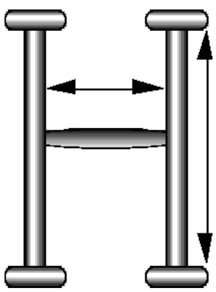
Chapter 7
Printing and Imaging Systems

Modern Printing Systems and Their Inks—New Approaches to an Old Art



For over forty years, SRI has repeatedly provided innovations to what has become a renaissance in the old art of printing. Linking much of SRI's motivation to the revolution in computer-generated text and graphics, virtually all these innovations served the need for faster, more flexibly programmed printing mechanisms and machines. The computer revolution that was supposed to have eliminated our need for paper has clearly done just the opposite: printed material is now more prevalent than ever.

SRI's work in printing began with the large Bank of America project known as ERMA (see Chapter 2). ERMA introduced the need for individual checks to bear an account number that would enable automatic posting and account maintenance. Before this change, checks could be literally written on anything. But because checks of even standard size could be written over with cancellation marks or handwriting, SRI decided that the most reliable method for printing and automatically reading checks was to use ink that included a magnetic pigment. Thus, for ERMA, SRI invented a font-ink combination that could be reliably read by both machines and humans. For this innovation, SRI's Ken Eldridge was awarded U.S. Patent No. 3,000,000.

Here we trace just a part of SRI's role in printing. First, we describe SRI's work in the 1950s and 1960s on the technology of printers: the Videograph printer for A.B. Dick and one of the first inkjet printers, built for Recognition Equipment, Inc. From about 1970 to 1983, SRI had a working relationship with the R&D arm of the Savin Business Machines Corporation of New York that would, over time, aggregate to research of almost $10 million. Three types of the projects for Savin are described here: a new fax machine, new office copiers, and early work on inks and toners. We then cover SRI's attempts in the 1990s to commercialize its breakthrough developments on water-fast inks and even the technology of the paper itself.

A.B. Dick and the Videograph

One of SRI's early and very long-term commercial relationships was with the Chicago printing company, A.B. Dick. In the early 1950s, A.B. Dick had a substantial worldwide market in mimeograph technology for duplication. That technique was, by the way, old enough to have been licensed by A.B. Dick from Thomas Edison, and thus A.B. Dick knew that this venerable product area would soon be challenged. SRI's first project with A.B. Dick came in September of 1955 to look into the feasibility of electronic duplication.[1] A.B. Dick was seeking a new generation copier but, along the way, became diverted by another process in which they were involved—something as mundane as mailing labels.[A]

Then and now, weekly magazines with very large circulation such as *Time* and *Newsweek* face a big problem in their huge weekly mailings. They can produce upwards of 10 million magazines a week because the magazines themselves are all alike, but the labels for their mail subscribers are necessarily all different. Moreover, the master mailing list changes significantly each week. In the 1950s, slow label printers just weren't coping with this problem.[2] How could they manage to print the millions of labels needed every week, each tailored to a new, valid customer list? To do just that, SRI engineers reoriented the technology

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[1] In 1955 Xerox was still called the Haloid Corporation and Haloid's first successful copier, the 914 (called that because it could copy images as big as 9 x 14 in.), did not appear on the market until 1959.

[2] At the time, A.B. Dick was using more than 30 Addressograph-Multigraph printers, each operating 80 hours per week. And there was the formidable task of handling millions of embossed metal stencils each week, one for each subscriber.

they were exploring for A.B. Dick for electronic duplication into something called the Videograph.

Because of the speed requirement in this kind of printing, SRI did not pursue the selenium photoconductor approach Xerox was using. During the electronic copier investigation, staff of SRI's Television and Tube Labs had invented a cathode ray tube with an array of very small wires embedded in its face.[3] These wires were oriented in the direction of the scanning electron beam and perpendicular to the direction of the paper. In its raster motion, the electron beam would selectively deposit charge on the inside ends of those wires needed to form the desired character. Those wires, so excited, would directly transfer the charge to the paper that was in contact with the outside of the Videograph tube. The paper's charge pattern was then mechanically dusted with a black powder (toner) that clung to the paper in those regions of charge. The toner was then heated and pressed on the paper to make the print legible and permanent.

The Videograph printer, shown in Figure 7-1, could print as many as 50 labels per second and was completed in 1958. With it A.B. Dick captured a market for rapid printing and, with continuing upgraded technology, held that market for many years. In the late 1960s, A.B. Dick adopted inkjet printing for making labels and thus came its popular Videojet printer. According to A.B. Dick's company web page, the Videojet was the world's first commercial inkjet printer.[B] This printer came after some of SRI's own inkjet technology and so SRI helped develop the ink for the Videojet. But more on SRI's role in inkjet printing below.

Though briefly pursued, the technical approach to the Videograph should not be thought of as adequate for electronic duplication; that is, what we call today a copier. Because of the interwire capacitance in the wire-embedded face of the Videograph's cathode ray tube, there was a fundamental limit to its ultimate resolution.[C] However, this early electrostatic printing concept led to many uses and projects from A.B. Dick and others. For example, SRI explored that technology for computer output printers and reported to

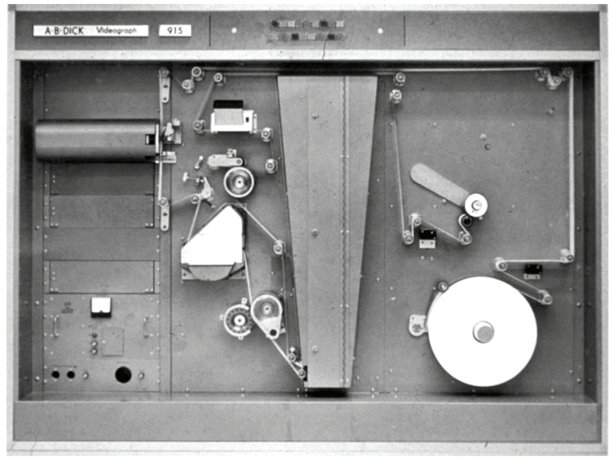

Figure 7-1. Front panel of the SRI-developed videographic label printer.

A.B. Dick in 1957 that Videograph-like systems could theoretically print as high as 30,000 characters per second. In 1963 a facsimile-type printer was built that could print images of billboard size.

Inkjet Printing[4]

The pressure for greater flexibility and speed in the way documents were machine processed continued to increase in the early 1960s. Of particular difficulty was the "lifting" or reading of printed text by a machine. At that time optical character readers (OCRs) were much slower than other document processes such as searching or sorting. To circumvent the problem of rereading such text at each step in document processing, there arose the idea of creating from the first OCR scan a text representation that could be machine-read much faster thereafter. That way any later document processing step that involved rereading could be done more rapidly. One of the larger OCR companies of the day was Texas-based Recognition Equipment, Inc. (REI), which was building equipment for processing credit card transaction receipts. To meet the needs of this equipment, REI was looking for a faster-read, higher quality, intermediate form in which to carry forward the details of the transaction. SRI suggested a bar-code system of character representation and a corresponding

[3] The principals were Phil Rice, Wayne Crews, John Papacosta, Jack Kabell, Howard Murphy, and Howard Borden, with Bob Tobey and Bill Barnes making the theoretical assessments.

