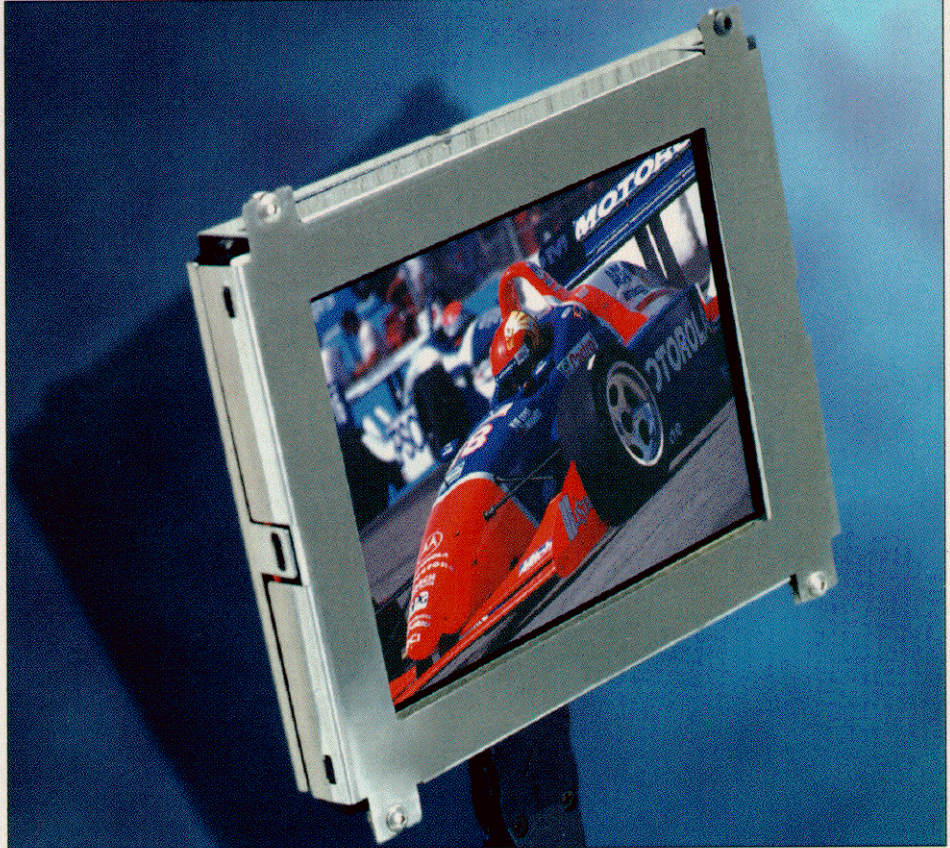


[1] The prototype of a full color field emission display capable of running video in real time in a 1/4-VGA mode was recently demonstrated by the Flat Panel Display Division of Motorola Inc. A high anode voltage of 5000 V yields a luminance in excess of 300 cd/m<sup>2</sup> and the viewing angle is 160 degrees—both improvements on liquid-crystal displays. The flat-panel prototype is 14 cm on the diagonal and 3.5 mm thick; pixel pitch is 0.325  $\mu$ m.



MOTOROLA INC.

# FED UP WITH FAT TUBES

Since the dawn of television, engineers have dreamed of slim, flat displays that could deliver as good a picture as the bulky cathode-ray tube. Today the properties sought from flat-panel displays include a full range of colors and grays, high brightness and efficiency, wide viewing angle, and fast refresh rates. Also, the displays should be thin, lightweight and consume minimal power.

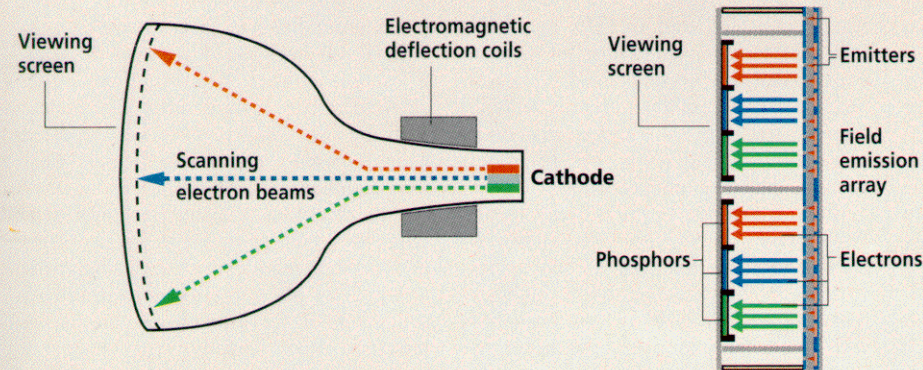
For some time, the liquid-crystal display (LCD) has ranked highest in this market. In fact, the active-matrix LCD is the benchmark for flat panel performance ["The flowering of flat displays," *Spectrum*, May 1997, pp. 40–49]. Yet it has shortcomings in critical performance areas: restricted temperature range, limited viewing angle, and sluggish response to fast-motion video. Its flat panel competitors are electroluminescent displays and plasma display panels [Table 1]. Now, however, field emission display

technology could be coming into its own for commercial low-power, flat-panel multimedia purposes, as well as for automotive and avionic applications, where brightness is critical.

Field emission displays (FEDs) have much in common with cathode-ray tubes (CRTs). In both, cathodes launch electrons in a vacuum toward a phosphor coating, which then lights up with video images [see "The tip of the field emission iceberg," p. 46]. But FEDs have more room to improve and over the past several years have advanced on more than one front. Today, the FED is as bright as a CRT, and as flat and thin as an LCD—about 10 mm, though prototypes of 3.5 mm are being demonstrated [Fig. 1]. In brief, it combines the best features of a CRT with the thinness and linearity of a flat panel.

