an improvement over die cutting. Berry appears to be the first to describe the circuit etching process. Later, Bassist gave specific details of photoengraving including the use of photosensitive chromium salts [4]. Although his patent dealt with print plate making, the process could easily be adapted for circuitry since Bassist described preparing flexible plates by electrodepositing copper foil onto dielectric laminate.

Early Commercial Circuit Processes

Figure 2. Schoop Process.

One successful inventor, Max Schoop, commercialized a metal flame spraying process that was used for many years. Keep in mind that early electronics was power hungry and vacuum tubes required heated filaments and high voltages. The practical circuit in the vacuum tube era needed to carry substantial currents. The Schoop process deposited thick patterns of metal by flame spraying through a mask and produced the hefty and robust circuits and coils that were required. Figure 2 shows the 1918 Schoop Process [5].

But the Schoop flame spray system never solved problems of cost and wasted metal even though subsequent inventors added improvements. A practical printed circuit process was still needed. In 1925, Charles Ducas described both etching and plated-up conductors. One version involved electroplating a copper, silver or gold pattern onto a low temperature metal alloy through a contact mask [6]. Heating allowed the conductor (typically a coil) to be separated from the fusible bus plate and mask. Another Ducas process involved forming grooves in dielectric such as wax and filling them with conductive paste (composition not disclosed). The paste was then electroplated. Conductive paste could also be printed, or stenciled onto dielectric and then electroplated. Both sides of the dielectric layer could be used for circuitry. Ducus went on to describe multilayer circuits and a means of interconnection layers.

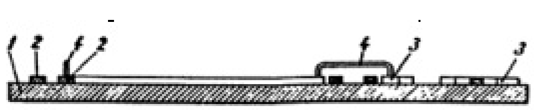

Figure 3. Parolini Circuit with Jumper.

In 1926, Frenchman Cesar Parolini came up with improvements in additive plating [7]. He described the printing of patterns with adhesive onto dielectric followed by dusting on copper powder onto the wet ink. The excess copper particles were shaken off and the ink hardened with heat. This is the basic Edison concept, but Parolini reduced it to practice and added jumpers, or crossovers. "U" shaped metal wires were imbedded into the wet conductive ink that was then hardened. The inventor was aware that the fresh metal powder would oxide and increase electrical resistance and added electroplating to form continuous metal over the copper ink and also connect the jumpers. Figure 3 shows the Parolini Process complete with a jumper.

A parade of inventors soon followed, but most offered variations and small improvements on themes that had been disclosed by predecessors, as is typical today. For example, Franz, in 1933, made a printing paste with carbon filler that could be screen-printed or stenciled onto cellophane [8]. The hardened ink, although stable, had high resistance compared to metal. Franz, perhaps aware of the Parolini Process disclosed seven years earlier, added a copper electroplating step. Franz also described flexible folding circuit as a replacement for windings in transformers, a rather clever idea.

WWII and Hybrid Circuits

World War II brought circuit developments that took a different turn. The need for extremely robust microelectronics for military ordnance spurred development of ceramics. Secret projects developed highly reliable ceramic substrate and conductive inks, called cermets---ceramic-metal. This process, now widely practiced in the ceramic hybrid industry, involved screen printing or stenciling circuit inks, followed by high temperature firing. The process was used to produce tens of thousands of electronic ordnance fuzes and is discussed in detail by Cadenhead and DeCoursey [2]. The war efforts resulted in both the development and optimization of high volume thick film printed circuit manufacturing.

After the war, the U.S. government under the auspices of the National Bureau of Standards (NBS) disseminated printed circuit technology. Conferences were held and publications described virtually all of the circuit making concepts, including subtractive etching [9]. A Circuit Symposium sponsored by the U.S. Aeronautical Board and the National Bureau of Standards was held in Washington, D.C., in October 1947. Dozens of speakers and hundreds of attendees interacted at the conference. The more than two-dozen processes were condensed down to six methods:

1. Painting (really printing): Metal-filled inks are applied and cured or fired, includes Ceramic Thick Film (CTF) and Polymer Thick Film (PTF) that remain important today.

2. Spraying: Molten metal or composite conductor material is sprayed through a mask or stencil. The mask can be a resist applied to the substrate. Process is no longer used.