[4] A review of early inkjet work can be found in Fred J. Kamphoefner, Inkjet Printing, *IEEE Trans. on Electron Devices*, ED-19(4), 584-593, April 1972. This became one of the most cited papers during the 1970s and helped stimulate the field, even in the later dot-on-demand inkjet techniques.

fast bar-code printer that would convert the output of the OCR system to this new intermediate form. So, in 1965 REI embarked with SRI on a three-phase study to develop a bar-code printer.

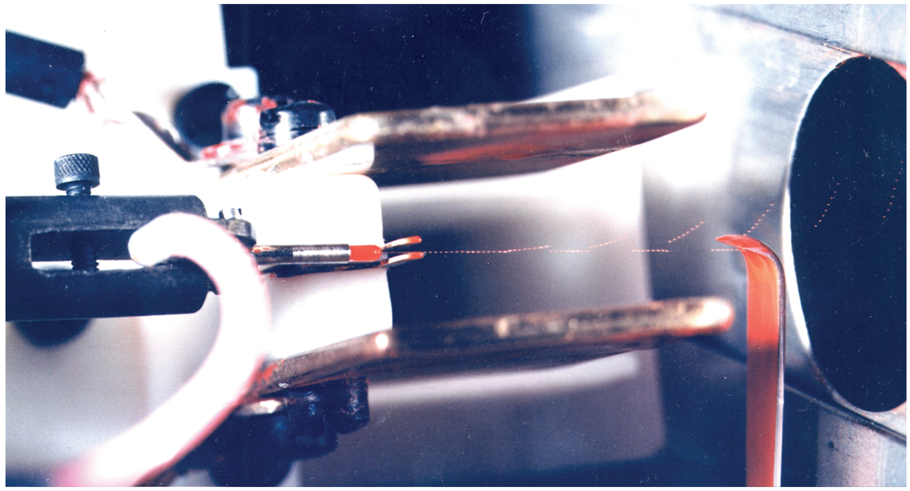

Figure 7-2. One of the first inkjet printers, built by SRI for Recognition Equipment, Inc. Shown are a droplet source, electrostatic deflection plates, and a stream of deflected ink droplets (1966).

In the meantime, Richard Sweet, a member of Stanford's System Techniques Laboratory, had invented an electrostatic inkjet technology for printing the output of an oscillograph. He had won an Army contract with three phases.[D] Phase I showed the feasibility of building such a printer, and Phase II developed a fast-drying, fluorescent ink and a satisfactory barcode-sensing system. The printing system used in Phase II was the original experimental apparatus constructed by Sweet, which had been designed for different ink. Phase III was to generate an experimental model of a printer that would print a simulated bar code using the fluorescent ink as well as meet the client's required level of operating performance. This entailed the redesign of the nozzle, flow modulator, valving system, drain, and controlling circuits. These changes were done at SRI and the result was a printer with a different, axially modulated drop formation system.

SRI developed a method that formed a reliable and synchronized ink-droplet stream. A strobe light system was used to photograph the in-flight droplets, as shown in Figure 7-2. Portions of the train of droplets are deflected by a time-varying electric potential on the two large plates and proceed through the hole to the paper. The undeflected droplets, then, are collected on the curved collector and returned to the ink reservoir. Given the needs for a non-particulate fluorescent ink and a complete stream cut-off valve, it was a difficult research problem to get the nozzle and ink-impulsing system to form uniform droplets while at the same time using ink that would dry quickly without smearing. The system produced the required droplet rate of 48,000 per second and was successfully built and licensed to several companies, including REI the sponsor, A.B. Dick, and 3M Corporation.[E] This same encoding process was later used to encode information on the backs of bank checks, credit card invoices, and, in a Post Office project, to encode ZIP-addresses on envelopes so that in subsequent handling they could be more easily and reliably read by inexpensive readers/sorters (see Chapter 3). That SRI project with the Post Office produced their first experimental inkjet printer for zip code printing.

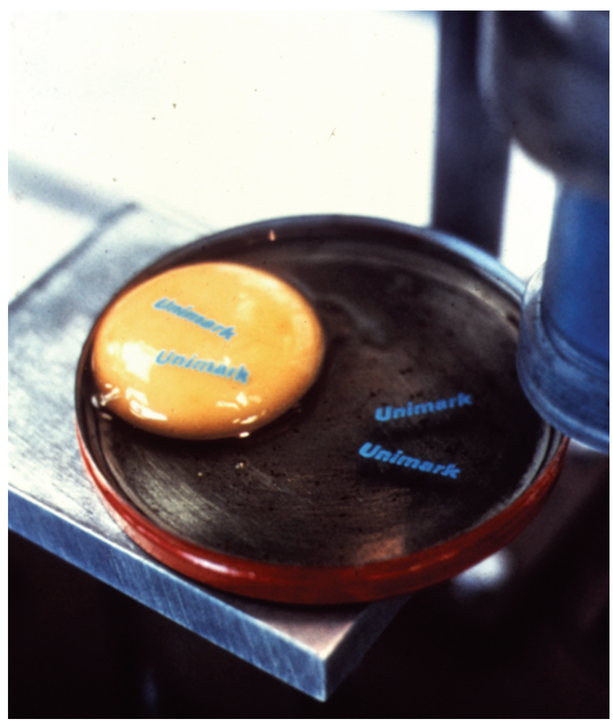

Figure 7-3. Nonimpact, stenciled printing on the yolk and white of an uncooked egg.

SRI also developed some stencil systems that, in about 1965, could even print on surfaces as delicate as the egg-yolk shown in Figure 7-3. This technique involved the flow of toner through a stencil, first by applying a potential between the toner cartridge and the opposite side of the target and later through the use of implanted charge on the target object itself.

Nonimpact inkjet printing would have a host of other applications such as printing labels on the plastic insulation of wires for the Boeing Company and, for A.B. Dick, the now commonplace printing on bottles, cans, and a variety of manufactured products. In this last case, A.B. Dick had developed a "Sweet-type" printer and SRI's Sam Graff and Dean Parkinson developed its ink. Significantly, this new ink had to dry fast, be very durable, and do both on nonabsorbing surfaces.

While SRI had very early roles in inkjet printing, to be clear, it did not participate in the development of the "drop-on-demand" inkjet printers so popular today as computer peripherals. As we will mention later, however, SRI did make innovative changes to their inks.

A New Fax Machine

The facsimile machines of the late 1960s were expensive, slow, and much larger than the desktop sizes common today. To those who believed in the information revolution, this was an opportunity. So, on November 24, 1970, representatives of Savin, CBS Television Services, and a new company called Dacom sat down at SRI to explore a new, more rapid, and more affordable facsimile machine. Within a month of that meeting, SRI had a contract for $239,000 to build just that. SRI's role was to design the printing component and do the overall design and integration effort. CBS's participation was largely financial. Dacom was a Bay Area company formed by two Lockheed engineers, one of whom had developed a compression technique that seemed attractive for facsimile.[5] Arthur D. Little had also been targeted as having a promising optical scanning technique that would be useful.

