PACKING POWER INTO TINY PACKAGES

DARPA's Work in Microsystems Technology

By Henry S. Kenyon

Since its establishment in 1958, DARPA has pushed technological boundaries to develop electronics and components for the Department of Defense (DoD). In the early 1960s, the agency conducted intense research to develop integrated circuits for lightweight systems modules. To operate efficiently, strategic and tactical sensor and communications systems require small, compact microelectronic components such as microprocessors, electromechanical systems, and photonic devices – now known as microsystems.

In the mid-1970s, integrated circuits (ICs) became the core of the commercial electronics industry while vacuum tubes largely disappeared from general use. During this period, DARPA research in command and control systems led to developments in computer processing power and speed. After the first computer networks went online in the late 1960s to form the core of what became ARPANET, research moved to related areas such as artificial intelligence and communications applications, and these drove continued enhancement of microelectronics. Beginning in the early 1980s, DARPA began advancing the concept of strategic computing, which rationalized investments across a range of technologies including very large-scale integration technology, dense integrated circuits, and computer-aided design (CAD) tools to support the creation of those circuits.

With the continuing reduction in transistor feature size and integration density, and to deal with both the increasing complexity of integrated circuit design and fabrication and the increased demand to push the boundaries of computer performance, the Very High Speed Integrated Circuits (VHSIC) program was spawned. The VHSIC program drove development of CAD tools, and these capabilities, together with the agency's support of largely academic research in the 1980s, created a broad program for innovative chip-scale architectures, including, for example, the development of Application Specific ICs (ASICs) for signal-processing applications. With further DARPA support provided by the DARPA-sponsored Metal Oxide Semiconductor Implementation Service (MOSIS) facility, which enabled researchers without easy access to IC fabrication facilities to have their ideas transformed into prototype hardware, these programs contributed considerably to advancing microelectronics and led to a surge of chip-scale computational and architectural concepts.

Beyond microelectronics, the microsystems research supported by DARPA during this period included major investments in components for sensor systems. According to DARPA's Deputy Director Robert F. Leheny, the agency's optics research ranged from work on communications and sensing systems to laser weapons. DARPA provided significant support for the development of lasers, which within the DoD were initially investigated for high-power weapons applications. During this period, relatively little government funding was directed at optical communications, but as the bandwidth required for communication among digital systems continued to increase through the 1980s, interest in employing lasers for this application grew.

Leheny notes that from an engineering perspective, diode lasers for use in communicating over short distances do not require high-performance designs, which enabled development of very inexpensive-to-manufacture diode lasers for commercial applications. Costing less than a dollar per unit to manufacture, these lasers became the basis for laser discs, point-of-sale scanners, laser pointers, and other mass-produced systems.