To illustrate: FEDs do not use thermionic cathodes like CRTs, but instead depend on field emission from an array of small micro-

BABU R. CHALAMALA &  
YI WEI, *Motorola Inc.*,  
&  
BRUCE E. GNADE  
*Defense Advanced  
Research Projects Agency*

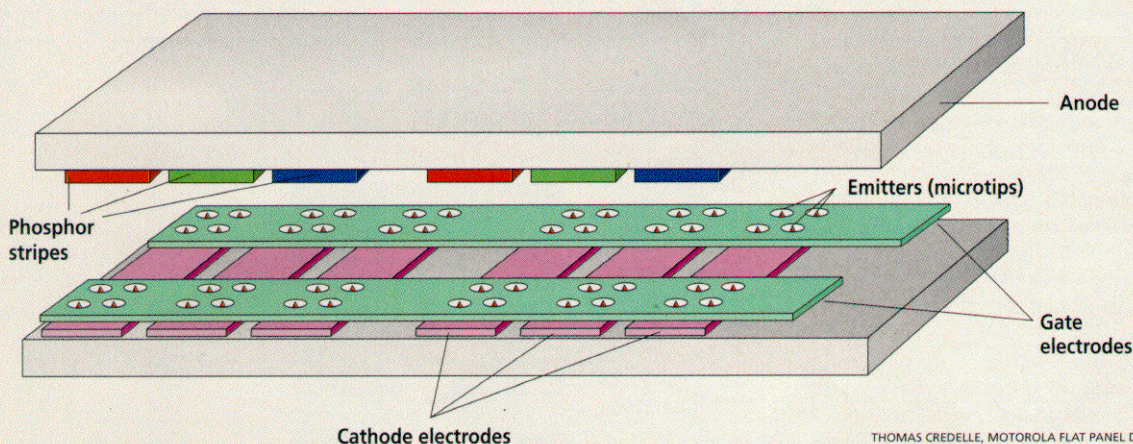


[2] Field emission displays (FEDs) and cathode-ray tubes (CRTs) are both vacuum tubes that create images by propelling electrons to phosphor-coated screens.

In this CRT [left], electrons from a trio of hot cathodes are scanned across the screen by deflection coils.

In the FED [below], electrons from an array of millions of microscopic field emitters are propelled directly to the screen. As no beam deflection is needed, the distance between the cathodes and the screen need be only a millimeter or so.

Nonswitched anode scheme



THOMAS CREDELLE, MOTOROLA FLAT PANEL DISPLAY DIVISION

[3] In the nonswitched anode scheme [above], addressing is managed by one column (gate) electrode per color stripe. That is, the microtip emitters are dedicated to specific red, green, or blue phosphor stripes.

In the switched-anode scheme for an FED, all of the phosphor stripes of a given color are electrically connected to activate simultaneously; electrons from the emitters are drawn to whichever stripe is charged.

tips. Because of the shape of the microtip and its proximity to the gate electrode, very high fields are present at the tip, which allows field emission of electrons to occur. A large number of these tips can be built simultaneously, many per pixel. Because the tips are so near the screen, there is no need for beam steering, and hence no problems with convergence or alignment. The electrons strike the phosphor-coated screen and light is emitted much as in a CRT.

In short, the similarities to the CRT are reliance on vacuum, electron optics, and cathodoluminescence. What gives FEDs an edge in the full-color display market is their much lower operating voltages: most FEDs operate at 300 to 5000 V, as opposed to the 15 000 to 30 000 V used by CRTs. Also, the FED's myriad tiny electron sources make very much thinner devices possible.

### Why FEDs?

Ever since 1985, when the first FED was demonstrated by a group led by Robert Meyer at the Laboratoire d'Electronique, de Technologie et d'Instrumentation (LETI) in Grenoble, France, its appeal has been growing. The list of companies that believe the new technology will better serve the demands of consumer displays has lengthened steadily [see "The who's who of FEDs," p. 49].

The visual and video attributes of FEDs have many uses—particularly in consumer displays where they have distinct advantages over the LCD, namely greater brightness, wider viewing angle, low power consumption, and full motion video capability. Investors in FED technology believe the displays will compete directly with LCDs as early as year 2000 for use in computer monitors, television sets, electronic instruments, automotive and avionics applications, and camcorders.

### The meaning of the term

While the FED emits electrons in a vacuum like a CRT [see "The vital vacuum," p. 50], it is unlike the CRT with respect to the configuration and number of its electron emitters. The FED relies on an array of microcathodes, fabricated from silicon, molybdenum, palladium oxide, diamond-like carbon, or a host of other materials. A CRT, on the other hand, relies on just one to three electron gun structures.

The CRT's cathode is heated to produce electrons, which are focused by the gun and accelerated toward an anode plate even as electromagnetic deflection coils are scanning the electron beam across a phosphor-coated faceplate. To have enough room to scan the beam, the deflection coils and faceplate must be quite far apart. The larger the CRT viewing area, the greater the depth

## components

Field emission

displays yield

bright pictures in

trim flat-panel

packages

(anode-to-cathode distance) required to scan the beam.

In an FED, in contrast, electrons are produced by cold-cathode emission [see "The metal-vacuum work function," pp. 50-51]. Several electron emitters or cathodes are associated with every pixel, so there is no single beam. Electrons are ejected from a cathode when a bias of less than 100 V is applied between the emitter and a control electrode (gate). These field-extracted electrons are then accelerated toward a phosphor-coated faceplate biased between 300 and 10 000 V. In a CRT, this potential is between 15 and 30 kV [Fig. 2].

Unlike the CRT, a field emission triode (cathode-gate-anode) device applies no, or minimal, focusing to the electrons. Images are created simply by turning the cathodes on or off in sequence. Thus, in an FED, a small spot size requires just a small gap, less than 1 mm, between the cathode array and the anode faceplate. Hence the flatness of the FED versus the bulk of the CRT. Also, since the emitter layout is an addressable x-y matrix, an FED is a stranger to the nonlinearity and pin cushion effects associated with CRT images.

### How FEDs light up

The picture on the display side of a CRT or FED is created when electrons systematically bombard the phosphors on the faceplate that generate light. The light results from the excitation and subsequent relaxation of the molecules giving off light (also known as the active species) in this inorganic material.

Cathodoluminescent phosphors have been used in CRTs for decades. Most have been tailored for use with electron beams in the high energy range of 10-30 kV—well above the usual acceleration voltage of 300-10 000 V in a field emission display. To prevent high voltage breakdown, an FED's acceleration voltage is limited to about 10 000 V by the size of the electric field that can be sustained in the narrow gap between anode and cathode. Phosphors, though, get more efficient the greater the electron energy. So to obtain a brighter display, the anode voltage is raised.