The goal of a new product was evident early, and the pace was rapid. Earle Jones, the SRI project leader, and representatives of Dacom and A.D. Little were off to Japan within the first two months of the project. There they looked over Ricoh as a potential manufacturer and surveyed the status of Matsushita and NEC, the dominant players in the Japanese fax market. As the project progressed, several sources of a digital modem were examined and that of a subsidiary of Rockwell was chosen.[6] With the optical scanner and modem sources in hand and using SRI printer and signal processing skills, the development proceeded rapidly.[7] The prototype, called the Z-60, resulted in a facsimile machine that, though initially bulky, could scan, compress, and transmit data at 4800 bps—fast enough to give it a clear market advantage over existing fax machines.[8]

By October 1971, Ricoh would invest in the project as Savin created a specific subsidiary called Rapifax to continue its development. By March 1973, Ricoh acquired the technology and formed a subsidiary, Rapifax Corporation, in the United States to market and distribute the new machine. Ricoh would, over time, also engineer the digital machine to more modest dimensions and a lower manufacturing cost. According to the Ricoh web site, the first commercial realization of this machine, the RIFAX 600S, became the world's first digital fax machine. A later version, the Rapifax 100, and its derivatives would soon become one of the most important factors in leading the world to the high speed, affordable fax machines used everywhere today. Although Ricoh takes credit for inventing the digital fax machine, SRI and its partners as listed above provided the first prototype.[F]

Savin Office Copiers

The SRI-Savin connection actually had started with an SRI project for Sun Chemical to explore building an office copier that didn't infringe on

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[5] Dacom was founded in Sunnyvale, CA, by Lockheed engineer Dan Hochman, exploiting a run-length encoding technique designed by colleague Don Weber. Savin and CBS had their eyes on Dacom. According to the *Wall Street Journal* of January 4, 1971, Savin and CBS would partner to purchase 60% of Dacom with options to buy the rest. SRI's facsimile work would eventually be funded through Dacom.

[6] The subsidiary was American Data Systems.

[7] Seven prepatent disclosures were collected on the project, but no applications were filed.

[8] The machines of the day were typified by Western Electric's "Teledeltos," 3M's "Thermafax," and Xerox's "Phonocopy." All these required about six minutes per page regardless of the density of information on the page.

the rich and unfolding Xerox patent portfolio. It wasn't an easy pathway, but many were probing it, including Sun and consequently SRI. A person at Sun Chemical had come to SRI with an idea for a non-Xerox copier and from that visit came a research project to explore it.

The Sun researcher's approach used a difficult process of moving a cloud of liquid toner through holes in a mask. SRI helped replace that process with one that projected light through a negative to a photo-electric surface. While SRI's process was feasible, the ultimate need for special dielectric rather than plain paper ended the project. During this work, however, the Sun researcher introduced to SRI a very energetic and entrepreneurial person by the name of Paul Charlap. As a ranking officer of Savin, Charlap had been trooping the world looking for new technologies that had relevance to office products such as those that copied or handled information. He must have first arrived at SRI about 1970.

Charlap's global technology search focused on ideas for non-Xerox-like copiers that still used plain paper. He had formed a working relationship with the Japanese office product company, Ricoh (which, by the way, means "copy" in Japanese), and was trying to find some additional technology that Ricoh could license. Charlap was already getting some royalties from them, but more important for SRI, he began to use SRI as the source of technical improvements of the Ricoh copier development so that he could harvest even more royalties. Hence, SRI had a significant input to the design of a machine that by 1976 was the world's largest selling copier. Principal areas where SRI helped in the development of the copier were an automatic plate bias system that kept the drum clean, an automatic document feeder, and its variety of toners. For several years, the copier was widely sold in the United States as a product of the Savin Corporation. By 1995 Ricoh would acquire all of Savin.[G]

Inks, Toners, and Paper

SRI's first in-depth interest in toners arose between 1976 and 1978 as part of its substantial work for Savin. That work led to a liquid-toner approach to copiers, and it became an important alternative to dry toner because it provided a higher resolution, given a much smaller particle size. The approach also included a lower-powered fusing operation that enabled (1) the use of normal power outlets rather than the special high-amperage circuits then needed for the high fusing energy to melt dry toners and (2) a more rapid fusing process because of a shorter warm-up time. This last advantage also avoided the occasional fires that occurred when paper became stuck in the fusing apparatus of dry toner machines.

The SRI formula for black liquid toner and the associated Ricoh- and SRI-designed copier helped take Savin quickly from a minor player to a dominant player in the office copier marketplace. In spite of early success, this particular liquid toner had a problem: it released a hydrocarbon gas as it dried. Unfortunately, enough people were allergic to this gas that the Canadian government effectively embargoed liquid-toner Savin copiers. Savin then dropped its use.

Some ten years later, however, interest again arose at SRI in the use of liquid toner—this time for color. Kodak and Xerox had been putting a lot of research into color liquid toners. SRI research staff had also been looking at these toners for use in the higher quality industrial copying systems and where the air pollution problems mentioned above might be more easily mitigated. At the same time, the people at SRI's exclusive venture capital investment broker, CommTech, also caught interest in these toners. To CommTech, it was the convenience copier market that had the big market potential. After surveying the major printer manufacturers, CommTech picked Hewlett-Packard (HP) for further negotiations. In this relationship, HP gave CommTech about $1 million to explore how SRI's color liquid toners might lead to a new, nontoxic product. Unfortunately for SRI, HP too was targeting the convenience copier market and toward that pursuit, its business plan required a two-cubic-foot copier—a size constraint that SRI's more industrial process could not meet.[H]

Water-Fast Inks and Paper

SRI's work in water-fast inks had its roots in the drying properties of the inks in the earlier continuous flow inkjet printers. For these inks to dry quickly, given the very high speed of the paper they printed on, their base contained volatile organic compounds, which were unfortunately toxic. Inks based on water rather than volatile organic compounds would be nontoxic, but because they were water-based, they were likely to run or smear on contact with water.

In 1995, using about $50,000 of internal investment money, SRI chemist Dr. Asutosh Nigam conducted a feasibility study in which he developed a proprietary approach to black water-soluble, water-fast, polymer-based, nontoxic ink. According to SRI commercialization specialist Dan Morris, this was a surprising accomplishment in the field. The new ink used easily available monomers and polymers, was resistant to water and solvents, and could be stored in solution without changing its characteristics. The U.S. Postal Service laboratory made a wide range of chemical and physical attacks on the ink, and it passed them all to become the best available indelible color ink available.[I]

SRI licensed Nigam's new ink to Domino Ltd. for just Post Office use, retaining all other rights. After a number of years of failing to license the technology, Domino dropped the license. This became yet another good technology that didn't sell. But there would be continued intellectual resilience and still more disappointment.

From the first introduction of today's common $50-$500 inkjet printers, they have used inks that water will smear even after the ink has dried.[9] Given that problem, there would seem to have been an enormous market for cheap, water-fast inks usable in the cartridges sold by the likes of Canon, Epson, and HP. So, during the 1996 internal investment year, Nigam continued development of the same water-based, water-fast inks, both black and color—this time for inkjet printers. His search was on and, if successful, it seemed commercialization would be a veritable slam-dunk. It wasn't. While admitting the SRI inks were better, none of the major players in the printer/ink cartridge business would change their lucrative in-place processes. Another factor was that Nigam's black inks were either nearly black and water-fast or they were very black and not as water-fast as the colors. Though close, there was no cigar. The water-fast issue was evidently not an important enough marketplace differentiator at the time to warrant a completed product.[J]

The resourceful Dr. Nigam returned to another opening that had surfaced in the 1995 feasibility study—the paper itself. SRI understood the chemistry very well, and if the ink manufacturers wouldn't support him, perhaps the paper manufacturers would. Once you knew the reactions needed, you also knew that it didn't make any difference how the water-based ink, the water-soluble polymer fixing-agent, and the paper came together. Applying a polymer coating on the surface of the paper during manufacture was actually simpler than the more precise approach of mixing it directly into the ink. That this new polymer-treated paper was no longer "plain" should not be seen as inconvenient to the end user because photo-quality ink-jet paper is already special and clearly not inexpensive. SRI tried unsuccessfully to commercialize this technology through a newly formed spin-off called Cyance.