3. Chemical Deposition: Electroless and electrolytic plating are included. Dozens of early patents described electroless, electrolytic and combination plating. Chemical deposition remains an important process in many circuit-making schemes.

4. Vacuum Deposition: Sputtering and evaporation through a mask were the key processes mentioned. Thin film circuits are made by vacuum depositing copper, gold and other metals. The method is still used today.

5. Die Stamping: Many of the early patents claimed cutting and die stamping as the process for patterning conductors. Modern methods simultaneously bonded the weakly adhered metal foil to the substrate during the die cutting process. This was accomplished by using B-staged adhesive and a heated die bed. The method, although low cost and environmentally friendly, has become all but obsolete as tolerances become tighter and density demands increase.

6. Dusting [conductive powder over tacky ink]: Application of graphite or metal powder over wet ink or adhesive is one of the earliest processes reported. Some of the later patents apply solder to the dusted conductors. The process does not appear to be in use today.

Paul Eisler: Father of the Printed Circuit?

Paul Eisler began developing circuit manufacturing processes during WWII but claimed it was as early as 1936, offering no proof for his earliest claim. Eisler eventually obtained several British patents dealing with the etching process [10-12]. His approach is similar to well-known photo-etching that is still the most popular method now in use. During the 1800s, photosensitive coatings were discovered and perfected that enabled the widespread use of photoengraving. Eisler apparently adopted this well-established technology to the electronics, but he was not the first as asserted, a fact we have already shown. He used his British patents to support U.S. patents [13-15], but there were procedural irregularities.

Now armed with U.S. and British patents, Eisler commercialized circuit production under Technographic Printed Circuits Ltd., but sought to limit competition by lawsuit. He sued Bendix Corporation using an etching process in the U.S., through his Technograph Printed Electronics Inc. The case went to a lengthy trial. Eisler was unable to substantiate claims of earlier work and could not produce his "book of circuit samples," but it wouldn't have mattered.

Bendix, the defendant, countered with an overwhelming amount of prior patent art and asked that the Eisler patents be declared invalid. Bendix also claimed that Eisler had simply patented well-established photolithography [16] from the printing industry and his own written statements supported this. Eisler had also been granted several U.S. patent claims on the basis of his British patent claims that had actually been rejected. This was not an accepted practice and the ethics are questionable. One mystery is why the U.S. patent office first rejected all claims, and then abruptly accepted them, after a confidential meeting with Eisler and council.

On May 27, 1963, the infringement trial concluded and the complaint was dismissed [17]. Eisler had been defeated and dethroned as the father of printed circuitry. Eisler felt that he had been wronged by the American justice system and died a bitter man, yet it's obvious from the vast amount of prior art that he was not first. Eisler certainly contributed to the printed circuit industry, but he came after the great circuit innovators. The printed circuit was not really invented by a single person, but by many who contributed to the total concept.

The Circuit Industry Today

Subtractive photolithography, borrowed from the ancient printing industry, still remains the workhorse circuit process. Fully additive copper methods have not really succeeded although ceramic and polymer thick film remain popular. The etching process has also weathered storms stirred up by environmentalists as better waste recovery methods evolved. However, subtractive etching is under attack by semiadditive. The semiadditive circuit process requires a thin conductor layer, or "seed" metal, to serve as a temporary plating bus. A typical process involves applying a plating resist over the thin metal, followed by imaging, developing, electroplating, stripping resist and etching away the thin background layer. Although etching is still involved, the process does not define the conductor shape and very little metal is removed. The semiadditive process is gaining momentum since it can produce very fine lines (<10 microns), build straight-wall conductors (no etch factor), and generate minimal waste. Flex adhesiveless producers now supply dielectric with just the right thickness of copper for semi-additive processing, but the rigid laminate industry seems to be waiting.

The Future

Will we continue to use century-old processes to make circuits? Are we just going to improve etching and plating for another century? Perhaps! But sooner or later, there will be a disruptive event that will change circuitry forever. Perhaps Nanotechnology will alter both electronics devices and circuits. Carbon nanotubes have already been used to make transistors and other solid-state devices. Future circuits could be based on molecular-level processes. The real question is how long will it take? And the answer is, less than 100 years!

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