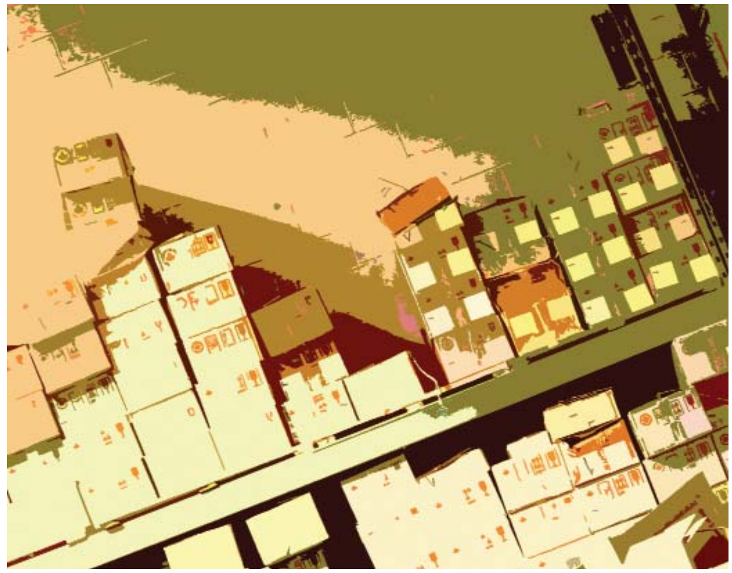
A Reflection of the Future: RFID Today



Rapid growth in technology is making RFID tags competitive with printed barcodes. Increased research and development of innovative fabrication techniques is further reducing the costs.

The application of Radio Frequency Identification (RFID) technology as a substitute for the ubiquitous barcode has been available for at least 10 years. RFID has distinct advantages over the barcode. For example,

- Human intervention is required to scan a barcode, whereas in most applications an RFID tag can be detected "hands off."
- Barcodes must be visible on the outside of product packaging. RFID tags can be placed inside the packaging or even manufactured into the product itself.
- You must have "line of sight" to read a barcode. RFID tagged items can be read even if they are behind other items.
- The readability of barcodes can be impaired by dirt, moisture, abrasion or packaging contours. RFID tags are not affected by those conditions.
- RFID tags have a longer read range than barcodes.

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- RFID tags can have read/write memory capability; barcodes do not.
- More data can be stored in an RFID tag than can be stored on a barcode.

RFID data is also easily managed by software used to control inventory and manage the supply chain. IT migration from barcode to RFID is virtually seamless. It is even possible to simultaneously manage RFID data and barcode data on the same platform applications.

RFID Basics

The easiest way to understand RFID is to think of signal mirrors. For centuries we've known how to communicate messages with just a mirror by flashing the sun's reflection in the direction of the recipient. The flashes are sequenced to represent a code known by the recipient, such as Morse code, that communicates intelligence without the necessity of an infrastructure that establishes physical contact, such as a telegraph line. So, messages can be sent through the air simply by reflecting radiated sunlight. That is the basic idea behind RFID, except that instead of using radiated sunlight as our communication medium, we reflect radio waves.

The basic theory underlying RFID technology has been understood since the 1930s. Early on humans discovered that introducing a conductive material into an electromagnetic field could alter the field's characteristics. This occurs because the conductive material both absorbs and reflects the energy in the field. If the field is a radio frequency, or RF, the conductive material is capable of imparting a reflection of the source field radiation. RFID technology takes advantage of that characteristic by manipulating the sequence and rate at which

By **Richard Moscatiello,** Founder and CEO, Mountain View Systems LLC

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that reflection occurs, called modulation. RFID tags are designed to deliberately reflect the source RF in sequences that are interpreted as information in the form of digital data.

There are two general categories of RFID tags, *passive tags* and *active tags*. So-called active tags have a battery to power the tag circuitry. The battery allows for greater memory capacity in the tag, increases the linear range from which the tag can be read and allows the tag to independently announce its presence by periodically transmitting its ID code. These tags are more expensive, but have advantages for tracking large, complex items. For example, active tags are used to identify sea-land shipping containers, and the entire contents of the container can be stored in the tag's memory.