The coating Nigam developed actually renders the chroma and hue of the existing inks much better than uncoated paper. I remember my introduction to these new inks when I walked into Nigam's lab and saw a faucet running in a sink, on the bottom of which were several brightly colored prints. Each of these had been made on normal inkjet printers of various brands using normal ink cartridges and yet the water was having no influence on their clarity and brilliance!

Besides the plain and coated paper options in this technology, SRI also developed two other print media. One was a type of metallic coating that would accept color inks and the other was an ability to color-imprint cloth. These two print media have been licensed. As yet, the coated plain-paper option has not, and SRI is still trying to work through the reasons.

One lesson in the above story illustrates the difficulties of commercializing even excellent technology. Because the inks of the various major printer manufacturers were an enormous source of profit, the manufacturers were uniformly reluctant to experiment with new inks. And because they each had a lot of chemists working this problem, they weren't willing to disturb their present market position or pay royalties. The circumstance was similar when SRI offered its set of color liquid toners to HP for its new color laser printers. That offer came very close to happening but in the end also failed in spite of producing superior images when HP, although seriously behind the

[9] Epson has very recently added some water-fast capability to their inks.

This is a good place to draw attention to the diverse skill base of a flexible research institution like SRI. Designing and building the office machines described above required a broad range of in-depth knowledge and talent, including electronics and mechanical design, the chemistry and physics of the optics and charge-retention surfaces common to copiers, the intricate chemistry of dry and liquid toners and the paper to which they would adhere. However, all these are a normal part of the working life of skilled researchers at SRI. Getting these results did not require hiring specific talent, and it is that characteristic of SRI that best defines the technical grounding of its research staff. Add to that expertise the need for meeting the cost design of a particular product or project and the ability to replicate such work over a wide range of applications and you have an idea of the talent level that has defined SRI from its outset.

Not all SRI research projects succeed, of course, including those in printing. In 1961, a company wanted SRI to devise a paper and ink system that would make a document self-destruct in a specific number of years, so that an outdated drawing or classified report would crumble to dust. After a brief investigation the staff could not conceive of a paper and ink system that would destroy itself after a particular time and yet remain stable and usable until then.

learning curve, chose to develop its own toners in-house. According to SRI's Ron Swidler (May 2002), part of the HP decision was also related to the return that the SRI venture capital associate, CommTech, was seeking. It was more than ten times what HP was willing to accept.

Rapid differentiation in a highly competitive, commodity market would seem to be highly desirable. In fact, it was not. Color images have not yet seriously made it into the business world. Until the cost of color copies comes down substantially and their reproduction speed is increased, the business community will be content with black and white images whenever large printing jobs are needed.

Development of the First Optical Videodisc

Optical discs, in the form of Videodiscs, CDs, CD-ROMs, and DVDs, are now everywhere. Cheap and accurate lasers, perhaps more than any other technology, created this revolution in recording media. And the revolution is far from over. Future advances in blue lasers will permit even more compaction of information than we see today.

But, even before the availability of lasers that could modulate the material of today's optical records, videodiscs had been built at SRI. In fact, SRI developed the first optical disc for recording video signals. In March 1961, 3M Corporation asked SRI for help in determining the feasibility of recording a full-bandwidth television signal on a disc similar to those used in phonograph records. 3M had been experimenting with extending that approach to video to create an inexpensive home video system but had encountered difficulty in resolving the micrometer size "bits" needed for video bandwidths.[10] 3M then began pursuing an electron beam technology that was expected to yield 10 to 15 minutes of playing time on each side of a disc for monochrome video. By the end of the first monthly reporting period, however, SRI had ruled out 3M's method in favor of optical recording and playback, using a high-resolution photographic plate. Such an approach looked much more promising, but it still needed to be tested.

The method for testing whether the optical approach would work was clever and resembled what one might do if a digital recording were to be made.[K] An array of 1-micrometer latex spheres, suspended in distilled water, was spread over a glass microscope slide and the water was evaporated. A thin but opaque film of aluminum was then deposited over the top of the slide. The latex balls were then broken off, leaving small 1-micrometer holes. These holes were used to determine if the signal-to-noise ratio of a photodetector receiving a light signal through the hole was adequate for commercial use. It was. Given the adequacy of the static test, detection at a 4-MHz rate was then verified, as was the ability to make a contact print of the pattern of holes.

Although the presence or absence of a transparent hole lent itself to digital signals,

[10] A micrometer is one-millionth of a meter.

digitizing the video caused a large increase in bandwidth, so SRI decided to record the analog signal. This approach required some type of graded surface emulsion, and by February 1962, a small photographic glass plate containing an image was pasted on a disc and read optically to produce the image shown in Figure 7-4, a single video frame. The SRI researchers then knew that an optical, photographic disc would work.

Figure 7-4. SRI optical recorder with insets showing an analog disc where each 180-degree annular trace created one frame, a reproduced image, and the final lab prototype of a playback unit.

One problem with the photographic plates of the day, however, was the time and energy it took to expose the emulsion. Because this work was before lasers, high-pressure mercury or xenon lamps had to be used and a special (Kerr) cell was designed and built to modulate their output. An overall recording and playback system was then built that laid down a spiral track in the disc's photographic emulsion, with radial lines on the disc forming the horizontal and vertical synchronization pulses. One line of a video frame was entered between each set of horizontal synch pulses at each track of the spiral. By October 1962, SRI had successfully recorded and played back black and white video at 24 frames per second. By the time SRI's role in the project ended in June 1963, several 16mm movies had been recorded on these photographic discs. The disc format created in this work was used for later analog video recordings. Although approaches were explored, SRI never placed an audio channel or color information on its disc. 3M carried the SRI technology into the laboratory prototype shown in Figure 7-4.[L]

The period from 1965 to 1975 was a time of intense movement in the technology of recording materials. Lasers were introduced and many types of disc materials were examined. In the meantime, and in parallel, 3M had developed an electron beam recording disc of very high resolution. This was an unwieldy system and difficult to commercialize. Being more a materials company, 3M concentrated more on the problem of finding optical disc material appropriate to the mass market. By 1981, 3M was providing optical recording discs to Thomson-CSF and Philips and never went into the disc playback business.

SRI continued to explore videodisc technology. In late 1975, through an enterprising individual named Lee Sowicki, SRI entered into a project to build a digital read/write optical storage system.[11] The notion was to write once and read many times. Using a tellurium coating on a plastic substrate, SRI achieved disc storage densities of about 100 million bytes per square inch with seek times of about 1 second. SRI was issued a patent on this storage technique.[12] Gas lasers were used for both reading and writing. The prototype was intended only for the scanning and storage of text documents. The approach was eventually sold to Toshiba, which produced a file storage system that was ultimately brought to the marketplace. It was billed as the world's first optical document storage and retrieval system.[M] The Laserfile prototype, as it was called by the SRI sponsor, is shown in Figure 7-5 along with most of those responsible for developing it.