Other aspects of phosphor efficiency involve color and current density. Phosphors are chosen for good chromaticity coordinates, that is, their ability to give off light in the color ranges to which the human eye is most sensitive. Also, typical phosphors glow even brighter as the electron current density grows—but only up to a point, beyond which their efficiency at generating light declines. This effect is called current saturation. But, increasing the anode voltage generally increases the phosphor efficiency, so that the brightness desired is achieved with a lower current density.

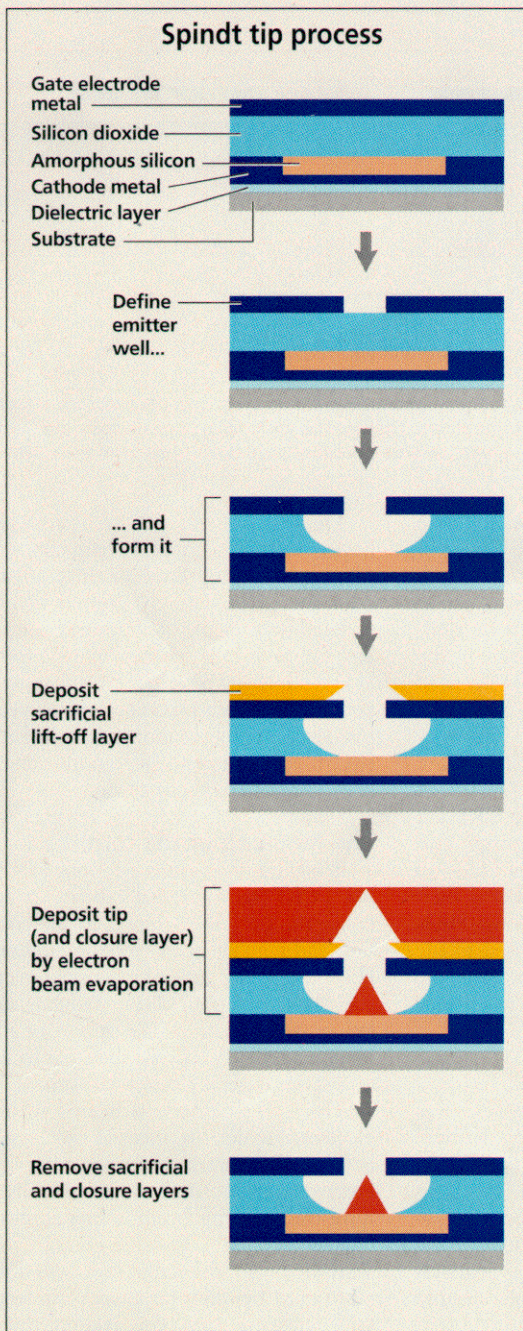
Effective electron current density is another difference between the light gen-

eration in a CRT and an FED. In a CRT, each pixel is addressed in turn, for no more than several nanoseconds, as the electron beam sweeps across the screen. In an FED, an entire row of pixels is addressed at once, in parallel. The pixel is "on" for much longer, a matter of microseconds.

This difference in dwell time means FEDs need different phosphors than do CRTs. Phosphors that decay rapidly are less sensitive to the saturation due to high current densities. CRTs depend on phosphors with a long decay to "damp" the flicker that would be caused by scanning the image a pixel at a time. If the decay is too short, by the time the beam reaches the bottom row, rows at the top of the screen could have decayed in brightness. Short-decay phos-

phors enter the picture (as it were) only when dwell times last longer, as in the FED. Some phosphors, notably those with allowed radiative transitions, dim in less than the FED dwell time. In fact, repeated excitations can occur during the row selection, augmenting the light output.

The drawback is faster phosphor degradation, which gives rise to the problems of phosphor maintenance and differential aging. The phenomenon is normally a reflection of the phosphor's cumulative electron dose. Low-voltage FEDs use higher current density to offset the lower excitation voltage. With a lower anode voltage, all other things being equal, the phosphor is less efficient, more of the anode power is supplied by the electron



[4] The Spindt semiconductor process for making field-emitter tips starts [top] with an initial dielectric layer deposited on a glass substrate to serve as a diffusion barrier and passivation layer. A metal film (which serves as cathode), for electrical contact to the emitter tips, is deposited, then patterned and etched to define pixel geometries.

Then follow a doped amorphous silicon layer (to act as a current-limiting resistor) and a second dielectric layer of silicon dioxide, for example (to isolate the gate from the emitter tips).

A second metal layer (the gate electrode) is deposited in which [next two diagrams] the gate pattern and emitter holes are patterned on and etched in. Next, a thin, sacrificial layer of metal is evaporated on.

The emitter material is then evaporated on by an electron beam, forming a cone in the emitter well and gradually closing the hole. Finally, the sacrificial layer is etched away, lifting off the excess emitter material.

current, and so the phosphor degrades faster. The solution is low-voltage phosphors that are more efficient.

One highly efficient low-voltage phosphor is blue-green zinc-rich zinc-oxide (ZnO:Zn), familiar from the vacuum fluorescent display. However, its chromaticity is unacceptable for color displays. As of now, in fact, efficient low-voltage phosphors for red-green-blue [RGB] displays do not exist, though the phosphors are available for bright RGB FEDs with operating voltages over 1000 V.

Two companies use ZnO:Zn in monochrome displays that they are now supplying as samples. Made by Futaba Corp., Mobar City, Chiba Prefecture, Japan, and PixTech Inc., Rousset, France, the 1/4-

VGA displays operate with an anode voltage in the range of 150–300 V and utilize a pixel pitch of 360  $\mu\text{m}$ . The Futaba devices have a reported luminance of 300  $\text{cd}/\text{m}^2$ , with a contrast ratio of 40:1, which may be compared with the 200- $\text{cd}/\text{m}^2$  brightness and a contrast ratio exceeding 100:1 of typical LCD devices. Both PixTech and Futaba have demonstrated monochrome FED displays with a life of over 10 000 hours.

