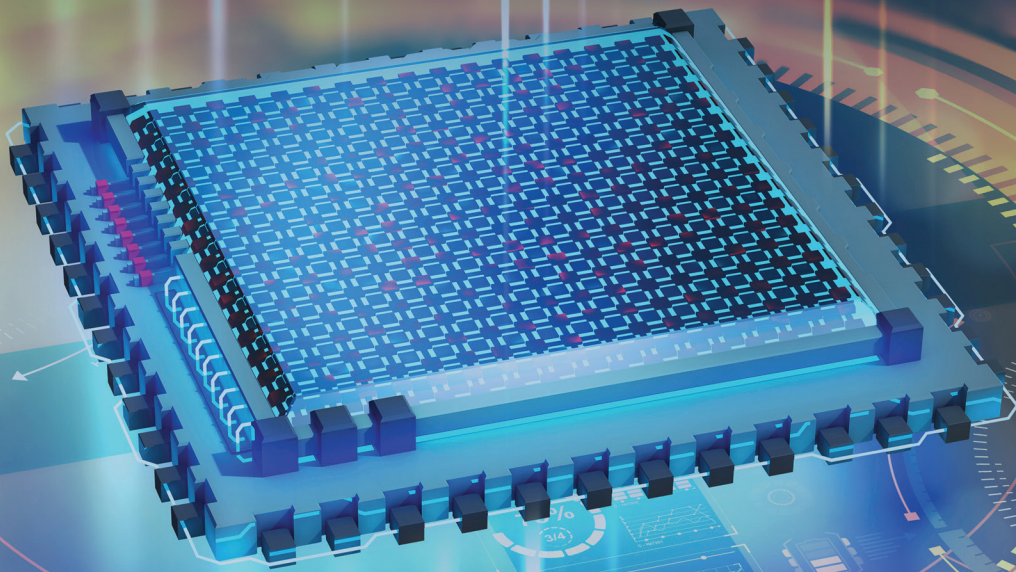




QUANTUM SENSING AND COMPUTING



Advancing National Security Through Fundamental Research

QUANTUM SENSING AND COMPUTING



THE NEED AND OPPORTUNITY

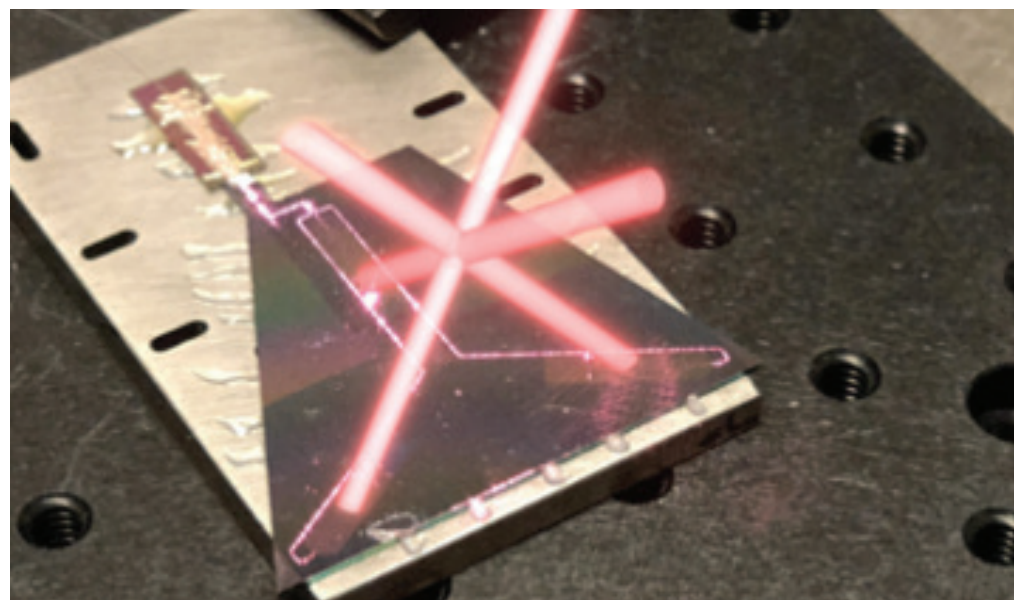
An epitome of high technology since the middle of the last century has been built on breakthroughs in the fundamental physics of electronic behavior in solids and in the engineering it takes to manipulate and exploit that behavior. That led to nothing less than the microelectronics and computer revolutions, which in turn have accelerated advances in all other categories of technology while transforming almost all aspects of life and society, including national security.

