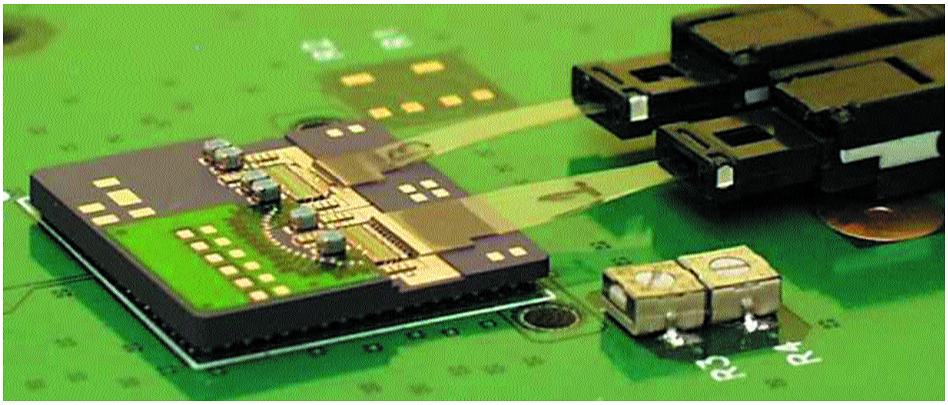
by Jennifer Ouellette

Smart Pixels Wed Optics and Electronics

The staggering computing requirements of the near future will further push the limits of a technology already strained by high data-transmission rates. Smart pixels are an emerging optoelectronic technology that could be crucial to meeting the demanding performance needs of tomorrow, particularly for high-speed switching, optical interconnects between and within computers, and flat-panel display applications.



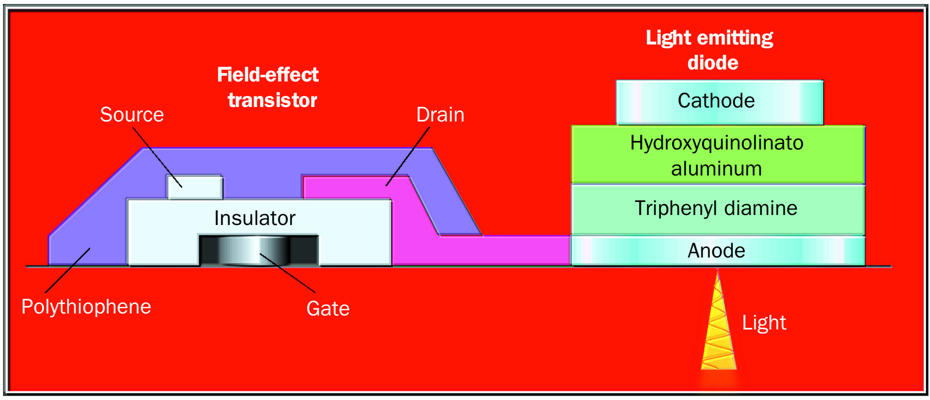
Hewlett-Packard Laboratories

Figure 1. In this optoelectronic device, signals from a computer on the left drive arrays of surface emitting lasers that output signals through 12-channel polymer waveguides (Polyguide) and connectors to the optical-fiber ribbon. Return signals pass through photodetectors back to the computer.

The term "smart pixel" is not well defined, even within the field. Scott Hinton, professor of electrical and computational engineering at the University of Colorado, Boulder, offers the generally accepted description: an optoelectronic device that combines optical inputs and/or outputs with electronic processing circuitry that can be integrated into two-dimensional arrays. The term pixel came into use because it implies an optical component in a two-dimensional array. The smartness comes from the integration of the optics with electronics bonded to silicon.

Smart pixels emerged from the interest in optical computing in the mid-1980s, specifically the symmetric self-electro-optic-effect device (SEED) structures invented by David Miller (now at Stanford University), which were subsequently adapted as switching devices in simple optical-computer systems.

However, it soon became apparent that although optics were good for communications, they were less useful for logic functions, largely because significantly more energy was required to perform such functions optically than electronically. Another advantage of using optics for communication is that photons travel at the speed of light and do not interact with each other, virtually eliminating interference, or cross-talk, problems. This property is a disadvantage, however, for logic functions, which require a certain amount of interaction for processing. So researchers began integrating field-effect transistors (FETs) with the SEED technology to produce optoelectronic devices that required significantly less optical power.



Bell Labs/ Malcolm Tarlton

Figure 2. This smart pixel, made entirely from organic materials, consists of a light-emitting diode controlled by a field-effect transistor. As well as being bright (important for use in flat-panel displays), it can be printed rather than etched.