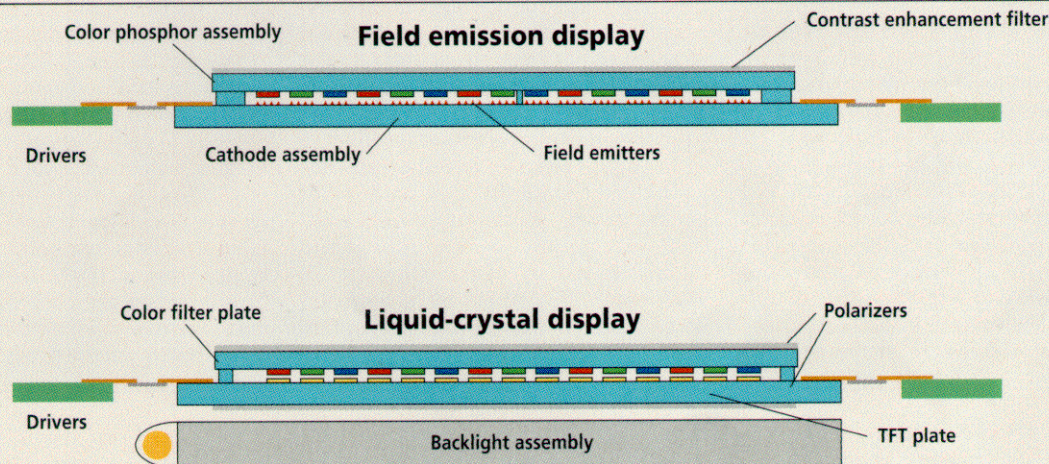
### To switch or not to switch

The choice of anode voltage in an FED influences the choice of anode and cathode addressing schemes used to obtain full color. For full-color FEDs, two addressing schemes have been developed: switched anode and nonswitched anode. The first

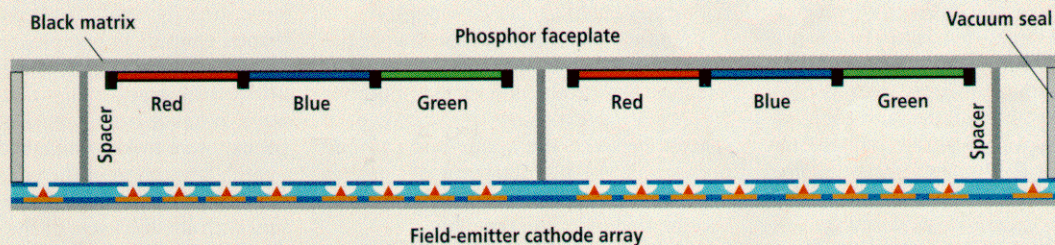
scheme has several variations, but only the most general case is described here.

In the switched-anode scheme, the phosphors are defined as stripes, with all the stripes of a given color electrically connected so that all phosphors of a given color will activate simultaneously. The use of this switched-anode, field-sequential (rather than frame-sequential) scheme simplifies the manufacture of the FED.

In the scheme, three fields comprise one frame. The switched anode in effect triples the number of field-emitter tips per pixel because colors do not need emitters dedicated individually to R or G or B. The scheme also relaxes the anode-cathode alignment needed since specific emitters are not aligned to a specific color. Color purity



### Field emission package outline



[5] Field emission displays are similar to liquid-crystal displays, but lack the backlight and

polarizers. Spacers are used in the evacuated FED package so that the glass anode and cath-

ode plates do not bow or break under a differential pressure of at least one atmosphere.

## Defining terms

**Cathodoluminescence:** emission of light from an inorganic substance as a result of electron beam bombardment.

**Electrophoretic deposition:** electroplating of phosphor powder particles from solution phase onto phosphor screens.

**Fermi level:** energy level of the free electrons in a metal.

**Field emission:** emission of electrons from a surface caused directly by high-voltage gradients at that surface.

**Field emission display:** a thin flat-panel display incorporating a field emission cathode array and phosphors in a vacuum

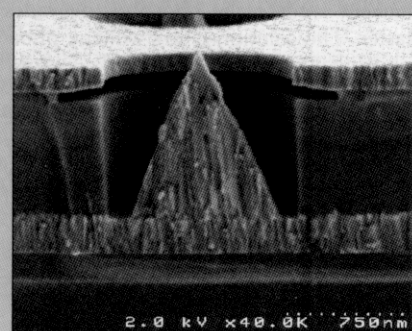
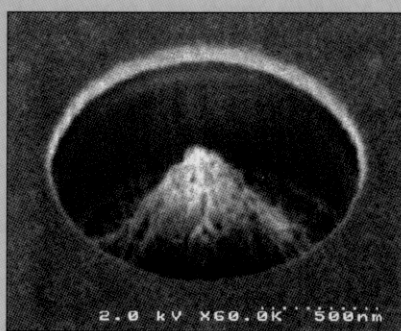
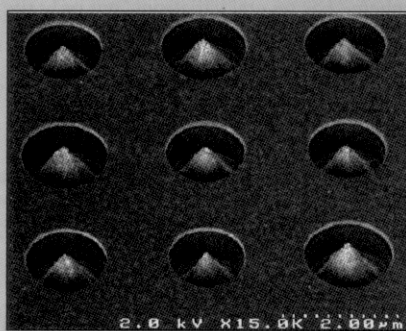
package; light is produced by the phosphors when excited by the field-emitted electrons.

**Inelastic scattering:** an electron scattering process in which the energy of the electrons is not conserved.

**Luminous efficiency:** ratio of the total amount of light produced to the electrical energy put into the system.

**Spindt cathode:** a microelectronic electron-emitter constructed by the Spindt deposition process.

**Vacuum microelectronics:** electron emission devices fabricated using microelectronic processing techniques.



## The tip of the field emission iceberg

Vacuum microelectronics refers to the fabrication of electron-emission devices by means of microelectronic processing techniques. Its study began in 1961, at the Stanford Research Institute, Menlo Park, Calif. (later renamed SRI International), when Ken Shoulders proposed electron-beam micro-devices based on field emission of electrons.

The first real devices were built in 1968, when Charles Spindt worked out how to apply established semiconductor processing methods, such as photolithography, thin film deposition, and reactive ion etching, to building self-aligned tip and gate structures. These cone-like structures are at the heart of

field-emission cathode array technology. By reducing the space between the tip of the cone (the electron emitter) and the gate electrode (or surrounding extraction electrode), the electric field required to get electrons emitted is minimized. This thin-film deposition process is now called Spindt tip deposition. The structures thus prepared are referred to as Spindt tips or arrays [see photos].

