GaAs Readied for High-Speed Microcircuits

Military applications predominate, but supercomputers and direct satellite to home broadcasting may also depend on gallium arsenide semiconductors

"Gallium arsenide is the material of the future now and it always will be."
—Electronics industry aphorism

For over two decades, the semiconductor silicon has been more than up to the task for microelectronic circuits of every stripe. This has bred a certain complacency among practitioners of the microelectronics trade whenever alternative materials with possibly superior properties are mentioned, as exemplified by the slogan above. Nonetheless, silicon does have physical limitations. In particular, gallium arsenide has a distinct advantage in speed, so that it is the material of choice in, for example, high-frequency microwave and millimeter wave telecommunications systems and ultrafast supercomputers. As judged by the presentations at a recent conference devoted to gallium arsenide integrated circuits, appearance of these devices in large volumes will not come until the mid-to late 1980's, but the technology for making them is rapidly maturing.*

A close-to-home example of what gallium arsenide microcircuits could help bring to fruition is direct satellite to home broadcasting, which could include cable television–like services, such as videotext. Communications satellites now transmit at frequencies in the neighborhood of 4 gigahertz (GHz) (C-band), and home receivers for their transmissions cost from $5,000 to $25,000. Direct broadcasting satellites would use higher power transmitters and would send 12-GHz signals (K-band). The greater power and higher frequency would allow the use of much smaller receiving antennas (dishes), and these consequently would be much less expensive. For example, one of eight companies in the United States that have already received approval from the Federal Communications Commission to offer direct broadcasting to homes, Comsat's Satellite Television Corporation, has proposed a service for which customers would have to pay only $100 for purchase and installation of an antenna three-quarters of a meter in diameter.

Already, the Toshiba Corporation in Japan has announced that it has a prototype receiving antenna that is 1 meter in diameter, weighs 10 kilograms, and will cost a little over $500 once high-volume production begins. The amplifiers in the electronic circuits that select the channel and carry the signal toward the demodulation stage are gallium arsenide integrated circuits.

Many observers expect that direct satellite broadcasting systems will provide the first large commercial market for gallium arsenide integrated circuits. At the New Orleans conference, Kenneth Sleger of the Naval Research Laboratory suggested as a conservative estimate that 10 million to 100 million gallium arsenide chips costing about $10 each would be the U.S. requirement for this application. It is widely believed, however, that Japan and Western Europe, where the research on this material is less military oriented, will be the early leaders in exploiting gallium arsenide for civilian satellite communications.

The gallium arsenide microcircuits needed for the receivers and transmitters in satellites and for the ground receivers are deceptively simple because they are, in the jargon of semiconductors, small-scale integrated circuits. They contain only a few transistors, for example, as compared to the tens of thousands on silicon chips for computer memories. Sleger pointed out, however, that the transistors in high-performance devices have very complicated geometries as compared to transistors for digital circuits, and these make their fabrication far from trivial.

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Most transistors made from gallium arsenide are field-effect transistors or FET's of a particular type known as Schottky barrier FET's. The speed advantage of gallium arsenide over silicon derives from the fact that its free electrons reach high velocities at comparatively low applied voltages. In addition, the maximum electron velocity is greater than that in silicon. Field-effect transistors, whose switching action depends only on the motion of the electrons, can therefore take full advantage of the high mobility of electrons in gallium arsenide.

Field-effect transistors have three parts: a source, a drain, and a gate. Current flows to the source from the drain. A voltage applied to the gate provides the transistor switching action by modulating the source-drain current. The unusual structure of microwave and millimeter wave FET's is that the gate is only a fraction of a micrometer long, but the width of the gate may be from 100 to 10,000 micrometers. One of the problems limiting the yield or percentage of viable manufactured chips is that of making such a long, thin line with no faults. Sleger mentioned one company, Westinghouse, that was achieving yields of 13 to 36 percent for such structures, depending on the complexity of the microcircuit. Sleger characterized this as " a bit low, but getting better."