The respective strengths of optics and electronics led to the smart-pixel research community's mantra: "Process electronically, communicate optically." With the addition of electronics, the scope of the devices and their potential applications has expanded considerably. Smart-pixel uses now include neural networks, packet switches and other switching devices, simple cross connects, interconnection networks, signal processing, and flat-panel displays. The emphasis has also shifted from monolithic integration (purely optical components) using gallium arsenide FET technology to hybrid integration that combines optics-based SEED modulators or lasers with complementary metal oxide semiconductors (CMOS).

The two most promising smart-pixel technologies are the CMOS-SEED technology from Lucent Technologies, and the hybrid CMOS-VCSEL (vertical cavity surface emitting laser) technology. Lucent's approach combines silicon CMOS circuitry with gallium arsenide SEED devices using flip-chip bonding, in which each part is created separately and the two are then bonded together. The other approach integrates VCSELs with CMOS electronics, with optical sources instead of modulators as the output device in each smart pixel.

One promising smart-pixel application is optical data access, particularly the use of optical interconnects for intercomputer communications. "There is a problem right now with the way computers communicate," says Elias Towe, who heads a program at the Defense Advanced Research Projects Agency that funds smart-pixel R&D. "You can do all the computations and processing internally very fast, but if you try to get the information out of the computer, you can't do it at anywhere near the same rate."

For example, an Intel processor might operate at 300 MHz internally, but communication outside the computer can be as low as 33 MHz because the wires connecting the processor to the memory are limited in the number of data bits they can transport. To create better input–output functions capable of tracking the ever-increasing processing speeds of computer chips, researchers are using 16 ¥ 16 arrays of smart pixels. Each pixel can process up to 1 Gb/s, thereby achieving a much higher data-transfer rate.

Hewlett-Packard Laboratories (HPL) in Palo Alto, California, has a major research program in VCSEL-based smart pixels that focuses on parallel optical interconnects. Computer data is converted from its original parallel format into optical format and sent to another computer at the speed of light via a parallel-fiber ribbon. According to Waguih Ishak, Photonics Laboratory director at HPL, prototypes transmit at roughly 30 Gb/s (12 channels running in parallel, each at 2.5 Gb/s). Ishak believes it will be possible to increase the rate to 100 Gb/s while keeping device costs low (Figure 1).

Hewlett-Packard plans to introduce a commercial product in a year or so, although Ishak cautions that the initial device will consist of several chips rather than just one. "When scientists hear the term smart pixel, they understand that the whole function is integrated on one substrate; nobody has done that yet," he says. The forthcoming device "is what is economically and practically feasible right now, although our research is certainly going in the direction of fully integrated smart pixels."

Besides their advantages of speed and decreased cross-talk, smart-pixel interconnects will be lighter because feather-light fiber ribbons will replace today's copper wires. Furthermore, the devices are extendible and scaleable to even higher speeds, making them a crucial enabling technology for the emergence of terabit networks in about five years.

Eventually, Ishak and his HPL colleagues would like to apply the same optical technology that they plan to use for intercomputer communications for communicating among boards inside the computer. Currently, computers have experienced occasional bottlenecks of data at the backplane—the wiring board connecting logic, memory, and other printed circuits—largely because of the hardware compression necessitated by packing more electronics into smaller physical volumes. "One of the practical limiting factors in the development and acceptance of teraflop multiprocessor computing systems, as well as large asynchronous transfer mode (ATM) switching systems, is packaging," says Hinton.

Intelligent interconnects

Hinton is already trying to apply smart-pixel arrays as intelligent optical interconnects for backplanes. Computers incorporating this technology are expected to outperform even the most powerful supercomputers operating today.

He is developing a backplane composed of numerous optical communication channels, which, in turn, are created by optically interconnecting smart-pixel arrays. Not only does the larger temporal and spatial bandwidth of the backplane's optical interconnects allow the transfer of huge amounts of data, but the system offers a unique advantage. "Information can actually be managed and controlled as it moves across these backplanes and interconnects, so it helps alleviate a lot of other network problems that occur in standard big machines," says Hinton, whose work has attracted the interest of Intel and IBM.

At Honeywell Technology Center (Minneapolis, MN), researchers aim to develop smart-pixel modules. These devices would integrate VCSELs and photodetectors on a single chip, which would be flip-chip bonded onto silicon integrated circuits, and then another optical component would be added on the surface to focus and collimate light.