History of DARPA Microsystems Technology Program Areas

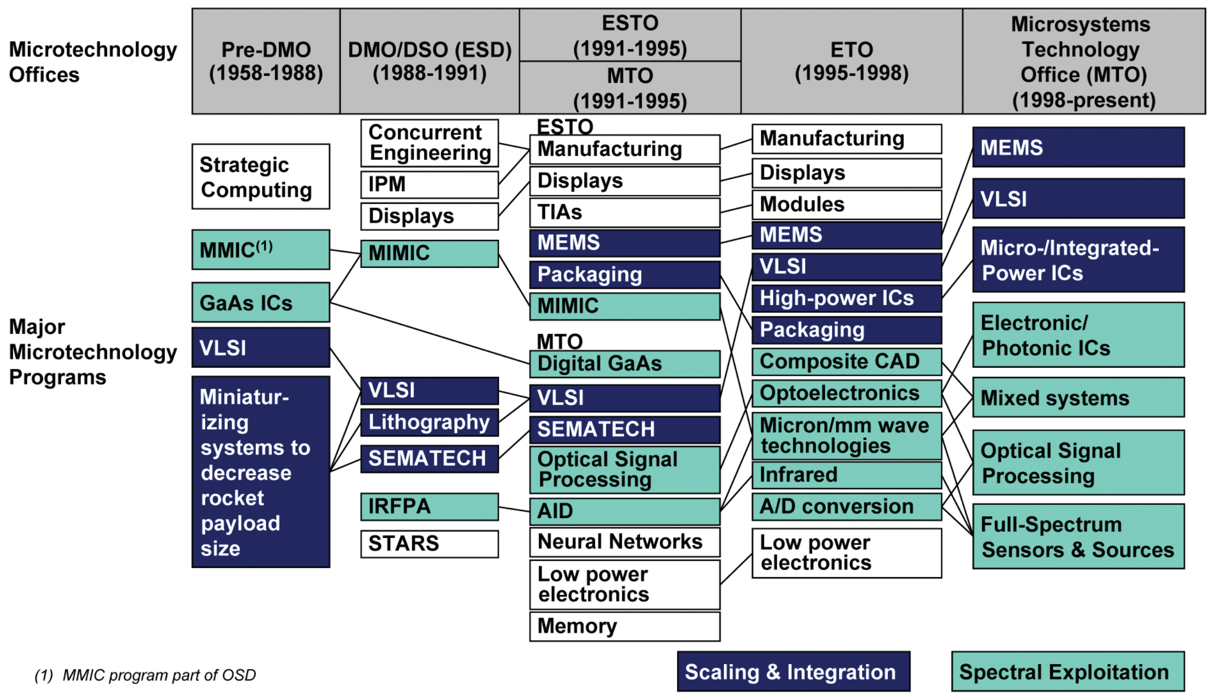


Image courtesy of DARPA

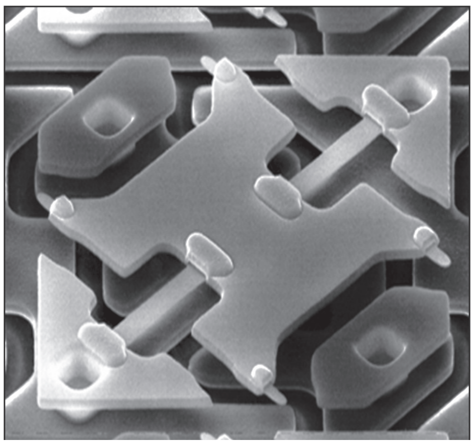
But lasers for communications require greater performance and are more difficult to fabricate. Leheny explains that in the 1980s, these systems could cost as much as $10,000 each. For telecommunication applications, a single communication-grade laser supports the transport of many signals, with the cost of the device distributed across thousands of users. During the 1980s, commercial telecommunications firms developed cost-effective means to send data over hundreds of kilometers, and Leheny notes, "The cost of these optical components per user was measured in dollars, making the use of lasers economically attractive. But at DARPA, we had a situation where we wanted the quality of a telecommunication laser in a package that was cost-effective for use in interconnecting racks of equipment in a computer system. The challenge for optical interconnection in digital systems was to get the cost of the optics down to an affordable range." In the mid-1980s, DARPA set out to develop very inexpensive diode lasers based on a novel vertical-cavity design. With these devices, known as vertical-cavity surface-emitting lasers (VCSELs), the agency ultimately solved the challenge of sending data over low-cost optical links for short distances ranging from 10 to 100 meters.

In parallel, beginning in the mid-1980s, DARPA undertook a variety of computer systems infrastructure activities. Leheny notes that the Semiconductor Manufacturing Technology (SEMATECH) consortium was founded with government support in the late 1980s to help overcome competition from foreign semiconductor firms. The government/commercial partnership was established to reverse this trend, with DARPA representing the government's interests to achieve this goal. The outcome of the SEMATECH effort was the development of a new set of tools and process capabilities that helped reestablish U.S. leadership in microelectronics.

During the 1990s, the agency was also heavily involved in a number of other major efforts including: developing microwave and millimeter-wave monolithic integrated circuit (MIMIC) technology for use in electronically scanned phase array radar; research on new microelectronics capabilities for microelectromechanical systems (MEMS); lithography technology research, including short-wavelength-laser-based lithography tools for fabricating semiconductor chips; and support for High-Definition System (HDS) display technology. Leheny explains that the latter activity was begun in recognition that foreign firms had achieved a competitive and technological lead in developing flat-panel, liquid-crystal displays just as these technologies were becoming important for use in military systems as they moved away from displays based on cathode ray tubes. The HDS program was aimed at correcting this situation.

By the end of the 1980s, the agency's microelectronics programs had grown very large, prompting DARPA to create two new offices: the Microelectronics Technology Office (MTO) and the Electronics Systems Technology Office (ESTO). In 1995, MTO and ESTO were merged to form the Electronics Technology Office

Below: MEMS technology enabled the digital micromirror device, the engine of digital light processor (DLP®) high-definition television systems. Right: DARPA launched MEMS technology in the early 1990s and early 2000s by developing processes to design and manufacture the structures. Tiny MEMS gears are seen here.



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(ETO). This office was subsequently renamed the Microsystems Technology Office (MTO) in 1999 to more accurately represent the broad mix of component technologies it was developing.

CURRENT RESEARCH

MTO has a broad portfolio of technologies in different microelectronics subject areas. Its research focuses on integrated microsystems as "platforms on a chip" and falls into five areas: electronics, photonics, MEMS, architectures, and algorithms.

The office has just launched a program to put optical networks on chips. Former MTO Director John C. Zolper explains that a key bottleneck in current computer design is the interconnect bandwidth on a complex circuit. One way to solve this issue is to use photonics. However, the challenge is building small, low-powered components with the right performance metrics to be compatible with a complementary metal oxide semiconductor (CMOS)-type fabric. If this goal can be achieved, he believes that it would be a hundredfold power advantage, particularly in the multi-core microchip architectures being developed by the commercial computer industry. He describes the multi-core processor challenge as a network issue, with each node requiring connection in a high-performance network on a circuit board.

Another area of MTO research is examining new ways to build transistor switches while addressing power dissipation. Classic CMOS transistors are limited to near 1-volt operation. DARPA has a program examining a new type of physics with the aim of developing a device that can operate at voltages as low as a quarter-volt. Called the Steep-subthreshold-slope Transistors for Electronics with Extremely-low Power (STEEP), the program's goal is to drastically cut the voltage consumed by transistors without reducing performance. STEEP program contractors are examining different device concepts that commercial industry views as too high-risk or too advanced for immediate application. "If we can show it's something that can be done, it's something that will be quickly adopted," Zolper says.