In the United States, military applications for gallium arsenide microcircuits far outnumber civilian, perhaps because most of the funding is from the Department of Defense (DOD), with just a little from the National Aeronautics and Space Administration (NASA). By the same token, most of the research and development is in the laboratories of companies that traditionally are active defense contractors, such as Rockwell International, Hughes Aircraft, McDonnell Douglas, Honeywell, Westinghouse, TRW, RCA, Raytheon, and Texas Instruments. Scientific instrument manufacturers such as Hewlett-Packard and Tektronix are also active in gallium arsenide integrated circuit development. The mainframe computer makers have largely been interested observers, although Cray Research was looking for researchers to hire at the New Orleans meeting. The two "big name" research laboratories, IBM Yorktown Heights and Bell Laboratories, have been leaders in basic research involving gallium arsenide but have been cautious in publicly commenting on device development efforts.

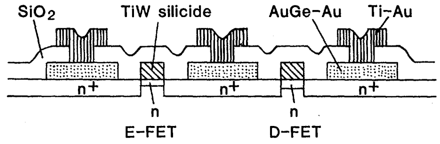
Sleger revealed that since 1977, when federal support for gallium arsenide research began to rise rapidly, DOD and NASA spending on this material has totaled about $35 million. With contributions from the companies involved, the actual total is more like $60 million, he estimated. Most of this work is devoted to the eventual development of microcir-

*IEEE Gallium Arsenide Integrated Circuit Symposium, New Orleans, Louisiana, 9–11 November 1982.

cuits considerably more complicated than the small-scale microcircuits used for satellite communications receivers.

One application requiring a particularly large number of chips, although probably less than one-tenth of that required for satellite broadcasting, is transmitter/receiver modules for phased-array radars. Phased-array radars scan electronically rather than mechanically. The radar is divided into a large number of modules, and the relative phases of the electronic signals in the modules determine the direction in which an outgoing beam is sent or from which an incoming one is arriving. Phased-array radars are being built with existing technology, which is based on individual or discrete circuit components (transistors, diodes, resistors, capacitors, and inductors), but they would be much less costly if gallium arsenide microcircuits costing $100 or less were available. Another example where cost is absolutely decisive is the so-called terminally guided submunition in which a missile dropped by parachute first locates a ground target, such as a tank, before going after it. Target tracking is by the transmission of millimeter wave (30- to 140-GHz) beams and the reception of return signals. With current technology, the missile would cost more than the target, according to Sleger. Sleger also briefly discussed a wide range of other military uses for gallium arsenide, including ground- and space-based radars, satellite telecommunications, electronic warfare (jammers and decoys), and intelligent weapons.

Microcircuits that deal with signals received from the "real world," such as the modules in a phased-array radar, are necessarily linear or analog circuits. For many telecommunications, signal processing, and computation applications, digital circuits are required. For the most part, digital gallium arsenide devices differ only in detail from their silicon FET counterparts. However, in addition to switching speed, gallium arsenide has two other advantages. Switching action requires a smaller voltage change applied to the gate electrode, so less power is dissipated. Power dissipation ultimately limits how densely packed a microcircuit can be because there is a maximum practical heat flux (watts per square centimeter per second) that can be removed. After that the chips overheat. Aircraft- or satellite-borne systems are also intrinsically power conscious because power supplies are heavy. Gallium arsenide's second advantage is the increased resistance of microcircuits to damage from ionizing radiation, which is a distinct benefit for space-based systems or for



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Gallium arsenide FET's

Schematic cross section shows elements of enhancement mode (E-FET) *and depletion mode* (D-FET) *devices. Heavily doped gallium arsenide layers under the source and drain electrodes are labeled* n^+*, while the more lightly doped material under the gate electrode is labeled* n.

those in nuclear warfare environments.

Gallium arsenide FET's come in two basic varieties: depletion mode and enhancement mode. The gate electrodes are usually made of metals such as platinum. Free electrons from the electrically active gallium arsenide flow into the metal, forming a thin layer at the gallium arsenide surface between the source and drain that is devoid of electrons. This is called the depletion region. The entire FET is constructed on top of a thicker substrate of gallium arsenide that is insulating and hence electrically inactive. Whether current can flow in the FET depends on the thickness of the electrically active gallium arsenide and the voltage applied to the gate electrode.