The first significant work on another emitter variety—silicon-based field emitters—was done by Henry Gray at the Naval Research Laboratories, in Washington, D.C. Arrays of cone-shaped silicon-based emitters can be variously fabricated, by orientation-dependent etching

or by oxidation and chemical mechanical polishing.

One problem with simple Spindt-type cathode structures is that they can be destroyed by uncontrolled emission current. The threat arises when a few active emission sites on the tip produce most of the current. Extremely high current density can cause localized heating, leading to catastrophic device failures and gate-to-cathode electrical shorting. To improve matters, Robert Meyer and Robert Baptist at LETI in Grenoble, France, introduced a resistive layer under the emitter cones. The layer acts like a load resistor or a current limiter. Granted, this current-limiting structure increases the gate voltage and reduces the maximum emission current, but it also boosts reliability, as well as the spa-

is achieved because electrons are drawn only to the energized pixel columns.

The drawback to the switched-anode scheme is the limit placed on the anode voltage by the breakdown voltage between adjacent phosphor stripes (typically less than 1000 V). The data rate is triple the frame-sequential rate because three fields are displayed per frame. And a custom video controller and extra video memory are required since the color data is presented in sequence. Field-sequential operation can produce artifacts such as color break-up unless high frame rates are used.

The nonswitched anode, conversely, can operate at the higher voltage required for very bright and very efficient displays [Fig. 3]. In fact, companies pursuing high-voltage FEDs use only this mode of operation. In these FEDs, addressing is managed by one column or gate electrode per color stripe. The nonswitched-addressing scheme also accommodates conventional video controllers and lower frame rates. On the other hand, three times as many column drivers as before are needed, and each subpixel is matched to one-third as many emitters; focusing may be required at high voltage, and anode-to-cathode alignment is critical for color purity.

### Marrying chip and tube practices

FEDs integrate the new and the old in electronics. Whereas their cathode emitter

arrays and phosphor-coated anodes are fabricated microelectronically, the cathode and anode plates are integrated with the aid of glass-to-glass vacuum packaging, much as in electron-tube manufacture. In effect, FED systems engineering requires expertise in both semiconductor processing and vacuum tube packaging plus methods of maintaining a high vacuum and maintaining high voltage across small vacuum gaps.

Standard manufacture starts with the microfabrication of the FED's emitter structure and production of the phosphor anode plate. Next comes the placement of spacers between the anode and cathode plates and the introduction of vacuum gettering material. The culmination is the vacuum sealing of the assembly.

For color displays employing the nonswitched anode, every subpixel element must be accurately aligned with its electron emitter partner to produce saturated colors; and the alignment of the two pieces of glass must not be upset by the sealing method used. As in LCDs, the device drivers and the addressing electronics are placed along the edges of the package.

### Fabricating the emitter array...

Out of several approaches to manufacturing field emitter arrays, the Spindt tip process is the best established. Molybdenum-based, it is used by such FED developers as Motorola, PixTech, Raytheon,

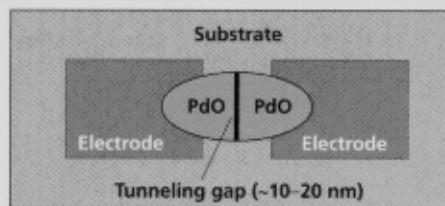
Futaba, FED Corp., Samsung, and Candescant Technologies. Micron Display Technology uses a silicon-based emitter technology, in which a proprietary chemical mechanical polishing (CMP) process is key to manufacturing the emitter arrays.

The Spindt tip process is a self-aligned, self-limiting process for producing millions of submicrometer structures over a large area. It "seats" well-defined cone-shaped emitters in micrometer-sized wells [Fig. 4]. The emitter holes may be defined photolithographically in a variety of ways, ranging from semiconductor stepper exposure to low-voltage ion tracking.

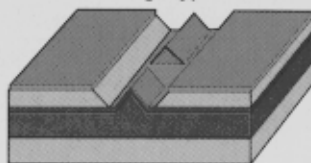
Still, fabrication of the emitter cone is a tough proposition. Its shape and height vary with the thickness of the silicon dioxide dielectric, the thickness and composition of the gate metal, the diameter and shape of the emitter hole, the composition of the emitter material, and the temperature of the substrate during the emitter deposition—over half a dozen factors in all. Silicon-based emitter fabrication differs from the Spindt process in that in most cases the silicon emitters are deposited and etched before the gate is formed.

Because of the fabrication complexities and cost, research continues into planar emitters, such as diamond-like carbon films, and surface-emitting structures, such as the Canon surface conduction emitter (SCE). Work is also in progress on

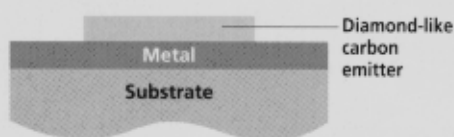
Surface-conduction edge emitter



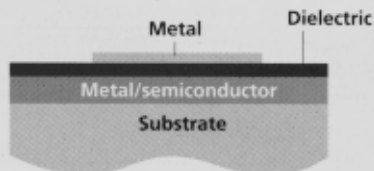
Wedge type emitter



Planar emitter with DLC emitter



Metal insulator semiconductor emitter



At the positive edge of the gap, some of the electrons scatter inelastically. These emitted, or scattered, electrons can then be attracted to a positive phosphor-coated anode.

Canon recently demonstrated a 25-cm-diagonal full-color prototype display based on this technology. Millions of these "gap emitters" were placed in a vacuum structure less than 10 mm thick. The SCE structure can be created with simple printing techniques, like ink jet deposition, with minimal use of expensive semiconductor processing.

Other device configurations include edge emitters, diode emitter configurations using diamond-like carbon-type materials, and metal/semiconductor-insulator-metal tunneling (MIS and MIM) devices [left above]. The goal here is to develop emitter structures that are inexpensive to manufacture, as well as capable of stable, long-term emission. Driving manufacturing costs down is crucial for FED technology's success in the commercial market place.

—B.R.C., Y.W., & B.E.G.

tial and temporal uniformity of the current. The same effect can be obtained by making the emitter structure resistive.