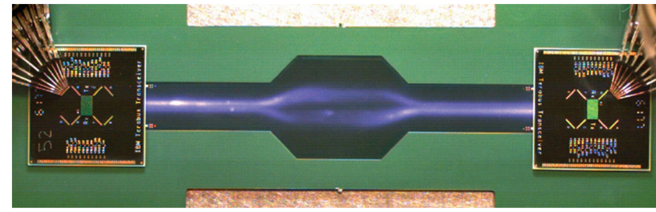
MTO is also pushing fundamental performance in photonic devices. One effort is emphasizing laser efficiency, which Zolper notes is important for systems such as tactical high-power laser weapons. Powerful lasers have been demonstrated in laboratories for decades, but they tend to be huge devices with massive power sources, making them impractical as tactical weapons. DARPA is examining semiconductor diode lasers for use as first-stage pump lasers for larger systems. The Super High-Efficiency Diode Sources (SHEDS) program has increased the efficiency of laser diodes from 30 percent to between 60 to 80 percent. He notes that these efficiency increases ripple throughout an entire high-power laser system and will have a large impact on achieving small enough form-factors to make these systems practical for tactical platforms.

By emphasizing research into vital components for laser systems, Zolper maintains that the technology's state of the art is pushed forward. "MTO won't build the whole high-power laser system, but we'll enable a viable path to a tactical system," he says.

For photonics detection systems, MTO is seeking to increase the sensitivity of systems until they can detect single photons in different wavelength bands. This research is driving the development of focal plane imagers for new classes of thermal- and infrared-imaging systems. Zolper explains that the DoD has enjoyed an advantage in night-fighting systems by "owning the night" for decades. But many of these technologies are now either commercially available or used by other nations. The agency is driving the next generation of focal plane technology to maintain the United States' advantage in imaging in harsh environments, such as at night or through smoke. But he cautions that these devices face key design issues such as increased

Image courtesy of Sandia National Laboratories sensitivity and the need for room-temperature performance to reduce size and power-consumption requirements.

Zolper notes that a past DARPA success was developing long-wavelength microbolometers that can operate at room temperature, which enabled room-temperature, soldier-portable infrared sensors. The MTO is working to extend this room-temperature approach to mid-wave infrared detectors that currently are cryogenically cooled. "We're really working across the whole spectrum, from ultraviolet to long wave," he says. MTO is also examining areas such as millimeter wave and terahertz focal plane imaging, where different phenomenology will afford new imaging and sensing capabilities in the future.



DARPA is looking to photonics to solve the problem of interconnect bandwidth on complex circuits. It has recently launched a program to put optical networks on chips.

Image courtesy of DARPA

ELECTRONICS

In electronic components, in addition to the digital electronics mentioned earlier, MTO is pushing the frontiers of high-frequency analog circuits and mixed-signal circuits, such as analog-to-digital and digital-to-analog converters. Zolper notes that mixed-signal conversion is often a major bottleneck for defense systems, especially in the areas of signal processing and detection in applications such as electronic warfare and electronic intelligence. "We want to be able to detect very broadband signals, and we want to be able to detect small signals in the presence of large background signals with requirements that extend well beyond current commercial needs," he says.

MTO is working on methods to increase signal precision and resolution and reduce the power requirements of mixed-signal circuits. One part of this effort is to focus on enhancing core transistor performance. For mixed-signal circuits, Zolper says the ideal transistor is highly linear with good noise performance and high bandwidth. DARPA has developed a family of indium phosphide compound semiconductor transistors known as heterojunction bipolar transistors (HBTs). Zolper explains that HBTs are typically used in analog-to-digital converters. For example, the goal of the Technology for Frequency Agile Digitally Synthesized Transmitters (TFAST) program is to develop transistors capable of operating at 500 gigahertz, with plans to develop transistors that can perform at terahertz levels. "If you have a transistor that can switch at 500 gigahertz, you can build circuits that have higher dynamic range and broad bandwidth," he says.

Mixed-signal circuits will typically operate at a tenth of the transistor speed. TFAST circuits will clock at 20 to 50 gigahertz and directly synthesize radio frequency (RF) signals at half this frequency range. He adds that this approach changes how engineers think about RF architecture, allowing them to exploit digital control of the RF signals in new ways.

The work on TFAST is being leveraged into other programs to push the boundaries of RF and mixed-signal technology. DARPA is examining circuit architectures to help enhance bandwidth and reach theoretical design limits. Zolper notes that there are ways to achieve this approach through algorithms performing digital correction techniques. These methods exploit advances in digital signal processing and algorithms to correct for nonlinear effects to provide enhanced performance. He adds that while these advances have been demonstrated in laboratory environments, they have required large amounts of power and hardware, which is not practical to implement in a tactical military system. A major requirement will be to move these technologies into smaller form-factors at lower power for tactical use. By developing more advanced algorithms and employing advanced digital circuit technologies, it may be possible to map the algorithms into a chip that might require only 5 watts of power as opposed to an entire rack of electronics. "Then it becomes interesting," he says.