In depletion mode FET's, the active layer is about 0.3 micrometer thick and is thicker than the region depleted of electrons, so current can still flow with no applied gate voltage. If a negative voltage is applied to the gate, more electrons are pushed out of the gallium arsenide, thereby thickening the depletion region. When the depletion region becomes as thick as the layer of electrically active gallium arsenide, current flow halts and the transistor switches off. In enhancement mode FET's, the situation is the reverse. The active layer is customarily only about 0.1 micrometer thick, and the zero-voltage depletion region is already thick enough to choke off all current through the device. A positive gate voltage, however, will draw electrons into the gallium arsenide, turning the transistor current on.

For applications requiring densely packed integrated circuits, such as computer memories, or low power, as in airborne systems, enhancement mode FET's are preferred over depletion mode devices, because they consume no power in the switched-off state. Unfortunately, it is presently harder to reproducibly control the electrical properties of the thin gallium arsenide under the gate of an enhancement mode FET as compared to depletion mode devices, so the production process is farther from maturity.

At the New Orleans conference, Masayuki Ino and his co-workers from the Nippon Telephone and Telegraph Public Corporation's Musashino Electrical Communication Laboratory near Tokyo discussed the most complex gallium arsenide integrated circuit to date, a 1024-bit (1K) static random access memory chip. For comparison, silicon random access memory chips that store 64K bits are commercially available, although these are mostly of a simpler type called dynamic RAM's. The contents of memory cells in dynamic RAM's have to be refreshed periodically, whereas the contents of static RAM cells are stable. Nonetheless, since the 1977 acceleration in federal funding for gallium arsenide circuit development, the complexity (expressed in the number of devices on a chip) has been approximately tripling each year. If this growth rate were to continue, gallium arsenide microcircuits could match the complexity of silicon chips by about 1990.

In making their 1K static RAM, the Japanese took advantage of two tricks that have become popular in the last year or two. The first is the use of enhancement mode FET's in a particular configuration with the jargon name "direct-coupled FET logic." Direct-coupled means that the output of one FET can be directly the input of another without having to use capacitors or diodes as found in depletion mode circuit designs. In particular, quite compact memory cells are possible when enhancement mode FET's are used. Another advantage is that circuit designs already developed for silicon chips can be almost directly carried over to gallium arsenide. The Musashino 1K static RAM cell contains six FET's. The entire chip, 3.32 millimeters square, consists of 7084 FET's, including those needed for input-output circuits.

The second trick, which makes the fabrication of the enhancement mode FET's easier, is the so-called self-aligned gate process. Gallium arsenide integrated circuits are made by the same kinds of photolithographic pattern formation steps as silicon chips. Controlling the electrical properties, for example, is by way of implanting impurity or dopant ions from a small accelerator into the gallium arsenide surface. A mask of insulating material such as silicon dioxide controls what part of the surface is implanted and what part is not. In the self-aligned gate process, the gallium arsenide channel under the gate, source, and drain is formed by implanting silicon ions that donate free electrons to the normally insulating gallium arsenide. The gate electrode is then deposited. After some intermediate steps, the source and drain are further defined by implantation of additional silicon ions, so that they become more highly conducting than the active channel. In the latter process, the gate itself acts as the mask determining the boundaries of the source and drain, thereby ensuring that all the device elements are precisely aligned.

Participants at the New Orleans meeting were disappointed to hear that the Japanese researchers had not yet produced a 1K static RAM chip in which every memory cell functioned properly. But this failure does give U.S. investigators a chance to catch up. "We can all breathe a little easier," said one relieved American. At least four U.S. companies, Rockwell International, McDonnell Douglas, Texas Instruments, and Hughes Research Laboratories, are working toward 256-bit static RAM's. Rockwell International researchers have recently succeeded in making fully functional chips.

The concentration on memory chips is appropriate, for many observers see an early application of gallium arsenide digital microcircuits in a particular kind of high-speed memory called a cache. A cache memory holds the information needed for current and about to be executed instructions in a computer. The development of an entire computer central processor unit and main memory is much more speculative. The Japanese government, however, in January 1982 launched an 8-year, $200-million National Superspeed Computer Project (*Science*, 17 December, p. 1189), and gallium arsenide logic and memory microcircuits are under development as part of that six-company effort. The goal is a supercomputer capable of executing ten billion floating point (arithmetic) operations per second, about ten times the speed of U.S. supercomputers now being readied for production.