Figure 7-5. One of the first read/write optical filing systems, called Laserfile. Toshiba ultimately made a product starting with this laboratory model. Staff who worked on the unit are (from the left) Termpoon Kovatona, Lou Schaefer, Hugh Frohbach, Phil Rice, Jim Young, John Nelson, and Gerry Pierce (June 1979).

[11] From Hugh Frohbach on September 20, 2002.
[12] Patent 4,189,783 was granted to SRI with inventors Ivor Brodie and John Kelly. *New York Times*, February 23, 1980.

Vacuum Microelectronics

Imagine a flat panel display for your computer or television set that is perhaps a quarter of an inch thick, exudes very bright colors, changes faster than video rates, has no viewing angle restrictions, and draws very little power. Such is the promise of an emerging technology known as field-emission displays (FEDs). These displays are a consequence of the field of vacuum microelectronics, a technology born at SRI in the late 1950s. In spite of its potential, this technology still has not appeared in the commercial marketplace, with perhaps one or two exceptions, after 40 years. We review here the origins of this work, what promise it holds, and the trouble it has seen in becoming accepted.

For much of its early years, SRI had a place for those whose thought patterns poked strongly at the edges of known technology, trying to break new ground. The condition for that freedom has always been, however, that someone with equal imagination could be found that had the funds and the fortitude to sponsor such privilege. During the very late 1950s, one such expansive thinker plied the frontiers of vacuum microelectronics at SRI. His name was Ken Shoulders, and though he didn't come equipped academically (only a high school education), his curiosity and innovative capacity seemed boundless. He loved to enter a new world from the laboratory side, acquiring theoretical underpinnings as they would help point the way to his vision. In this case and from the vantage point of 1960, he could see the future of electronics as the massive integration of extremely small components. He saw machines able to consist of 10^{11} parts and yet have overall dimensions of but 1 or 2 inches. This was at a time when integrated circuits were just being conceived in the laboratories of Silicon Valley, so Shoulders' components were to exist and operate entirely within a vacuum!

Shoulders' vision of micro-devices is documented in a lengthy article in the second volume of *Advances in Computers*, 1961.[N] That it appears in an account of the progress in computing is befitting of his concepts, even though semiconductors rather than vacuum devices would rapidly become the technology of choice for computing. His article describes triodes, tetrodes, and other active devices of micron size, both as standalones and as part of more integrated devices that could offer the functionality he knew computing needed. Figure 7-6 gives the schematics of one of these original devices, a triode. Shoulders saw such devices being "built layer by layer on two-dimensional surfaces." From such elementary components could come low-power memory and optical sensors.

Along with his description of devices are plenty of acknowledgments about the critical care that had to be given their design and manufacture and of the materials used. Mainly because of their miniature nature, the electron sources of Shoulders' devices were of the field emission type; that is, they required no heating.[O] Though not the first use projected, the notion of a flat display using field emission soon arose and became the subject of a patent issued in 1970, developed at SRI, and assigned to the sponsor, the U.S. Army.[13]

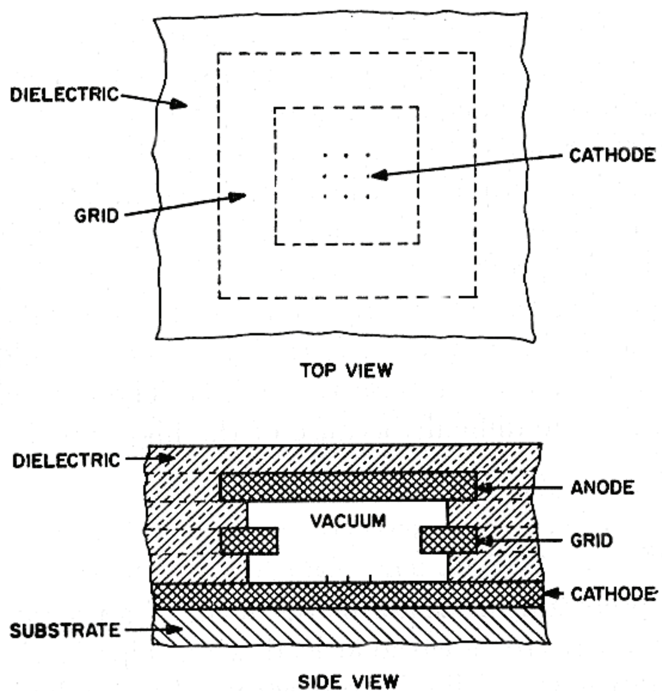

Figure 7-6. An early microscale triode depiction by SRI's Ken Shoulders.

[13] SRI, too, was putting its own money into getting the technology started. One indication was over $12,000 awarded in 1966 to explore the applications of these micron-sized devices.

Figure 7-7. Charles "Capp" Spindt, inventor of the cathode that carries his name.

In the beginning, however, the fabrication of the field emission devices was both inconsistent and without some of the desirable cathode characteristics such as high current density and long lifetimes. Forming the cathodes was also imprecise and slow, and sponsorship began to wane. It was at this point that Charles "Capp" Spindt (Figure 7-7), an early member of the same SRI group, developed a way to grow field-emission cathodes uniformly and monolithically.[P] This opened the way for the manufacture of cathode-grid base plates that achieved high currents, were controllable with modest operating voltages, and would work in a practical vacuum.

The SRI group also learned how to remove much of the contamination in the critical cathode tip region that was a by-product of the fabrication process. This purification and ultimately the introduction of resistive material in the cathodes helped stabilize the current across an array. With these insights and the onslaught of integrated circuit fabrication tools, the SRI approach was to become ever more powerful.

The configuration of today's field emission device looks something like those shown in Figure 7-8. The base plate is monolithically grown and the individual cathodes look very much like they did when Spindt first designed and built them in 1966. (The first regular two-dimensional array was created at SRI in 1973.) The individual cathodes appearing as black dots in Figure 7-9 are incredibly small, as can be seen in comparison to a human hair overlaid for perspective. The basic structure of part of an FED display is shown in Figure 7-10.[Q]

With an improved method in hand for making the small cathodes, SRI addressed other applications. Perhaps the first was as an electron source for a storage tube, a cathode-ray tube that would hold an image as long as desired. The field-emission array was capable of delivering high brightness to such a display. In another application in 1968, SRI performed some of the first electron-beam lithography to pattern a uniform, orthogonal array of these cathodes. Now, over 30 years later, these same

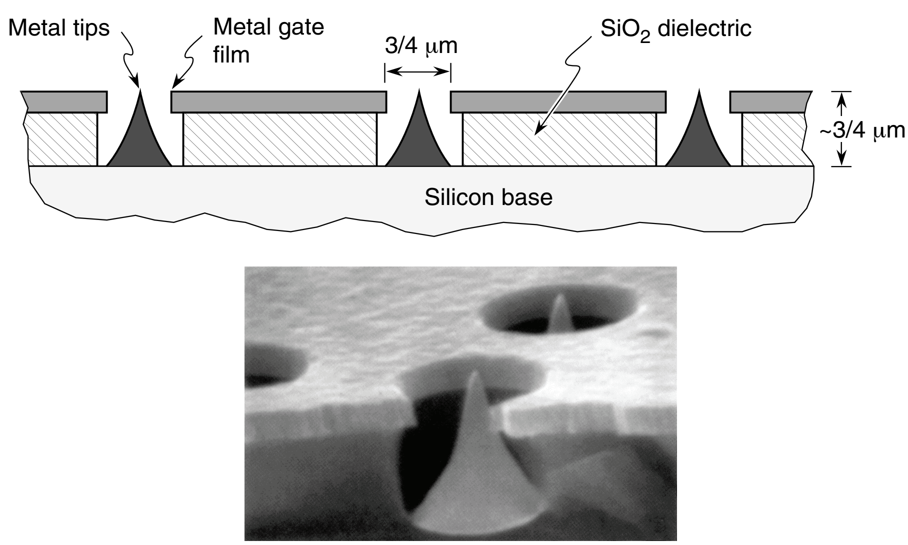

Figure 7-8. Configuration of individual field emission cathodes. (upper) cross-section of a Spindt cathode base, (lower) electron micrograph of a single cathode.