MTO and its predecessor offices were the key developers of gallium arsenide and indium phosphide MIMICs. These circuits were originally developed in the 1980s and early 1990s as integrated circuits for radar applications. Zolper notes that, at the time, it was seen that performance advances could be achieved in discrete devices. "People understood that if you had these devices, you would build your radar in a different way. You could make an active aperture radar that has improved sensitivity," he says, adding that active aperture systems have advantages over a single-source, corporate-fed, radar architecture.

However, in the late 1980s and early 1990s, the core components for these enhanced radar systems did not exist. The MIMIC program and the follow-on MAFET (Microwave and Analog Front End Technology) program established the first gallium arsenide RF technology that led to the cellular commercial infrastructure. Zolper explains that the front-end of commercial cellular telephones use gallium arsenide chips to transmit the signal because they provide better noise reduction and higher efficiency than silicon circuits. "When DARPA invested in this technology for defense applications, no one saw it as a key commercial market opportunity. But it absolutely enabled a huge market today that wouldn't exist otherwise," he maintains.

DARPA has historically worked with gallium arsenide and indium phosphide as the building materials for its RF circuits. However, since 2001, DARPA has developed wide bandgap materials such as gallium nitride for RF applications under the Wide Bandgap Semiconductors Technology Initiative (WBGS-RF). Transistors made with gallium nitride can operate at 10 times the voltage of silicon or gallium arsenide transistors because of the breakdown voltage of the wide bandgap semiconductor. This feature allows systems to operate at five to 10 times the power of conventional circuits, or it can be exploited to realize broader bandwidth circuits or higher efficiency circuits, depending on how designers chose to optimize transistor and circuit.

MTO is in the process of defining the next phase of WBGS-RF. The high-power amplifier circuits will then be inserted into radar and electronic warfare systems. Zolper says that initial commercial uses could include cellular base stations and applications where high power and efficiency are requirements. Another application with potential commercial appeal is in wireless WiMAX cards for laptop computers. He describes this as "third-generation" RF technology, with the first generation being silicon and the second being gallium arsenide and indium phosphide. The third generation will be gallium nitride wide bandgap technology. He predicts that this will have a huge impact on defense systems and potentially commercial systems as well.

MEMS

One of the major focus areas for MTO research is in microelectromechanical systems. The goal is to exploit manufacturing techniques originally developed to build integrated circuits and construct small mechanical devices. The initial focus was on sensors for equipment like accelerometers. Zolper notes that DARPA launched MEMS technology in the early 1990s and early 2000s by developing processes to design and manufacture these structures. "Today the airbag in your car is set off by a MEMS accelerometer. It's really low-cost and has a fast enough response time to trigger the airbag in time to protect the passenger after a collision," he says.

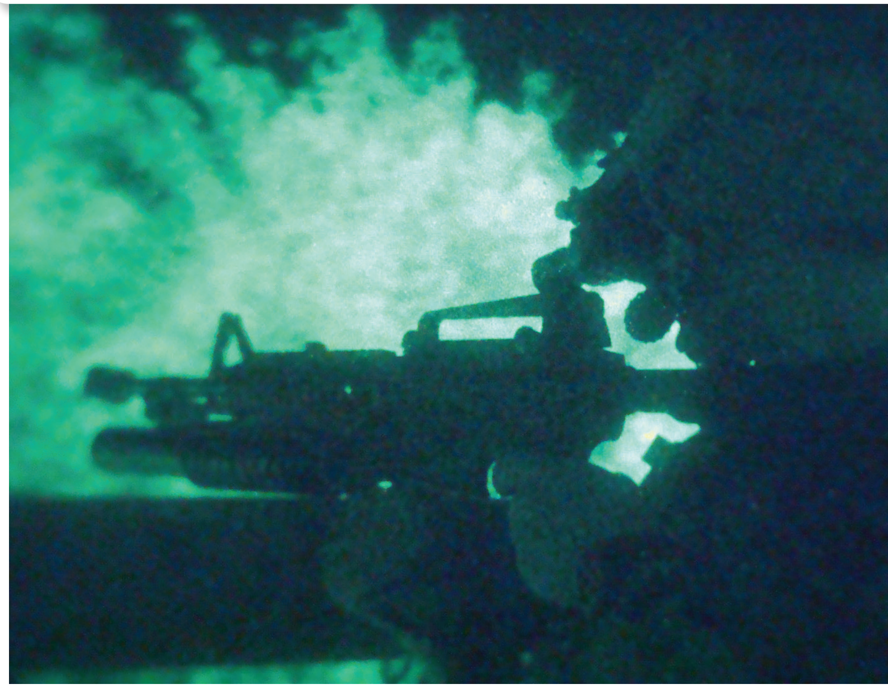
In defense applications, accelerometers and gyroscopes were initially used in navigation and guidance applications. DARPA is continuing to pursue this research by enhancing the performance of MEMS-based gyroscopes. A major challenge is to overcome the reduction in stability performance associated with the smaller mass of a miniaturized gyroscope. To counter this, MTO launched a program called Navigation-Grade Integrated Micro Gyroscopes (NGIMG), which is attempting to develop very small or microgyros, with stability equivalent to the larger gyroscopes used for navigation. The research is exploiting micromachining technology to build ultra-high-speed levitated disks, precision resonators, and resonant atomic vapor cells.