Conventional gallium arsenide microcircuits might not be up to such speeds. There is a still faster gallium arsenide-based structure, however. The mobility of electrons in a semiconductor is limited by scattering of these particles by lattice vibrations and by ionized impurities. Lattice vibrations dominate the scattering at room temperature and above because the amplitude of the vibrations increases with temperature, whereas ionized impurity scattering holds sway at the temperature of liquid nitrogen (77 K) and below. In 1978, Raymond Dingle, Horst Störmer, Arthur Gossard, and William Wiegmann of Bell Laboratories showed how to reduce the effect of ionized impurity scattering by surrounding a very thin gallium arsenide layer with layers of a related semiconductor, aluminum gallium arsenide. The doping impurities that provide the free electrons were placed only in the aluminum gallium arsenide layers. The electrons then flowed into the undoped gallium arsenide, where they could speed along unhindered by impurity scattering.

Researchers at Fujitsu Laboratories in Kawasaki, Japan, and at Thomson-CSF in Corbeville, France (near Paris), were among the first to use this idea in functioning test circuits called ring oscillators. Fujitsu scientists in the laboratory of Hajime Ishikawa measured a switching time of only 17 picoseconds in their so-called high electron mobility transistors (HEMT's) when cooled to liquid nitrogen temperature. The French group headed by Nuyen Linh reported shortly afterward in late 1981 its achievement of a 19-picosecond switching time at room temperature. They called their devices two-dimensional electron gas FET's or TEGFET's. Last December at the International Electron Devices meeting in San Francisco, J. V. DiLorenzo of Bell Laboratories told of reaching a switching time of 18 picoseconds in what he called selectively doped heterojunction FET's. The generic term for all these structures is "modulation doped," which refers to the ability to continuously vary the concentration of impurities with depth (doping profile) in semiconductor layers.

The United States may soon have a supercomputer program of its own, if plans proposed by the Defense Advanced Research Projects Agency (DARPA) materialize. DARPA's director Robert Cooper told the Government Microcircuits Applications Conference, held in Orlando, Florida, early last November, of his ideas for a supercomputer by 1990 that would, like the one being designed by the Japanese, operate at 10 billion floating point operations per second. Whether or not the supercomputer project receives approval, DARPA is already going ahead with a gallium arsenide microcircuit pilot manufacturing facility program. The goal, according to Richard Reynolds of DARPA, is for one or more pilot facilities to achieve a manufacturing (high yield) minimum throughput of 100 wafers per week at the end of 3 years. Wafers, which are thin gallium arsenide disks 7.5 centimeters in diameter, are the insulating substrates on which integrated circuits are produced. Chips on the wafers would contain either 16K RAM's or a type of generalized logic circuit called a "gate array" with from 6K to 10K gates. (Here gate refers to a logic device of one or more transistors rather than the gate electrode of a FET.) If all goes according to plan, contractors should be selected and the program under way by this fall. DARPA is asking contractors to contribute one-third of the program costs.

Equipment costs alone are considerable. At the New Orleans conference, Bryant Welch of GigaBit Logic of Culver City, California (a spin-off by former Rockwell International researchers), summarized what would be necessary to get into the gallium arsenide business in a modest way: an ion implantation accelerator, a photolithographic machine capable of delineating and aligning patterns with 1-micrometer feature sizes, a plasma machine for etching away oxide masks and other features, a vacuum deposition system, a testing machine, a large-area, dust-free clean room, and an automated system to transfer the fragile wafers from one processing step to another. A 5000 square foot facility could cost $7 million.

Reynolds explained that part of the motivation for having a gallium arsenide manufacturing program now is that the technology of this semiconductor has reached a kind of chicken and egg stage. Electronics companies are unwilling to make the major investment to jump from research to manufacturing because there is no firmly identified market for digital gallium arsenide chips. And DOD planners shrink from selecting gallium arsenide microcircuits for their weapons systems because there are no commercial sources. Demonstration of a pilot manufacturing facility could help bridge the gap. The government will have the right to buy up to 200 wafers per week for 5 years once the pilot facility is working.

—Arthur L. Robinson

TEGFET

In Thomson-CSF's TEGFET, the source-drain current is carried by a very thin layer of electrons that forms just below the interface between the undoped aluminum gallium arsenide and gallium arsenide (p) layers.