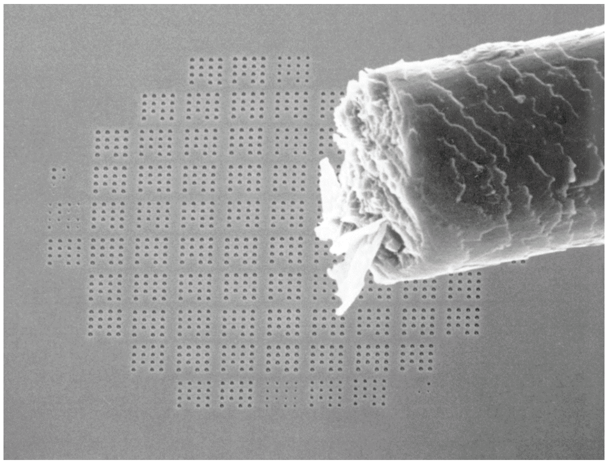

Figure 7-9. Overlay of human hair on an FED substrate

spectrometers. Of note is that a Spindt cathode array was used as an ionizer for a mass spectrometer on a Russian spacecraft that flew through the tail of Halley's comet in 1985 to analyze its gases. Over the years, SRI became the prolific source of the technology and sold hundreds of small field-emission packages for a wide variety of applications all over the world.

The ultimate promise for this technology, however, is still flat-panel displays. After the NASA satellite project had run its course in 1983, SRI began a relationship with a venture capital organization by the name of CommTech International (CI).[14] Under the arrangement, CI was to have a first-right-of-refusal on SRI's intellectual property. One of the properties they

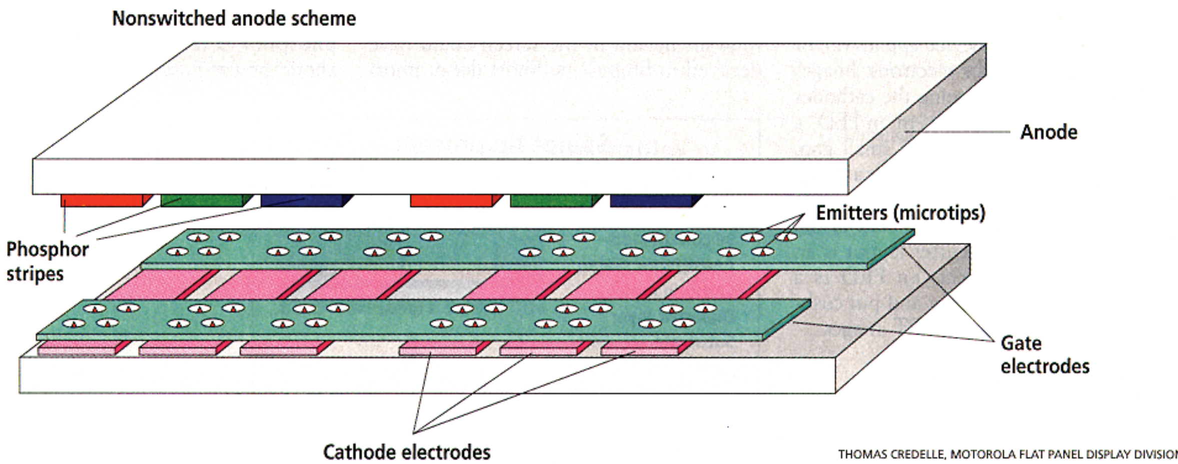

Figure 7-10. Diagram of a section of a color display

cathodes are being explored as sources for such lithography. They also offer advantages as electron sources for electron microscopes.

Satellites offered other potential uses for field emission devices. Because of their power efficiencies, the use of field-emission cathodes in microwave tubes would be ideal for space applications. To develop that use, NASA sponsored work on field-emission devices for about 13 years. Another, more recent space application was satellite space charge neutralization. Even in the vacuum of space, photo-ionization and solar wind particles can cause charge to accumulate on satellites that, if not limited, can discharge internally and disrupt sensitive electronics on board. The SRI cathode arrays are a power-efficient means to generate large neutralization currents. SRI also did a lot of work on adapting these high current arrays to other devices such as mass

singled out to help raise their funding pool was field emission technology. SRI had a good patent position in field emission and so under this new agreement SRI granted CI worldwide exclusive rights to its FED technology. This happened in early 1986, and within a year CI agreed to fund 18 months of continued development work. That effort was supplemented by a contract SRI had won with Boeing for the development of new, bright displays for the aircraft cockpit. As a show of good faith, SRI transferred the management of the contract to CI, but by about 1988 Boeing decided to withdraw its plans for an FED and CI, though still believing the technology promising, discontinued its direct support. In January 1990, CI formed Coloray Display Corporation (CDC) and transferred its SRI FED

[14] See Appendix D.

license to them. Over several years, CDC tried to get a sponsor to finish the development and manufacture FEDs. Alas, CDC repeatedly failed in its attempts at FED commercialization and because SRI had not included adequate due diligence conditions in the original license, SRI in effect became locked out of the development of FED technology. Some development of the general field-emission technology continued at SRI but in other, non-display uses. This SRI curtailment continued for over 10 years, during which time the world began to discover the promise of FEDs but also, on the critical competitive side, the continued manufacturing refinements of liquid crystal displays.

Figure 7-11. A prototype of a 14-inch field emission display made by Candescent of San Jose, CA (image received May 2000).

Seeing the inherent potential of FEDs, in the early 1990s the Defense Advanced Research Projects Agency (DARPA) began investing millions of dollars in a local FED start-up competitor called Silicon Video (see box on Candescent Technologies below). At SRI, after years of acrimonious discussions with a series of CI's failed and bankrupt licensees, SRI finally was freed enough to propose to DARPA for support in helping further FED technology. A 3-year contract was awarded in 1996 but SRI, at least to this point, has never reentered the commercialization field for FEDs. This inability to profit directly from innovation is one of the poignant downsides of intellectual property licensing.

In spite of this untimely curtailment, the SRI technology continued to have important effects on the field. Of the dozen or so manufacturers that have built some type of FED in the 1990s and later, only one has used a different cathode configuration and only two have used a different cathode material than the molybdenum of SRI's original units. The promise of this FED technology still remains. Liquid crystal, electroluminescent, and plasma panels don't have the combination of brightness, low power, viewing angle, operating temperature, and response time of FEDs—but they do have the market (see the box for why). The omnipresent liquid-crystal displays have continued to improve and with plasma are capturing the burgeoning flat television and computer monitor market.