THERMAL/COOLING PROJECTS

Dissipation of waste heat is a key challenge for all electronic systems. DARPA is exploring methods to mitigate heating by making microsystems more efficient; however, DARPA is also developing better ways to remove thermal waste. A new program called the Thermal Ground Plane (TGP) seeks to solve these issues by more efficient heat transfer from an active device to a heat sink. The most efficient way to move heat is with a heat pipe. Heat pipes are usually copper tubes filled with a vapor that moves the heat from one end of the pipe to another by exploiting the phase change inside the tube. The TGP program is attempting to use new technologies and advanced materials to make heat pipes more efficient and more compact. The effort is examining the use of nanomaterials and nanostructures to optimize heat movement.

Zolper shares that most electronics operate more efficiently when they are cooled down. However, the power and size overhead that comes with conventional cooling approaches can be an issue for lightweight military systems. MTO is approaching the issue of cooling through its Micro Cryogenic Coolers (MCC) program. These devices are designed to cool specific areas of critical components. Zolper explains that on a typical RF circuit, only the first transistor in the chain must be cooled because that is where the noise figure and performance are most critical. The effort is using MEMS devices to build local cryocoolers onto a microchip. This has a variety of applications because it allows selected parts of microsystems to be cooled instead of entire devices, requiring significantly less power.

Today's U.S. military "owns the night" in large part due to past and continuing DARPA research. Here, a soldier from the 2nd Battalion, 27th Infantry Division, provides cover fire while looking through his AN/PVS-7 night-vision goggles on Tinian Island during Exercise Tandem Thrust 2003.



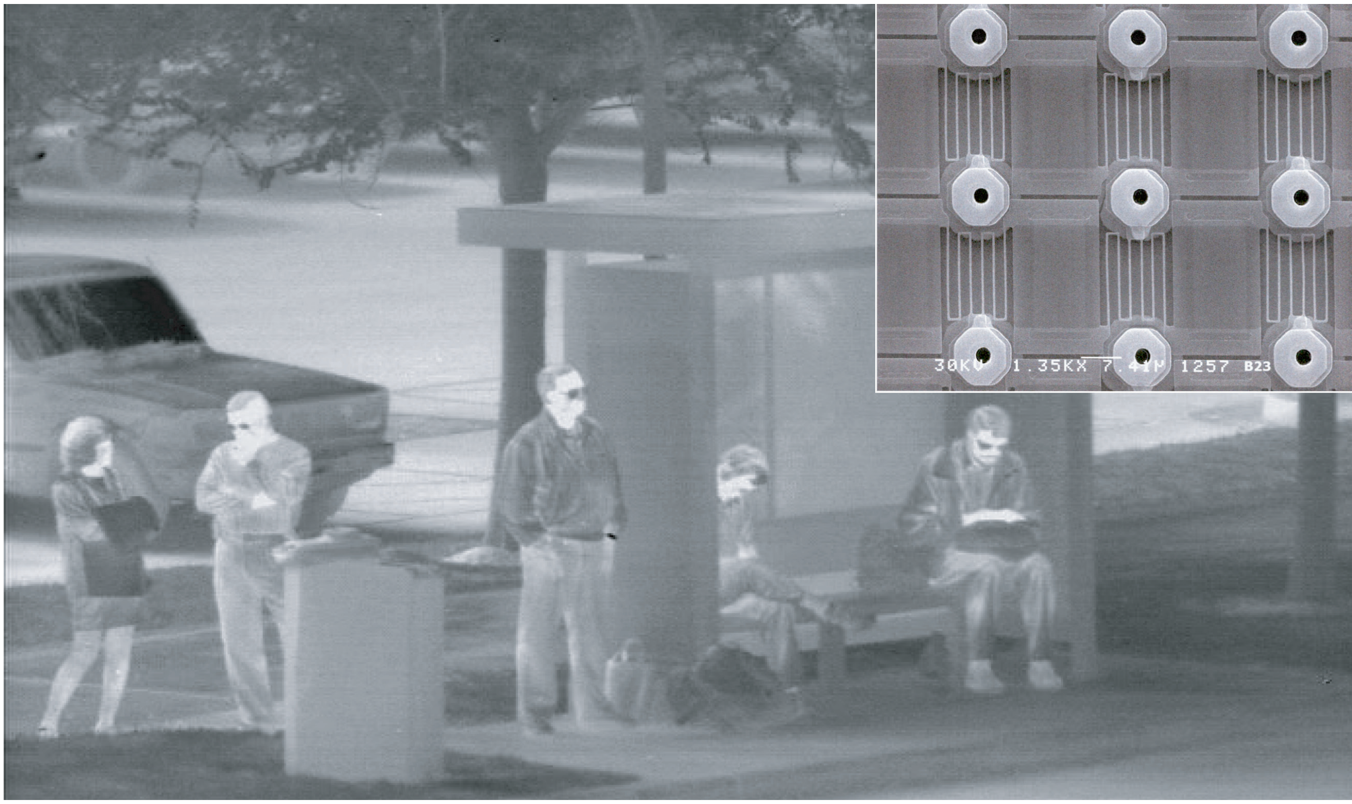
SSG Michael R. Picklo; USMC

MATERIALS RESEARCH

MTO also conducts a range of materials research as it pursues developing ever smaller and more power-efficient microsystems. Examples such as the Thermal Ground Plane and carbon nanotubes are areas where MTO researchers are seeking to use new methods to solve microsystems issues for the DoD.