The relentless miniaturization over the past 70 years of transistors, circuits, and other electronic components has enabled ever more sophistication in the computation, information, communications, and other technologies reliant on predictable electronic behavior. The size of components on chips is so minuscule now that quantum-mechanical effects are becoming both a limiting factor and an opportunity multiplier. In traditional integrated circuits, these quantum effects can reduce the stability of a one or zero state of transistors thereby eroding the technology's all-important reliability. At the same time, leveraging the strengths of quantum effects can open the way to new defense-relevant capabilities including more secure communications and computations of unprecedented complexities.

THE DARPA SOLUTION

For decades, DARPA's investments in quantum research has laid the foundation for next-generation military capabilities such as positioning, navigation, and timing (PNT) in GPS-denied environments; quantum computing; and ultra-secure communications. In the 1990s, DARPA made initial investments for studies into manipulating and measuring the quantum properties of an electron's spin. These commitments helped seed the field of spintronics, which became the source of pivotal advances in digital storage technologies. This fundamental research, along with more than a dozen subsequent quantum

science programs, opened pathways to a new generation of quantum sensing technologies. These have included ultraprecise timing, inertial measurement for precise position and motion sensing, and magnetic and electric field sensing. For example, the Chip-Scale Atomic Clock (CSAC) program (2001-2009) created a miniaturized, low-power, time and frequency reference unit. Compared to traditional atomic clocks, those that evolved under the CSAC program achieved a 100-fold size reduction while consuming 50-times less power and spawned commercially available CSAC technology.



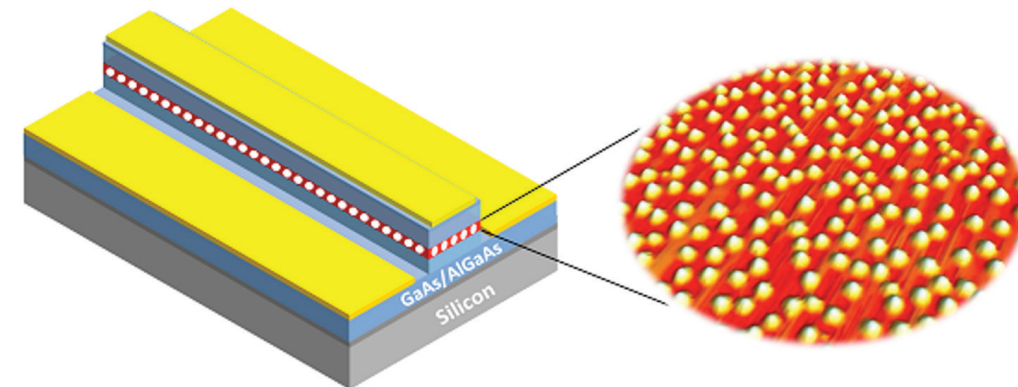
In this atomic-clock component designed to trap rubidium atoms for precise monitoring, light-guiding channels glow from the light they are directing. The otherwise invisible, intersecting atom-trapping beams coming out of the chip are indicated by a computer-rendered overlay. (Image courtesy of Honeywell)

THE IMPACT

DARPA's commitment to atomic-clock technology and quantum-centric R&D runs deep and wide. The Quantum Sensing and Readout (QuASAR) program (2010-2018), for example, was all about laying down the conceptual and technical foundations for quantum devices that could have broad applications across the DoD, particularly in the areas of biological imaging, inertial navigation, and global positioning systems. In 2013, researchers working under the QuASAR program reported building atomic clocks that measure time with a precision approximately ten times better than the world's previous best clocks, also developed under QuASAR. Since then, DARPA-funded atomic-clock researchers have continued to break world records.