SRI is not the only casualty in attempts to commercialize FEDs. Other organizations that have left the field are LETI of France, the first to build a monochrome display and whose commercial interests were transferred to PixTech, which in turn also acquired Micron's FED technology and business. In Asia, Futaba and Canon have abandoned the technology along with FED Corporation and Motorola in the United States. Only Silicon Video, now Candescent Technologies, maintained a continuous presence and, as of December 2002, that too seemed over (see box). But to show the progress Candescent made, note their May 2000 prototype of a 14-inch display shown in Figure 7-11. Sony now owns the Candescent technology and has yet to decide its fate. Both Sony and Samsung are exploring FEDs in the area of large, flat, HDTV-type displays with Sony having built a 20 in. version.[R] In spite of

By the late 1990s Candescent Technologies (originally Silicon Video) had emerged as the most promising supplier of field-emission displays. Founded in 1991, it raised over $600 million through initial Government (DARPA) sponsorship, participation by the venture capital community, and the development of well-chosen strong industrial partners such as HP, Sony, and Compaq. Much of this money went for building a pilot plant for large, 14-inch displays, but there have been ample challenges on the road to manufacture. The crucial weakness of many FED approaches was trying to maintain low (~100 V) anode voltage. This track required the very expensive and eventually dead-end development of low-voltage phosphors. Candescent opted for kilovolt anode voltages and was then able to use existing phosphors. But the spacers that held the glass plates apart under vacuum proved to be the next challenge. The spacers had to be invisible to the viewer and have minimal impact on the electron optics. Once that problem was solved, prototype 14-inch displays were made in small numbers. Curiously, the cathodes are still made of molybdenum just as those at SRI were 40 years ago.

The display has these advantages over back-lit LCDs: it is markedly brighter, has wider and more variable contrast levels, richer color saturation, the vastly better viewing angles of a regular CRT, superior video rates, a substantially wider range of operating temperature, draws about 25% less power at comparable brightness, and has the same or greater XVGA resolution. But the physical flexibility of LCDs is an important criterion for use in laptop computers, from the outset one of the large potential uses for FEDs. Sony now holds much of the intellectual property rights of Candescent, which has now ceased operation. So, only Sony and perhaps Samsung are perhaps still weighing the role of FEDs. After nearly three decades of development, a promising technology is languishing. Whether it will ever find a place in the burgeoning large flat television screen market remains uncertain.

A very similar technology is in the offing from a combine of Canon and Toshiba. That technology is called surface-conduction electron-emitter display (SED). Their production of flat-panel displays is scheduled for July 2007. Colors are said to be rich and vibrant, with no angle restrictions.

its superior characteristics,[15] FED technology, particularly in the laptop application, has suffered from the mass production of LCD displays and its future remains cloudy indeed. In a related front, Canon and Toshiba have recently announced their intention to build flat-panel television screens using a similar technology they call SED for surface-conduction electron-emitter display.[S]

One additional recognition of SRI's important contributions to FED technology came with the upsurge of interest in the mid- to late-1980s: the start of an annual worldwide conference on the field in 1988. It was called the International Vacuum Microelectronics Conference and, because of Spindt's role in the creation of the technology, he has had leadership roles in this gathering from the beginning. The conference still continues in 2004.[16]

[15] In addition to the characteristics above and those mentioned in the box, field-emission technology can offer currents of 2000 A/cm2 and even 100 μA for a single cathode, all while operating at temperatures from 4 to 1100 Kelvin. This makes them usable in tough environmental situations (such as in automobiles where LCDs have temperature problems) and for the brightest of displays such as large format, stadium displays, or just plain light sources.

[16] Major SRI players in the development of field-emission devices are Ken Shoulders, Capp Spindt, Chris Holland, Ivor Brodie, Paul Schwoebel, Bob Stowell, and Arne Rosengren.

Reliable Color Prints for the Movie Industry

It was a solid, well-engineered system and it resulted in an important award for SRI. In 1959 the Motion Picture Academy of Arts and Sciences awarded SRI and its sponsor, the Technicolor Motion Picture Corporation, their Scientific and Technical Award for solving a huge problem in the production of color film prints; that is, film that was distributed to the theaters around the world.

As happened more frequently in the early days of SRI than now, Technicolor came to SRI with a major problem: how could film negatives, taken by different cameras and exposed under wildly varying conditions by different cameramen in the making of a movie, be brought together to form one consistent, aesthetically pleasing print? It was early 1952, and achieving the consistency and quality of the distribution print was an intensely manual process. Highly skilled technicians would make repeated attempts to get an acceptable film print, controlling both the exposure and the chemical development process. It was called "timing the negatives" and it was critical to an acceptable product. This uncertain approach required several iterations and invoked unpredictable and therefore costly delays. Technicolor's technical director, Waddy Pohl, had the notion that a very carefully controlled television system, acting as an "analog computer" to mimic their photographic process, might work. However, Technicolor was unsure if the existing technology was adequate. Could SRI look at this problem and help them shorten the time to when a movie was generating income?

This was in the early days of color television and SRI had some perspective on this rapidly changing technology. Bill Evans, head of SRI's Television Laboratory, and Paul Bohlke, head of the Vacuum Tube Laboratory, believed that such a system could be built and that television-based equipment to measure the negative's color was, in fact, a good place to start. So, these labs created a high-quality closed-circuit television system that could accurately measure the color of the input camera negatives.[17] Then, converting the assembled camera negatives to the desired print required an accurate color transfer function that could be expressed in terms of the controlling variables: exposure time and the chemical development.

Getting that transfer right required being able to view a positive image on a cathode ray tube of high color fidelity. However, because such tubes were not available and because they needed to get each color component right, SRI actually broke out the component colors at the negative and retained that separation in three different primary color tubes (made in SRI's Tube Lab) that showed the corresponding color positive. The finished print had to be tailored for each segment of the negative film so that the final print would be consistent and reflect the feeling it was to portray.

By February 1953, about 10 months and $70,000 dollars later, Bill Evans, Werner Hopf, Bill Lynch, and Dick King had built a prototype print-producing system so accurate that it frequently produced an acceptable print the very first time. When the system was demonstrated to Messrs. Pohl and Howse of Technicolor, it worked so well that it was immediately put to use in producing films. This system gave Technicolor a big advantage because the number of color films was increasing. Two of the early films produced by the new timer were "The Naked Forest" and "Border River."

The industry so benefited from SRI's innovation that it received, along with its funding partner, Technicolor, the 1959 award shown in Figure 7-12.

[17] The color film technology was moving so fast during the project that, in the beginning, the Technicolor cameras produced three separate black and white negatives, one for each primary color. During the project, color negative film was introduced and the SRI negative timer system had to be changed accordingly.

Figure 7-12. Bill Evans, with his wife, Fleda, receiving the Academy's award for scientific and technical achievement from SRI President Finley Carter.

Encoding Color onto a Monochrome Video Camera

Producing a color image accurately requires an independent, accurately registered image in each of a set of three primary colors. In the early days of video cameras, and even today in the best of them, this requirement meant splitting the incoming image into three identical images, each to pass through its own color filter to a light-sensitive detector. Such cameras were, and still are, very expensive. Since each of the separate color detectors can then have the highest manufacturable resolution, the overall system has the highest possible resolution. Such systems suffer, however, from having to keep the registration between the three detectors near perfect. Needed, then, was a single tube color camera and, moreover, just *one detector* that would be used for all colors. This single detector would provide two important advantages: inherent registration of the three separate color images and a much lower cost to manufacture.