In MTO's STEEP program, researchers are developing new materials and structures to reach the goal of developing a low-voltage digital switch. He notes that the first phase of this program was a materials research effort to make new systems and structures.

DARPA is also working on power electronics for applications such as high-voltage semiconductor switches. MTO developed a silicon carbide transistor, for example, that can block and switch 13,000 volts. One application for these transistor switches is in power substations to convert voltages; for example, the U.S. Navy's



Above: The DARPA room-temperature infrared imaging system is the key element of soldier-portable night-vision goggles. Below: DARPA's Chip-Scale Atomic Clock program addresses the military priority of precise timing. The 1 cubic-centimeter devices integrate electronics, photonics, and MEMS.

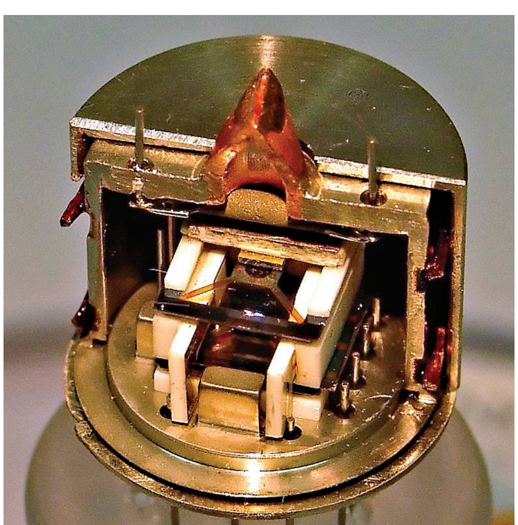


Photo courtesy of DARPA

Image courtesy of DARPA

next-generation aircraft carriers will distribute power at 13,000 volts, which is considerably higher than the 4,000-volt systems used by the current generation of carriers. The Navy is also considering using the MTO-developed silicon carbide switches to produce a compact solid-state power system for military applications.

The Navy's basic shipboard transformer is 10 cubic meters in size, weighs 6 tons, and has a fixed output. DARPA's goal is to develop a semiconductor version of the transformer that will not only be smaller and more efficient, but can be designed to have multiple taps. He notes that the Navy requires varying voltage taps of 440 volts, 270 volts, and 110 volts for a range of uses. DARPA has a memorandum of agreement (MOA) with the Navy's Program Executive Office for Aircraft Carriers and the Office of Naval Research to develop silicon carbide, high-voltage switches and diodes. The goal is to develop devices that can handle 13,000 volts and switch at 20 kilohertz, which is very high speed for a high-power transistor. The agency has developed the transistors and is now working with the Navy to build the first prototype solid-state converter as a potential solution for the Navy's future aircraft carriers. Potential commercial applications are power converters for hybrid vehicle engines.

CHIP-SCALE ATOMIC CLOCK

The Chip-Scale Atomic Clock (CSAC) program, which integrates electronics, photonics, and MEMS to form a timing module with atomic clock precision in a compact (1 cubic centimeter) package, exemplifies MTO's efforts in microsystems. As the U.S. military moves toward a network-centric force, timing is a key mission priority. "For the network to work, everybody has to have the same time reference," says Zolper.

According to Amit Lal, the CSAC program manager, the major need for chip-scale atomic clocks is in communications and navigation systems. Most modern radios operate by sending data in small packets using Time Division Multiple Access (TDMA), where the time reference is received from GPS satellites. Different times are allocated to different radios operating on the same frequency. These data packets have guard bands that protect individual packets from overlapping. This timing feature ensures communications; however, if GPS signals are jammed, U.S. forces face the risk of not only losing navigation, but also losing the time reference for the entire network and thereby losing communications. A chip-scale atomic clock provides a compact addition to their radio that not only preserves synchronization, but also allows reduction of the guard band so that twice the information can be transmitted, explains Lal.

Having a CSAC in each radio can also alleviate the issue of self-jamming. If several jammers in the same unit simultaneously attempt to operate, they will interfere with each other if their timing is off; they will also interfere with, or unintentionally jam, other communications systems in the area. "What an atomic clock might allow is to work the system much faster without self-jamming," says Lal.

For navigation applications, a major challenge is GPS-denied navigation. For example, if soldiers go into a cave or building, they can lose GPS connection. CSAC will allow timekeeping so accurate that when soldiers

DARPA's Vertically Integrated Sensor Arrays program integrates an infrared-sensitive layer of mercury cadmium telluride with a focal plane array, as shown in this cross section.