While the two most popular approaches to field-emission array fabrication remain the Spindt tip deposition process and silicon-based cone emitters, a number of groups are exploring other materials and geometries. One field emitter from Canon Inc., Tokyo, is based on

inelastic scattering of electrons at an electrode edge. Known as the surface conduction emitter (SCE), it starts with the creation of cracks in a thin film of palladium oxide containing nanocrystalline particles [schematic, top left]. Electric current is passed through 5–10-nm-thick film, leaving behind a single 10–20-nm-wide crack. When a potential is applied across the tiny gap, electrons can tunnel across.

## 1. Characteristics of some flat-panel displays

Characteristic	Thin-film transistor liquid-crystal display	Electroluminescent display	Plasma display panels	Field emission display
Emission type (if applicable)	—	Thin-film phosphor	Photoluminescence	Low- and high-voltage phosphors
Brightness, cd/m <sup>2</sup>	200	100	300	150 (low-V) >600 (high-V)
Viewing angle, degrees	±40	±80	±80	±80
Emission efficiency, lm/W	3-4	0.5 - 2	1.0	10-15
Response time	30-60 ms	<1 ms	1-10 ms	10-30 μs
Contrast ratio (intrinsic)	>100:1	50:1	100:1	100:1
Number of colors	16 million	16	16 million	16 million
Number of pixels	1024x768	640x480	852x480	640x480
Resolution, μm pitch	0.31	0.31	1.08	0.31
Power consumption, W (size)	3 (26.4 cm)	6 (26.4 cm)	200 (106.7 cm)	2 (26.4 cm)
Maximum screen size (diagonal), cm	55.8	26.4	106.6	26.4
Panel thickness, mm	8	10	75 to 100	10
Operating temperature range, °C	0-50	-5 - +85	-20 - +55	-5 - +85

thin-film edge emitters that use more conventional semiconductor processing techniques to produce emitter arrays.

### ...and the anode

The two principal anode-addressing schemes for color FEDs are fabricated differently. For the switched-anode configuration, the transparent conductor on the anode is patterned and etched, with each stripe of the same color electrically connected; and since the conductor is patterned, the phosphor can be electrophoretically deposited. (In electrophoresis, electrically charged particles are made to migrate toward electrodes of opposite charge by an applied electrical field.) For the non-switched-anode scheme, the RGB phosphors are patterned photolithographically.

CRT phosphor screening techniques include dusting, slurry, and centrifugation, each of which also requires photolithography and phosphor removal to produce an RGB pixelated screen. Here the flat surface of the FED anode makes photolithography easier than does the curved glass of a CRT screen. For operation above 4 kV, the anode screen of the FED is often aluminized, which reduces charge buildup and improves the phosphor's optical efficiency and maintenance. In aluminization, the phosphor layers are planarized a film of lacquer, dried, and aluminized. Lastly, the lacquer is removed by baking the anode.

### Packaging a void

The current FED package is like an LCD design without a backlight [Fig. 5]. As yet, no one way exists for packaging an FED. Two methods of sealing the required vacuum are being pursued: tubulation seals and full integral seals. In the former, the package is assembled with a small protruding tube through which the gases inside are evacuated. Then the package is completely sealed and the tube pinched off. The latter approach refers to complete package assembly in a high-vacuum environment. In either approach, spacer, vacuum, and sealing issues remain to be resolved.

To keep package weight down and to extend the viewing angle, flat-panel displays for FEDs are built with thin flat glass, between 0.7 mm and 1.1 mm thick. The glass anode and cathode plates must withstand a differential pressure of at least one atmosphere. Under this force, thin flat glass wider than 2 cm on the diagonal will bow, wrecking the display's optical uniformity, if it does not break altogether. So ceramic spacers, 50–75  $\mu\text{m}$  wide, are placed periodically between the plates to prevent collapse. Many spacer approaches are being pursued, ranging from spheres for low-voltage FEDs to high-aspect-ratio rods and strips for high-voltage displays.

In an FED, furthermore, spacers must withstand electric fields as high as 5 V/ $\mu\text{m}$ ,

## 2. Early field emission displays compared

Samples	Emitter type	Material	Display diagonal, cm	Voltage, V
Motorola Inc., Flat Panel Display Division, Tempe, Ariz. www.mot.com 602-755-5500	Spindt	Mo	13.2	5000
Futaba Corp., Mobara City, Chiba prefecture, Japan (81+43) 296 5111	Spindt	Mo	14.4	400
Micron Display, Boise, Idaho www.micron.com/mdt/ 208-333-7500	Spindt	Si	1.4	N.A.
PixTech Inc., Rousset, France, & Santa Clara, Calif. www.pixtech.com 408-986-8868	Spindt	Mo	13.2	300
Prototypes				
Canon Inc., Tokyo www.canon.com (81+3) 3758 2111	Planar	Palladium oxide	26.1	6000
Candescent Technologies Corp., San Jose, Calif. www.candescent.com 408-229-6150	Spindt	Mo	11.2	N.A.
FED Corp., Hopewell Junction, N.Y. 914-892-1900	Spindt	Mo & Si	10.2	8000
Fujitsu Laboratories Ltd., Kawasaki, Japan www.fujitsu.co.jp (81+78) 936 1221	Spindt	Mo	5.1	N.A.
Futaba	Spindt	Mo	12.4	400
PixTech	Spindt	Mo	26.7	300
Raytheon Co., Lexington, Mass. www.raytheon.com 508-440-2100	Spindt	Mo	6.3	15 000
Samsung Display Devices Co., Seoul, Korea www.sdd.samsung.co.kr (82+331) 210 7861	Spindt	Mo, diamond-like carbon	14.2	250

N.A. = not available

from the 300–5000 V applied between the anode and the cathode emitter array. The electron beam may also interact with the spacer, leading to secondary electron emission and charge buildup on the spacer—buildup that can deflect the beam, degrading display performance, or can lead to catastrophic electrical breakdown between the anode and cathode. LCDs, incidentally, also employ spacers, though they are much smaller, to control cell thickness.