DARPA has similarly invested over the past two decades in research investigating the intersection of quantum mechanics and information and communication technologies. In 2001, for one, DARPA launched the five-year Quantum Information Science and Technology (QulST) program. Prior to that program, no research effort had focused on the potential impact of quantum information and quantum networks on critical DoD and national level problems. QulST researchers included large commercial companies, 11 universities, military labs, and other government organizations - including the National Institute of Standards and Technology (NIST). This community of researchers continues to investigate the application of quantum mechanics to address computation, communication and networking challenges, some of which have proven intractable for classical approaches.

Much of DARPA's current effort in quantum technology is aimed at transitioning the world's most precise atomic clocks, which require pristine laboratory conditions to maintain their quantum characteristics, into operational devices for military use in



In this schematic of a quantum dot laser developed by researchers at the University of California, Santa Barbara, a gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs) quantum-dot laser is integrated atop a silicon substrate. On the right, an optical micrograph reveals the distribution of quantum dots.

rugged conditions. Such a capability could greatly reduce one of the more worrisome national security vulnerabilities: a deep and growing dependence on the Global Positioning System's (GPS) time reference signals. These master clocks at the heart of GPS have become pivotal components of the technological infrastructure not just within the military but also throughout the civilian sectors of the economy, from banking to telecommunications to the power grid. That's because the timing signals from satellite-based atomic clocks provide the key reference signals for synchronizing atomic clocks in use on the ground. The longer those clocks on Earth or on aircraft can maintain extreme accuracy in the absence of satellite reference signals, the lower the impact of any loss of satellite contact, whether due to natural causes or adversarial activities.

Building on previous DARPA CSAC research, the Atomic Clock with Enhanced Stability (ACES) program, which began in 2016, aims to develop battery-powered CSACs with 1000X improvement in key performance parameters compared to existing CSAC technology. The program is challenging innovators to deliver enhanced-stability clocks that demonstrate size, weight, and power (SWaP) reductions compared to laboratory-proven atomic clock technologies. The program also includes basic research efforts to explore novel component technologies and alternative-physics approaches that

could substantively impact future atomic clock architectures. Related to the ACES program, DARPA's Atomic-Photonic Integration (A-Phi) program calls for the invention of photonic integrated circuits as a tactic to miniaturize the optical atomic clocks developed in the QuASAR program as well as to shrink optical gyroscopes without any sacrifice in performance. Such advances would open up revolutionary capabilities for GPS-less PNT.

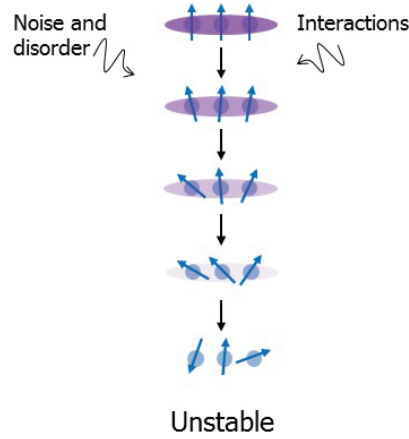
DARPA's focus on improving time-keeping has gone even deeper into quantum territory. Under the agency's All Together Now (ATN) program (2016-2020), researchers have been developing clocks that exploit optical frequencies instead of longer-wavelength microwaves. In this program, DARPA is aiming for optical-based atomic clocks with 1000-times greater stability and precision compared to current timing technology. Today's microwave-based atomic clocks on GPS satellites provide 10-nanosecond (billionth of a second) timing, whereas optical clocks could provide 10-picosencond (trillionth of a second) precision. This enhanced precision would allow for more robust GPS technology, since devices would require fewer updates. Based on a recent ATN demonstration of an all-optical atomic clock that outperforms all existing clocks, NIST has initiated an effort to develop a new optical time standard.