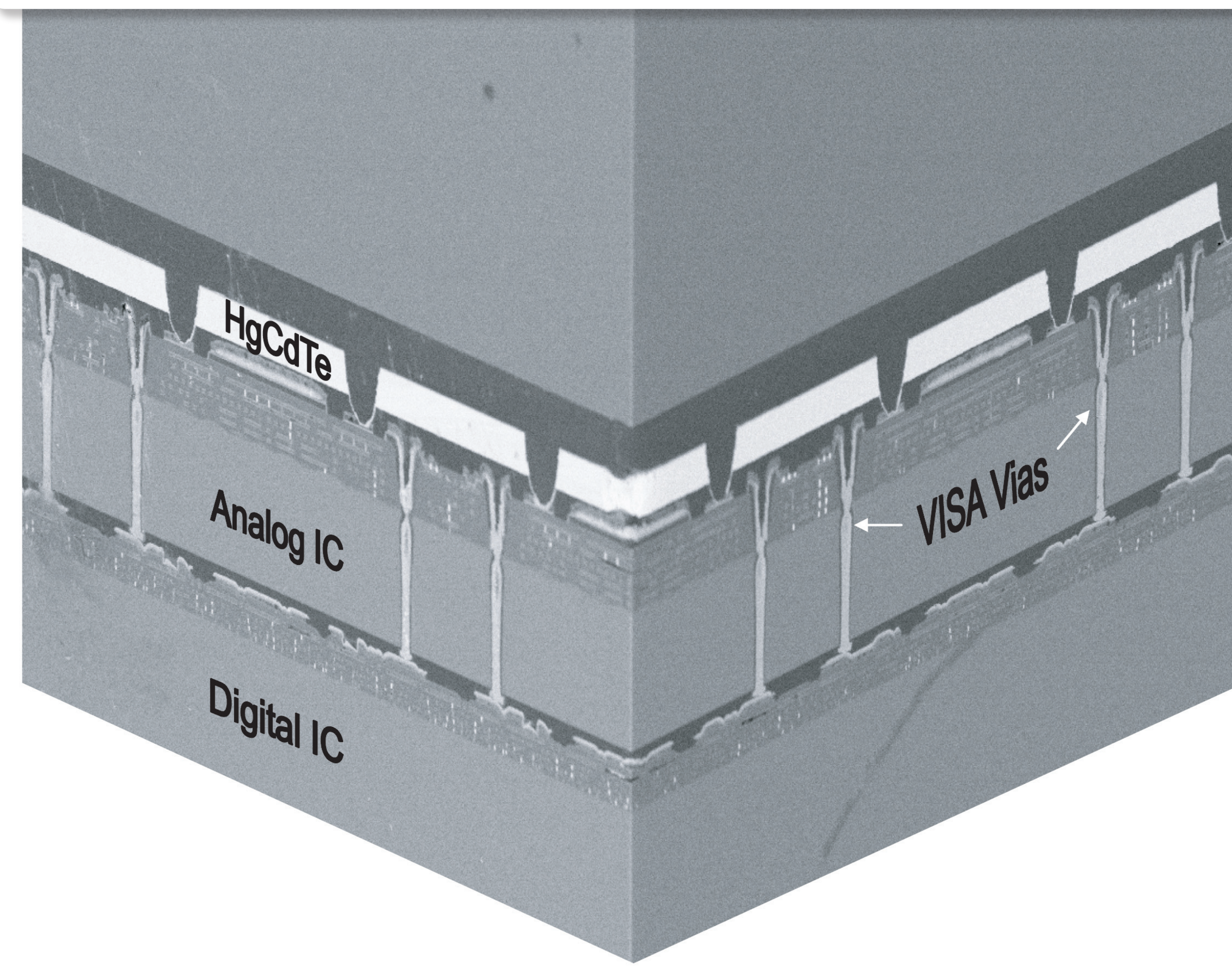
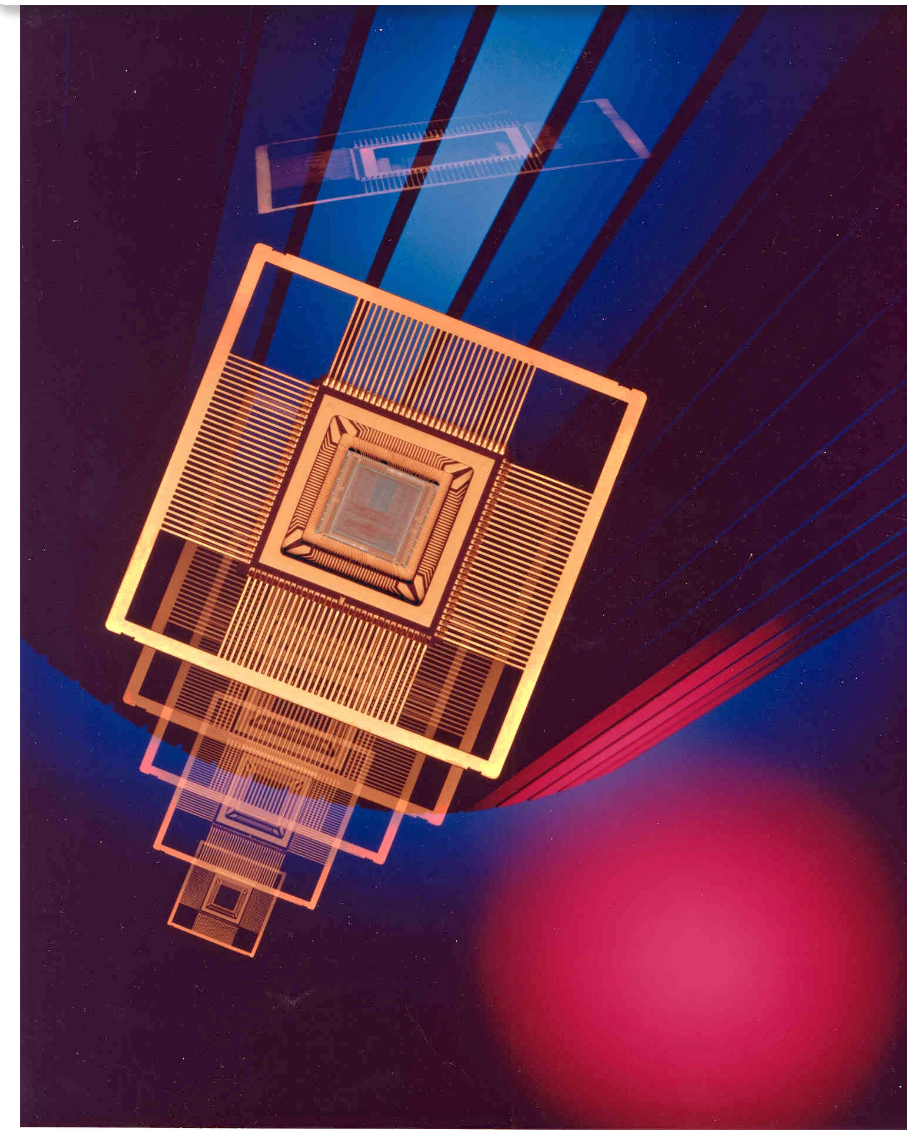