Much is asked of the spacers in an FED. They must be mechanically strong and stable, be compatible with a surrounding vacuum, and have a high breakdown voltage. In addition, their electrical resistance must be high enough to minimize leakage current between anode and cathode; otherwise, power consumption will rise, since the leakage current is being dropped across

the full anode-cathode voltage difference. Yet the resistance has also to be low enough for charge buildup to dissipate, and the secondary electron emission has to be controlled to keep charge buildup to a minimum to start with. Last but not least, spacers must be invisible to the viewer.

During FED operation, gases are continuously being generated through outgassing of all the surfaces. Exposure of the phosphors and other areas to the electron beams causes material degradation and desorption of adsorbates. If a high vacuum is not maintained, residual gases in the package will contaminate the emitter tips during field emission and as time wears on, degrade their operation. Poor vacuum in the display envelope also encourages arcing between the cathode and the high-voltage anode plate, again to the detri-

Pixel no.	Pixel size	Luminescence, cd/m <sup>2</sup>	No. of colors	Contrast ratio
320x240x3	0.325x0.50	300	262 000	>100:1
320x240x1	0.36x0.36	300	Mono	40:1
548x222x1	N.A.	50	121 656	100:1
320x240x1	0.33x0.33	240	Mono	100:1
240x240x3	0.65x0.29	690	256	>1000:1
320x240x3	0.33x0.33	100	N.A.	300:1
480x480x1	0.148x0.148	1000	RGBW	>100:1
320x240x1	N.A.	6	Mono	N.A.
320x240x3	0.103x0.309	80	16 million	>100:1
640x480x3	0.33x0.33	N.A.	Color	>100:1
128x128x1	0.35x0.35	34 000	Mono	>100:1
128x128x3	0.50x0.50	80	RGB	100:1

## The who's who of FEDs

Several companies have invested quite heavily in the commercial development of field emission display (FED) devices. One of the first out of the gate was Futaba Corp., Chiba City, the major Japanese manufacturer of vacuum fluorescent displays. It has been involved with FED technology for almost a decade and announced the availability of 12.5-cm-diagonal, monochrome, low-voltage displays back in 1996. Then at the 1997 Society of Information Display (SID) conference last May, it demonstrated a 12.5-cm-diagonal full-color display with 1/4-VGA resolution. Motorola Inc., Tempe, Ariz., recently announced the start-up of a 25 000-m<sup>2</sup> pilot line for the development of FED technology. The company recently demonstrated a display with a 14-cm diagonal and 1/4-VGA resolution, operating at the relatively high anode voltage of around 5000 V.

Somewhat earlier, PixTech Inc., of Rousset, France, had demonstrated a slightly larger (15-cm-diagonal) 1/4-VGA, low-voltage full-color display at that 1997 SID conference. "Low voltage" here means around 300 V.

Micron Display, a subsidiary of Micron Technology Inc., Boise, Idaho, announced it was in production with 1.4-cm color FED, 1/4-VGA modules, directed at head-mounted displays and camcorder viewfinders. Raytheon Corp., Lexington, Mass., has demonstrated rugged, high-brightness FEDs for avionics applications. FED Corp., Hopewell Junction, N.Y., has developed 10-cm-diagonal displays for avionics and automotive markets. Candescent Technologies (formerly Silicon Video Corp.), San Jose, Calif., is proceeding with plans for an FED production facility based on Spindt tip deposition.

Other Japanese and Korean electronics manufacturers are also energetically developing the technology: Samsung from Korea, and Canon from Japan. Samsung Electronics, one of the world's largest manufacturers of liquid-crystal displays, presented details of a 10-cm low-voltage color FED at that same SID conference last year.

—B.R.C., Y.W., & B.E.G.

ment of the emitter cones and phosphors.

Fortunately, the means of maintaining high vacuums in tubes is well understood. Materials used in the tube industry include evaporable getters, such as barium, and nonevaporable getter materials. Once activated, these materials react with the residual gases in the display, forming chemically stable, solid compounds and reducing the pressure in the package. But the FED geometry severely restricts the type and amount of getter material that can be used. The narrowness of the space between anode and cathode hampers the flow of gas across and through the channel, with the gas molecules diffusing from the outgassing source to the getter by colliding with the surfaces. Because of this limited conductance, the getter must be placed as close as possible to the source of the residual gas in the display. Outgassing

of the gas from the surfaces is a distributed effect, occurring across the entire vacuum-exposed areas of the display.

After placement of spacers and getters, the cathode-array plate is mechanically aligned with the anode glass plate and the two are vacuum sealed using sealing glasses with low melting points. The process normally includes high-temperature baking before sealing to remove any moisture or residues left over from manufacture.

In the integral sealed packaging technique, sealing is done in a high vacuum. In an alternative approach, the panel is assembled in an inert environment with an open tubulation, as it is called. The gas in the assembled panel is then pumped out through a small tube protruding from the package, which is then sealed by thermal or mechanical means. This latter method is a lot like the packaging of cathode-ray tubes.

## Catching up in performance

For FEDs to be commercially viable, they must perform at least on a par with rival technologies, such as active-matrix LCDs. So far, FEDs have fallen short, but developers are close to achieving LCD equality, to judge from the several working prototypes that have been built.

As mentioned, PixTech and Futaba are currently delivering engineering samples of low-voltage monochrome displays. Micron Display is sampling low-voltage FEDs, 14 mm on the diagonal, for camcorders and head-mounted display applications. Motorola, Candescent, and Canon have demonstrated prototypes of low-profile, thin, full-color FEDs operating at several kilovolts [Table 2]. Motorola is sampling 13.2-cm-diagonal, full color, high-voltage displays. Raytheon and FED Corp. have demonstrated a 10-by-10-cm high-



breakdown issues and improvements in the device engineering. Granted, higher anode voltage enhances beam collimation—but then the beam tends to diverge over the longer path required to maintain the anode-cathode voltage difference.

Motorola has recently demonstrated the prototype of a 14-cm high-voltage flat-panel display operating at an anode voltage of 5000 V (Fig. 1). The full-color FED is capable of running video in real time in a 1/4-VGA format with luminance in excess of 300 cd/m<sup>2</sup> and a 160-degree viewing angle. The prototype is a 3.5-mm-thick package with a pixel pitch of 0.325 μm.