Another of DARPA's fundamental research programs, DRINQS (Driven and Nonequilibrium Quantum Systems), is focused on new methods to extend the time that atomic clocks and other quantum systems can maintain their quantum characteristics in "noisy" non-laboratory environments. The goal is to enable quantum bits, or qubits — the essential element of quantum information processing — to remain useful at room temperature, rather than requiring expensive cryogenic laboratory equipment. DRINQS research aims to lay the groundwork for future work on quantum sensing and potentially computing due to the convenience of room-temperature operation. In yet another quantum direction, the agency's current Atomic Magnetometer for Biological Imaging In Earth's Native Terrain (AMBIENT) program is nurturing technology that could lead to some of the most sensitive magnetometers ever made and could push the state of the art in brain-machine interfaces for controlling, say, prosthetic limbs, and for precisely diagnosing concussions in the field.

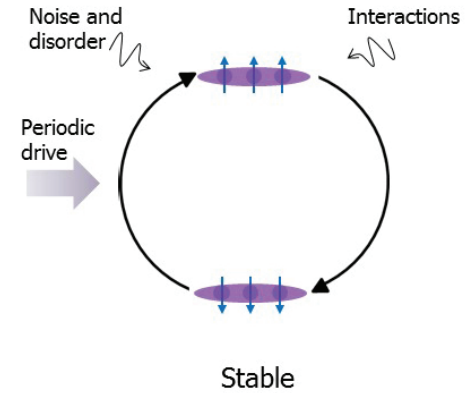
LOOKING AHEAD

Having laid a foundation for quantum computing over the past 20 years, DARPA now seeks to exploit emerging quantum processing technologies for national security. The Optimization with Noisy Intermediate-Scale Quantum devices (ONISQ) program is one of DARPA's newest programs in quantum information science. Announced in early 2019, ONISQ seeks to exploit and deploy quantum information processing before the

CONVENTIONAL SYSTEM



DRIVEN AND NONEQUILIBRIUM QUANTUM SYSTEMS APPROACH



In a typical quantum system (left) the combined effect of interactions, noise, and disorder leads to its coherence (denoted by the combined direction of the arrows) disappearing after a short period of time. The Driven and Nonequilibrium Quantum Systems (DRINQS) approach aims to stabilize the quantum system in the presence of the same disturbances by adding a periodic drive.

availability of fully fault-tolerant quantum computers (which still work even if some components fail), which seems likely to be decades away. Confronted by this delay, the ONISQ program is pursuing a hybrid concept that combines intermediate-sized quantum devices with classical computing systems with an eye on solving a particularly difficult category of defense-relevant problems known as combinatorial optimization. DoD optimization tasks include route planning, sensor/target assignments, and real-time supply chain management across the entire DoD Logistics Enterprise — still an intractable problem even with today's supercomputers. Along the way to an era of quantum computers, ONISQ seeks to demonstrate the advantage of quantum information processing by leapfrogging the performance of classical-only systems in solving optimization problems.

The Topological Excitations in Electronics (TEE) program also is addressing quantum computing challenges. The goal of TEE is to reveal how honing the ability to bend, stretch, or twist magnetic formations in materials can be used for realizing higher-density memory, more capable processing, new sensors, and stable qubits for fault-tolerant quantum information processing.

We have learned to build better clocks and sensors based on fundamental advances in our understanding of quantum physics. We also have glimpsed just how much we do not yet know as well as the potential that awaits. DARPA will continue to invest in fundamental and applied quantum research to ensure U.S. preeminence in these critical fields for national security.

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