The more common type, however, is the *passive tag*, so-called because it has no internal battery power. Passive tags are powered by "free space" energy drawn from the RF carrier wave transmitted by an RFID interrogator. In its simplest form, a passive RFID tag is an assembly of two major components:

1. A small antenna circuit tuned to the RF carrier frequency and
2. A silicon integrated circuit (IC chip) programmed with unique identification codes and communication protocols.

Antenna Circuit Fabrication Techniques

An RFID tag antenna circuit is made of a conductive material -- such as copper, aluminum or silver -- bonded to a substrate material. The substrate can be fiberglass (down to 1/64" thickness), or a flexible polymer such as PET or Kapton in sheets or rolls. There are a number of approaches to forming the conductive antenna image onto the substrate:

- Subtractive etching
- Printing with conductive inks
  - Screen printing
  - Gravure, also called intaglio or dry offset
  - Offset (oil-based inks, in development, not yet available)
- Vapor deposition

The earliest, and most cumbersome, method of antenna fabrication has been subtractive etching of a metal-plated substrate (e.g., copper-clad FR4 fiberglass). The antenna design is printed onto a clear film as a positive image (black on clear). The image can be laser, inkjet or photographically printed. The film positive is placed over the copperplating, which has been coated with a photo-resist and exposed to light. The copper-clad board is then processed in photographic development solution, which removes the resist from the exposed areas. The developed board is immersed in an etching bath (e.g., ferric chloride) until the exposed areas are etched away.

Subtractive etching has matured to the point where it has become a low-tech process requiring inexpensive off-the-shelf materials and equipment. The process can be done in anyone's garage. That is fine for prototype development, however, for larger production runs, etching creates significant amounts of metal salt and chemical waste products, incurring increased costs due to regulatory fees, reclamation charges and trucking expenses. By comparison, printing and vapor deposition methods differ primarily in that they are additive methods, resulting in reduced process steps, waste and cost.

The simplest additive method is screen printing with conductive ink. Screen printing is widely available and inexpensive (set-up as low as $50), however, it does have limitations. Screen printing is not well suited to very large production runs because it is relatively slow and the screens are not as durable as gravure or offset. Also, an important consideration in forming an antenna circuit on a substrate is image resolution, or how much fine detail is achievable with a given printing method. One RFID industry goal is tag miniaturization, because a smaller tag is less obtrusive when applied to a product, uses less materials and more tags can be ganged on a given area of substrate. But as a tag antenna design gets smaller, proper tuning to the RF carrier wave frequency demands that the antenna dimensions be reproduced precisely. A spacing of 230 threads per inch is common for screens, capable of printing a circuit trace of 0.5mm (127 mil) in width, but that is an order of magnitude coarser than is achievable with gravure. The trade-off is that, when using screen printing, a thicker deposit of ink can flow onto the substrate than is possible with gravure, resulting in higher conductivity (lower resistance) values. Companies such as Conductive Compounds, Inc. offer silver ink that can get as low as 0.005 ohms at 1 mil dry film thickness.

Gravure printing has traditionally been the preferred method for reproducing high

Method	Resolution	Deposit thickness	Printing Speed	Set-up cost
Screen Printing	10 lines/cm	>10 micron	slow	$50
Gravure	120 lines/cm	<10 micron	900 meter/min	$2000
Offset (inks not available commercially at this time)	70 lines/cm	1 micron	600 meter/min	$500

quality photography and art on a mass scale. Those finely etched portraits of U.S. presidents on currency, so difficult to counterfeit, are minted by the U.S. Treasury Department using the gravure process. Gravure printing with conductive ink is capable of producing resolutions of 50 microns (2 mil), or 120 lines per inch. Gravure is suited to very large production runs: the engraved plates are durable and throughput as high as 900 meters per minute. Set-up costs start at about $2000. New conductive inks for gravure developed by Precisia LLC (a division of Flint Ink) have a resistance of 0.1 ohms at a deposition thickness of about 8 microns.

Conductive inks are typically fine metal particles of silver or copper suspended in a polymer vehicle. A conductive ink's characteristic properties of flow, adhesion and cohesion are crucial to resolution of fine detail. In addition to fine detail, however, it is paramount that the printed image has the lowest possible resistance to electromagnetic energy. Metal particle density determines the conductivity of the printed antenna — that is, how efficiently the RF energy can be captured and returned by the RFID tag assembly. The higher the particle density of the metallization, the better the conductivity. But as the particle density increases so does the ink's viscosity, resulting in a thicker ink that is difficult to apply. Yet an ink with a lower viscosity could have the opposite problems: dimensional instability, poor adherence and a higher electrical resistance.