In 1960 Al Macovski came to SRI and to Bill Evans's Television Laboratory.[18] Macovski had been at RCA Laboratories and had become one of the most prolific inventors there in the development of color television. Sometime after arriving at SRI, Macovski became interested in how to encode color images on black and white

[18] As a measure of the stature of these men in their field, Macovski and Evans, with SRI's Phil Rice, would come to be awarded the IEEE Valdimir Zworykin Prize for contribution to television.

film using three spatially oriented gratings in a camera. While the techniques he developed with Phil Rice and Hugh Frobach worked, they didn't work well enough, given the limitations on the image projectors of the day. But his approach would eventually work as Macovski came to apply it to building a revolutionary single-tube, single-gun television camera.[19]

By the spring of 1966, Macovski was ready to embark on a project for RCA to simplify the color video camera. RCA's cameras at that time were multitube or multiple-sensor and cost about $60,000. RCA was looking for a new market enabled by a cheaper camera.[T] The project was client private and was expected to run for about 10 months at a cost of about $140,000. It actually wound up lasting more than 3 years.[U]

The single-gun technology SRI developed was based largely on the fact that the human vision system is dominated by luminance, the essentially gray-scale detail of an image. Because of the color sensitivities of the eye, separated color information requires much less transmission bandwidth than luminance.[20] Luminance, however, can be computed from the contributions of three primary colors at the same pinpoint location. The eye's varying sensitivity to different colors is also evidenced in the working definition of luminance:[21]

Luminance =
0.51 Red + 1.0 Green + 0.19 Blue

So, Macovski was looking for a way to exploit that particular aspect of how we perceive color. Needed were ways to eliminate not only a camera's multiple color tubes, with their associated individual power and registration problems, but even multiple electron guns and scanned detector arrays within a complex single tube. Could one design a single-tube, single-array system, resembling closely a monochrome camera, that would record a full color image?

Happily, the answer was yes and Macovski chose the following path: to place between the input lenses and the lone two-dimensional detector array[22] a spatial color filter or grating that would produce in the output scan of the detector array information appropriate to each independent color. Because color represents a fraction of the total video bandwidth needed, two orthogonal channels of color, in this case the two less-sensitive red and blue, were chosen to be separated from the unfiltered signal. Each of the red and blue gratings was rotated from the vertical a number of degrees that left the two color-modulated signals outside the passband of the luminance signal and also prevented them from interfering significantly with each other. Also, since each of the gratings consisted of lines alternately transparent and opaque to the color being sensed, they each saw a 50% loss in amplitude. However, these gratings, appropriately oriented, approximated the above luminance equation.[23]

Filtered Luminance =
0.5 Red + 1.0 Green + 0.5 Blue

The spatial frequency of the gratings, defined by the spacing of the grating lines, was made nearly as high as the camera lens could resolve. That choice, together with the grating lines being angled away from the vertical, had the effect of amplitude modulating the reds and blues on frequency subcarriers of a composite signal. The two subcarriers, after some further processing, plus the luminance signal were then sent to the receiver where the image was reconstructed. This separation of signals used, in principle, the same approach followed when black-and-white-compatible color television was first developed.

The SRI approach led to several patents that became valuable in later litigation with a Japanese company that, Macovski noted, was infringing on them. There was an out-of-court settlement, and eventually the know-how was assigned to RCA. The insight and the intellectual property gave RCA a commanding market position using the single-tube color camera. The cost of the new camera turned out to be less than a tenth of the earlier camera.

[19] SRI's Earle Jones says that during 1964-1965, concepts in building a single-gun color camera were explored at SRI using Institute funds. I didn't find any in IR&D reports around that time. The only film work in 1965 was by Phil Rice with no mention of collaborators.
[20] This characteristic was also used to build earlier black-and-white-compatible color television.
[21] These ratios of primary colors are those that best deliver a white image when a white image is scanned by a three-color camera.
[22] Then an electron-beam scanned the plane on which a charge distribution faithful to the image existed.
[23] The differences could be easily removed in later signal processing.

Although the single-gun color camera was innovative, it did not survive the progress in semiconductor electronics. Solid state, light-sensitive devices called CCDs, and more recently, CMOS arrays have replaced the electron beam tube cameras in almost all but studio settings. CCD-based cameras may have one or three detector arrays, depending on intended use. In single CCD cameras, the color filters are built directly into the individual elements of the CCD. There are a few different spatial arrangements of the red, green, and blue light sensitive cells, again with the green outnumbering the other two. Each set of colored cells is then scanned individually to form the output for that specific color. Now even that technology is being threatened by tri-color silicon detectors capable of resolving each color within the same pixel. In any case, before these advances were introduced, the single-tube color camera was a breakthrough for RCA, and RCA became one of the world's largest suppliers of television cameras.

Endnotes

[A] Earle Jones, personal communication, November 12, 1999. The technology SRI proposed for nonimpact electronic duplication would ultimately require special dielectric-coated paper and was thus discontinued. The approach was made jointly by the tube lab under Phil Rice and the television lab led by Bill Evans to A.B. Dick's VP of R&D, Allen Roshkind.

[B] See the Videojet Technologies, Inc., web page at www.videojet.com/pro_history.html.

[C] Conversation with Earle Jones on July 30, 1999.

[D] Richard G. Sweet, *High-Frequency Oscillography with Electrostatically Deflected Inkjets*, Stanford Electronics Laboratories, SEL-64-004, March 1964. A patent was submitted in 1963 and awarded in 1971.

[E] Conversation with Laboratory Director Fred Kamphoefner in the spring of 1999.

[F] From an interview of Jim Ivy, President of Ricoh (USA) Products Group, on September 5, 2000, by the *Digital Times*. "Ricoh…created the first digital fax machine, which was a Ricoh invention."

[G] Interview of Jim Ivy, President of Ricoh (USA) Products Group on September 5, 2000, by the *Digital Times*.

[H] Telephone conversation with SRI's Ron Swidler, May 2002.

[I] Email from Dan Morris, the SRI person then responsible for commercializing the intellectual property defining the inks, July 25, 2002.

[J] Email from Dan Morris, July 25, 2002.

[K] Phillip Rice and Richard F. Dubbe, Development of the First Optical Videodisc, *Journal of SMPTE*, 91(3), 277-284, March 1982.

[L] Philip Rice, Albert Macovski, Earle D. Jones, Hugh Frohbach, R. Wayne Crews, and A. W. Noon, An Experimental Television Recording and Playback System Using Photographic Discs, *Journal of the SMPTE*, 79(11), 997-1002, November 1970.

[M] *Asahi Evening News* (newspaper), Tokyo, October 16, 1979

[N] K. R. Shoulders, Microelectronics using electron beam activated machining techniques, *Advances in Computing*, F. L. Alt, Ed., 2, 135-293, 1961.

[O] Ibid.

[P] A retrospective view of the field and of Spindt's role in it is given in a review article: John A. Nation et al., Advances in Cold Cathode Physics and Technology, *Proceedings of the IEEE*, 87(5), 865-889, May 1999.

[Q] From the *IEEE Spectrum*, April 1998.

[R] Capp Spindt, personal communications, June 24, 2004.

[S] Canon and Toshiba Go Their Own Way in Flat Panels, *IEEE Spectrum*, page 24, November 2004.

[T] *SRI Intercom*, No. 164, August 11, 1971.

[U] Albert Macovski, *Encoded Color Systems*, SRI Final Report on Project 5941 for RCA Laboratories, October 1969.