Image courtesy of DARPA

Below, left: The Very High Speed Integrated Circuit program was DARPA's answer to the increasing complexity of integrated circuit design and fabrication as well as the demand for increased computer performance. Below, right: With its Technology for Frequency Agile Digitally Synthesized Transmitters program, DARPA is developing transistors capable of operating at 500 gigahertz and higher.



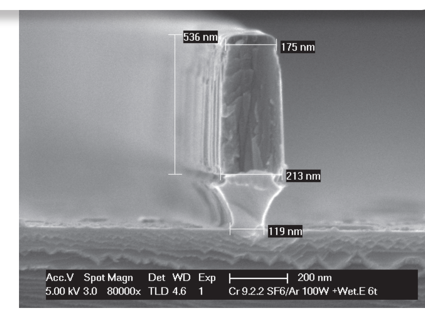


Image courtesy of DARPA

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emerge from a cave or building, their clocks are still synchronized with the GPS system, allowing rapid (within milliseconds) GPS re-synchronization.

Currently, atomic clocks have a power consumption of between 5 to 10 watts and the smallest available have a volume of 200 cubic centimeters. CSAC represents a reduction in size of 200 times, to 1 cubic centimeter – roughly the size of a sugar cube – and power requirements down to 30 milliwatts.

The technology enabling this extreme size reduction consists of a VCSEL, a micromachined metal vapor cell, a tiny photon detector, and integrated feedback and control electronics. However, the key enabler is the MEMS physics package: a gas cell a fraction of a cubic centimeter in size that contains alkaline metal vapor of cesium or rubidium, which is heated to produce the metal vapor at 90 degrees centigrade while drawing only 5 milliwatts of power.

Lal points out that micromachining processes are a key technology behind the CSAC program. He notes that techniques for bonding glass and silicon wafers together allow scientists to precisely control the properties of the gas cell. "Micromachining allows you to encase these metals in a controlled environment and keep them for months and years," Lal explains. He notes that the combination of novel thermal isolation and the low-power VCSEL allows the CSAC to operate with only 30 milliwatts of applied power, which at this level greatly extends battery life. Lal notes that before the program, it was an impossibility to put an atomic clock in every soldier's kit. "It's never been done before. It puts a new perspective on how people actually look at time," Lal says.

Even in applications where power is not important, size is still important. Lal notes that the Army could use four or five CSACs in each of its vehicles to synchronize sensors. "If you're keeping time and you're collecting data, if you time stamp accurately, then you can really see correlations in time. If your clocks are not synchronized, you won't get it," he says.

The CSAC program recently entered the final phase of its development. This phase will test the miniature atomic clock to military reliability specifications to determine failure modes. If the device meets military standards, then it will go into production and will spiral into combat radios and other applications.

Zolper notes, "This success in integrating all the components of a microsystem [electronics, photonics, and MEMS] into a chip-scale atomic clock is a precursor of future research directions in shrinking macro-scale systems to the micro- and nano-scale to not only reduce their size, but also reduce their power requirement and increase their performance."