To solve that problem Paralec, Inc. has developed a new ink chemistry that suspends the metallization in an organic carrier that decomposes after printing, leaving a 99% pure metal coating. The company claims their organic ink to be "3 to 10 times more conductive than polymer-based inks."[i]

Vapor deposition refers to the process by which a material in a vapor state is suspended in a vacuum and condensed onto the substrate to form layers of the material. The process is similar to that used to create silicon-based integrated circuits. Submicron resolutions of the circuit design are the norm. The vaporized metal can be deposited onto the substrate via chemical bonding or by ionizing the vapor and attracting the material magnetically. As the antenna designs and the IC chips become ever smaller (e.g., flip-chips), vapor deposition antenna fabrication becomes ever more necessary.

Assembly

There are several approaches to the assembly of RFID tags:

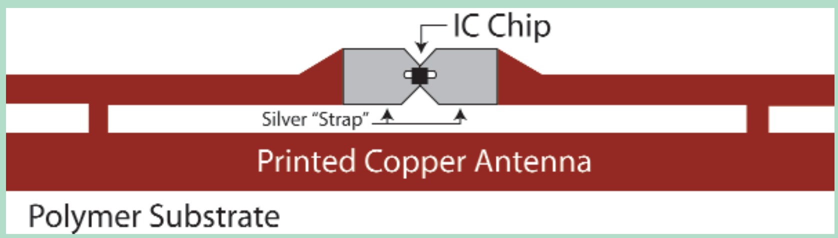
1. Surface mount technology (SMT) pick-and-place
2. Flip chip assembly
3. Fluidic self assembly
4. Roll-to-roll integration

The *SMT pick-and-place method* uses reels of fully packaged RFID IC chips. Each IC on the reel is enclosed in a sealed plastic or ceramic shell with metal contacts protruding from the sides, designed specifically for the SMT process, although chips in the older "flat pack" format may also be used. Pre-printed substrates are screen printed with solder paste and the substrate is fed into a robotic pick-and-place machine. Guided by optically controlled servomotors, the robot arm picks an IC chip from the reel and accurately places the chip onto the substrate. The assembly is then passed through an oven to melt the solder and the substrate is cut apart into individual RFID tags. Typical throughput is about 2500 units per hour. This is a relatively slow method by contemporary standards --one machine could make a billion tags in, say, 50 years -- but there is a huge amount of excess manufacturing capacity in the industry, making it a competitive low cost option for limited production runs.

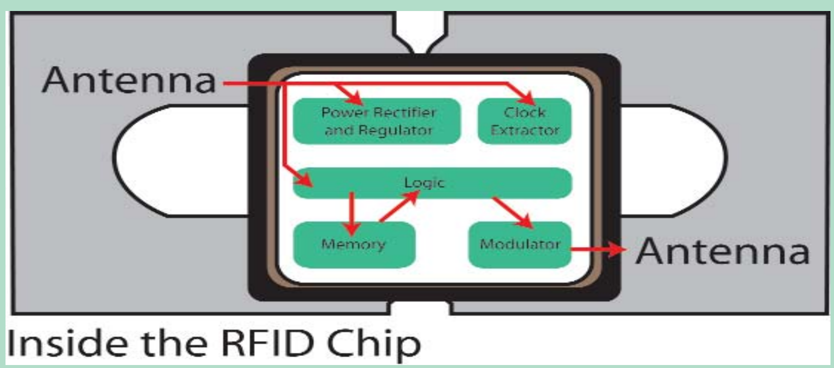
The *flip-chip method* bypasses the IC packaging stage. Silicon wafers containing hundreds of uncut ICs are fed directly into a Mühlbauer flip-chip assembler, the latest *tour de force* in precision machine engineering. The Mühlbauer removes each individual chip from the wafer, flips it over, applies an electrically conductive adhesive to its contact points and pushes it into the space provided in the antenna circuit preprinted on polymer sheets or rolls. A Mühlbauer is capable of throughput speeds of 5,000 to 10,000 units per hour. Those billion tags could be made in about 12 years. (Of course, 24 machines could do it in six months.)