Honeywell is focusing on large-scale switching and signal-processing applications using 16 ¥ 16 arrays of smart pixels on a single module. Lucent has been able to demonstrate even larger switching systems, and Hinton's team has been able to demonstrate parts of a large ATM switching system with roughly 160 transistors per smart pixel.

Some researchers are focusing on smart-pixel technology as a way to perform computational processing of images. William Babbitt, a professor at Montana State University in Bozeman, is developing smart-pixel arrays with a capability he terms "smart illumination." His device mixes roughly equal numbers of photodetectors and light emitters on a single chip. Rather than relying on external illumination, the emitters send out light to the image to be processed, which is reflected back to the chip's photodetectors. "Each pixel 'decides' what its illumination [brightness] is going to be based upon the signal it gets back from the detector," he says. "So you can increase the amount of illumination for any given pixel if, for example, a scene is dim."

Barry Shoop, who heads the Photonics Research Center at the U.S. Military Academy in West Point, New York, wants to take advantage of the high-speed switching and parallelism of smart-pixel technology for signal-processing applications. Specifically, he is developing image-compression algorithms for optical data communication. Other potential applications for smart pixels include heads-up displays, in which data is projected on a small screen worn by the user, and sensors."

At Bell Laboratories/Lucent Technologies (Murray Hill, NJ), researchers have, for the first time, fashioned a smart-pixel device entirely out of organic materials on the same substrate (Figure 2). The devices should ease the development of large emissive displays, particularly for high-definition television, by making system design easier and reducing the demands on the organic light-emitting diode (LED) materials. Organic materials are preferable to conventional semiconductor electronics because they should result in less expensive, lighter circuitry that can be printed rather than photolithographed.

The device's 300-µm pixels were fabricated using polymer FETs and LEDs made from a sandwich of organic materials, one of which allows electrons to flow, another of which acts as a highway for "holes," or the absence of electrons. Light is produced when electrons and holes meet, with a brightness of about 2300 candela/m^2 compared to 100 candela/m^2 for current flat-panel displays. Although Bell Labs' devices are not ready to market, their performance has been promising, according to Ananth Dodabalapur, who coordinates the research. (A research group at Cambridge University has also made an all-organic device).

Challenges

The biggest technical challenge to achieving full integration of a smart pixel on a single chip arises from the vastly different properties of the materials used. "Basically, you're doing something called heterogeneous integration; you essentially have three material systems with incompatible properties that you're trying to integrate," says Towe. The standard manufacturing process begins with a silicon chip, onto which is deposited a III-V compound semiconductor for the light-emitting function of the smart pixel. However, these two materials are, in their natural state, incompatible not only with each other but with the glass lenses needed to collimate and focus the light. Flip-chip bonding has provided an interim solution for integrating the first two materials, but researchers are still exploring methods that will enable them to add the glass lens structure.

Hibbs-Brenner foresees potential problems getting the electrical design to interact with the optics once Honeywell's fully integrated smart-pixel modules reach the prototype-testing phase.

Issues of alignment also become more critical once a signal leaves the smart-pixel module, especially because standard photolithography techniques are too expensive and often incompatible with integrated optoelectronic devices.

John Rogers is one of the team at Bell Labs charged with developing new printing, molding, and near-field photolithographic approaches for low-cost patterning of organic electronic systems, and to find ways of using these methods to fabricate and characterize simple working circuits and devices on plastic substrates. He adopted a high-resolution, reel-to-reel printing process using cylindrical rubber stamps to print the transistors and inverter circuits with 1-µm feature sizes. His colleague, Zhenan Bao, designed the “electronic ink” used in the process: a solution-based organic conjugated copolymer that self-organizes into a solid state once the solution is dropped on a plastic substrate. Amorphous and polycrystalline silicon, which are currently favored for many emerging flat-panel display technologies, cannot be easily integrated with plastic.

The Bell Labs team also had to overcome difficulties with charge leakage and with the need for periodic recalibration. The performance parameters of transistors on the organic smart-pixel array tend to change more with time than transistors on silicon chips. To address this problem, the team edges the organic material with silicon. This edging contains calibration circuitry, which measures and checks the parameters periodically, makes necessary adjustments, and stores those adjustments in memory.

Perhaps the greatest challenge facing smart-pixel technology is economic. Total federal and industrial funding for optical engineering has dropped by a factor of between 5 and 10 over the last five years, according to Hinton. “Smart pixels are in a difficult phase of technology development right now, requiring a great deal of engineering development, which can be a substantial money drain,” he says. “But there are companies that are putting money into it quietly, and as the technology evolves and matures, there will be more people interested.” ▪