Candescent has also reported a stable 10-cm FED operating at a high voltage. FED Corp. has built 10-cm-diagonal, color prototype avionic displays operating at 8000 V, with a reported luminance of 1000 cd/m<sup>2</sup> and a 160-degree viewing angle. Raytheon has demonstrated monochrome avionics displays with even higher brightness. Recently, Canon demonstrated 6000-V operation with its surface emission device, achieving a luminance of 690 cd/m<sup>2</sup>.

### Engineering challenges

Many of the obstacles to FED manufacturing have been surmounted. What remains to be done is converting laboratory processes into full-scale manufacturing methods, capable of producing FEDs at rates on a par with those for active-matrix LCDs. There is general industry agreement that these hurdles are thorniest in the vacuum sealing and processing area.

Material improvements, especially in phosphors, are needed to add to brightness. This is especially true for FEDs with low-voltage anodes. High-voltage FEDs could also benefit from advances in spacer technology, as well as phosphors. All FEDs could benefit from enhanced emitter stability. ♦

### To probe further

The annual International Conference on Vacuum Microelectronics is sponsored by the American Vacuum Society, the IEEE, and the Society for Information Display (SID). Its emphasis is on device physics and applications in microwaves and flat-panel displays. Its proceedings have appeared as special issues in the *Journal of Vacuum Science and Technology* and the *IEEE Transactions on Electron Devices*.

The annual Society for Information Display (SID) meeting is the major worldwide conference and trade show of the display industry. SID's World Wide Web site [www.sid.org] deals with all aspects of display technology.

Vacuum microelectronics are reviewed in two papers titled "Vacuum microelectronic devices," by I. Brodie and P. R. Schwoebel (*Proceedings of the IEEE*, Vol. 82, 1994, pp. 1006–34) and "Vacuum microelectronic devices," by I. Brodie and C. A. Spindt (*Advances in Electronics and Electron Physics*, Vol. 83, 1992, pp. 1–106).

For more specific information, see H. F. Gray's 1993 paper, "The field-emitter display," in *Information Display*, Vol. 90, pp. 9–14, and D. Cathey Jr.'s "Field-emission

Displays," in the same publication, two years later, in Vol. 11, pp. 16–20. A. Ghis, R. Meyer, P. Rambaud, F. Levy, and T. Leroux produced "Sealed vacuum devices: Fluorescent microtip displays," which appeared in 1993 in *IEEE Transactions on Electron Devices*, Vol. 38, pp. 2320–22.

Relevant and interesting Web sites are LETI: www-dta.cea.fr; SRI International: www.sri.com; Naval Research Laboratory: www.mil.gov; Electrotechnical Laboratory in Tsukuba: www.etl.go.jp; Display Technology Systems: www.distec.com; and the Asian Information Technology Program: www.atip.org/fpd/.

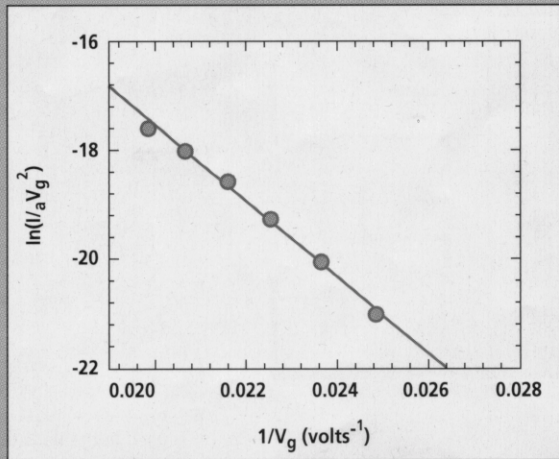
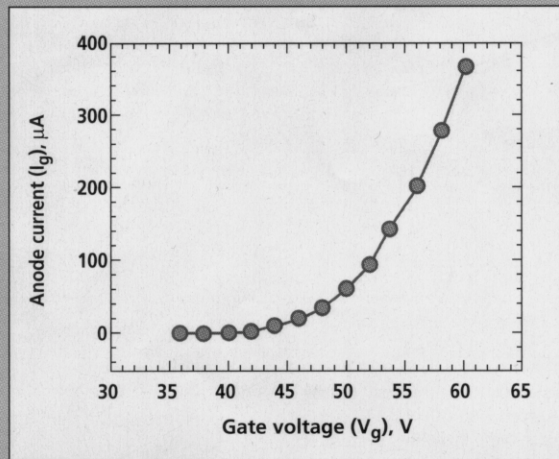
### About the authors

Babu R. Chalamala (M) and Yi Wei are senior engineers in the Motorola Flat Panel Display Division in Tempe, Ariz. Chalamala's expertise includes vacuum microelectronics, surface science, and gaseous electronics.

Yi Wei, prior to joining Motorola in 1997, was a research scientist at Texas Instruments Inc.'s Materials Science Laboratory in Dallas for two years. His expertise is in semiconductor materials and processing.

Bruce E. Gnade is manager of the high definition systems program at the Defense Advanced Research Projects Agency (Darpa), in Arlington, Va., having previously worked for Texas Instruments for 15 years. His areas of expertise include materials sciences, field emission displays, and display phosphors.

*Spectrum* editors: Linda Geppert and Elizabeth A. Bretz



the emitter tip. It is related to the applied potential  $V$  between the emitter tip (cathode) and the extraction electrode (or gate) as the product of  $V$  with an enhancement factor,  $b$ , divided by the cathode-to-gate distance. To emit many electrons at a low applied voltage, a low work function and a high  $b$  are needed.

The electron emission current density is strongly influenced by sites with unintended protrusions and hence an (unintended) large field enhancement factor. Field emission microscopy of individual emitter tips indicates that the emission is limited to a few atomic sites. The emitting area is typically 1–5 nm in diameter. The greatest possible field enhancement can be obtained for

a zero-dimension structure, or cone with a tiny radius, followed by a 1-D edge emitter, followed by a 2-D planar surface.

The preferred field-emitter configuration should have the highest aspect ratio and a low work function at its surface. Even though microtips are ideal for field enhancement, they are also the most difficult and costly structures to manufacture. To reduce manufacturing costs, there is an ongoing effort to develop planar cold-cathode field emitters, particularly those based on diamond thin films and high-aspect-ratio nanostructured materials.

—B.R.C., Y.W., & B.E.G.