Fluidic self assembly (FSA), a process pioneered by Alien Technology Corporation, is a "disruptive technology" in the electronics industry, having the potential to make SMT and flip-chip manufacturing obsolete. Normally chips are sawed apart from the silicon wafer with an extremely fine cutting tool (e.g., a stream of high speed water molecules), but even a tool that precise requires a percentage of silicon real estate to be set aside to allow for the saw width and increased chip spacing. Instead of using conventional sawing, FSA chips are etched apart along the silicon crystal edges. That allows for a denser population of chips on the wafer *and* results in a chip that is shaped something like the ice cubes that you make in your home freezer tray, the top wider than the bottom. Individual FSA RFID chips measure 350 microns in width. By comparison an RFID

In its basic form, an RFID tag consists of a silicon integrated circuit (IC chip) connected to a small antenna.



The modulated carrier wave transmitted by the interrogator is sensed by the antenna. The carrier wave induces a small alternating current (AC) in the antenna. Inside the IC chip, a power rectifier and regulator converts the AC to stable DC and uses it to power the IC chip, which immediately "wakes up." The clock extractor separates the clock pulses from the carrier wave and uses the pulses to synchronize the logic, memory, and modulator sections of the tag's IC chip with the interrogator.



The logic section separates the 1s and 0s from the carrier wave and compares the data stream with its internal program to determine what response, if any, is required. If the logic section decides that the data stream is valid, it accesses the memory section for the chip's unique identification data and any user data that have been stored there. The logic section encodes those data using the clock extractor pulses. The encoded data stream is input into the modulator section. The modulator mixes the data stream with the carrier wave by electrically adjusting the reflectivity of the antenna at the data stream rate, similar to the way one might adjust the angle of a signal mirror to reflect the sun's light. Electrically adjusting the antenna characteristics to reflect RF is referred to as backscatter.

flip-chip is 1.3mm wide and an SMT IC package is 5mm wide.

The key to FSA is that ice cube shape. The "F-for-Fluidic" part of FSA is that once the chips have been etched apart by hundreds of thousands, they are dumped willy-nilly into a big tank of water. An adhesive solution is released into the tank. A roll of flexible polymer sheeting with tens of thousands of ice cube-shaped indentations is fed through the tank. Now here's the "SA-for-Self-Assembly" part: the chips float down onto the polymer sheet and lodge themselves into the indentations. Any leftover chips are pumped back and used again. The roll of chips exits the tank, and is dried and over-printed with silver connection straps. FSA throughput can be as high as 2,000,000 chip-strap units per hour. The finished roll is sliced lengthwise into individual reels of straps. The chip-straps are mated to rolls of pre-printed antenna circuits using the roll-to-roll process.

Roll-to-roll continuous flow processing merges two or more rolls of flexible material to create a single roll of multi-layered material. This is a very efficient and speedy way to assemble RFID tags. A roll of preprinted antenna circuits is easily mated to a reel of flip chips or FSA straps. Label maker Avery Dennison has developed the ability to integrate up to seven separate rolls of material into a single product. One of Avery Dennison's applications for this technology combines rolls of conductors, dielectrics, plastic, paper and electrically sensitive color elements to create the battery tester circuits that come built into the dry cell battery packages that you buy at the store. Roll-to-roll battery tester packages are produced at a rate of tens of billions per year. Roll-to-roll manufacturers are well positioned to take advantage of rapid growth in RFID tag demand.

The 5¢ RFID Tag Is Here

Rapid advancements in circuit printing techniques, IC chip fabrication and tag assembly have combined to drive down tag costs faster than many conservative analysts (including this author) had predicted. The industry Holy Grail of the five cent RFID tag is no longer mythical. According to a 2003 Auto-ID White Paper by Swamy and Sarma, "overall RFID tag costs could be pushed as low as 4.49¢ using a traditional assembly process and 3.31¢ using a flip chip process. The semiconductor or die costs account for 1.15¢ and the remaining 2–3¢ are tag assembly costs."[ii] In fact, over the last four years tag prices have fallen dramatically. The steep drop in tag fabrication costs and the surge in new technologies and innovative applications suggest promising near-future growth for the RFID industry. Get ready for the networked physical world.

[i] RFID Journal, New Ink for Printed RFID Antennas, Feb. 5, 2003

[ii] Gitanjali Swamy and Sanjay Sarma, Manuracturing Cost Simulations for Low Cost RFID System, MIT Auto-Id Center, February 1, 2003.