History of Innovation

Texas Instruments Demonstrates Quantum Effect Transistor

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Research physicists at Texas Instruments in Dallas have fabricated the world's first quantum effect transistor. With critical dimensions 100 times smaller and transit speeds more than 1000 times faster the conventional transistors, the device operates on fundamentally different principles, known and quantum mechanical effects, which dominate the behavior of matter and energy at dimensions of 0.02 micron (20 billionths of a meter) and below.

Called a "bipolar resonant tunneling transistor," it becomes the first device to directly contact and control a "quantum well" base, an ultrathin layer of the device which allows only electrons with certain discrete energies to pass.

"Although quantum devices are strictly a laboratory development at this time, future chips incorporating quantum effect transistors might contain 100 times more functions in the same space and consume far less power than today's devices," notes Dr. George Heilmeier, senior vice president and chief technical officer at TI. "Practical applications are about a decade away, but one day we might see a laptop supercomputer that runs on flashlight batteries."

Devices integrating quantum effect components such as tunneling diodes into conventional transistors have previously been reported. Although such devices, in which a quantum structure is embedded in one of the transistor's terminals, exhibit certain quantum-related electrical characteristics, their size and function are essentially no different from conventional bipolar transistors.

By contrast, this first demonstration of a transistor in which all essential components of the device are confined to quantum dimensions and whose operation is based on quantum effects, marks a significant milestone in the development of a potential next generation of solid-state electronic devices, explains Dr. Heilmeier. "The increase in performance an decrease in cost per function that quantum effect devices promise make comparing them with today's semiconductors like comparing semiconductors with yesterday's vacuum tubes. This achievement is like a step toward realizing that promise."

The quantum effect transistor was developed by Drs. Mark Reed, William Frensley, Alan Seabaugh and other device physicists in TI's Central research Laboratories and is described in a paper being presented at the IEEE International Electron Devices Meeting (IEDM) in San Francisco. The bipolar device, a precursor to even smaller and faster unipolar quantum transistors that could revolutionize solid-state electronics, has active regions measuring on 10 to 20 nanometers (billionths of a meter) wide, about 10,000 times smaller than a human hair and 100 times smaller than the corresponding functional components in today's semiconductors.

At these ultrasmall dimensions, Dr. Reed explains, quantum mechanical effects, in which electrons act more like waves than particles, dominate the behavior of matter and energy. Electrons occupy discrete, non-overlapping energy levels or bands, and resonate, like one's voice in the shower, when confined to a region the size of their wavelength. These properties are critical to the operation of the quantum effect device, which offers the potential of extremely precise and efficient switching at speeds perhaps thousands of times faster than the best of today's semiconductor devices.

Possible applications for future superchips incorporating quantum effect transistors, explains Dr. Heilmeier, might include single-chip supercomputers and realtime image understanding systems.

A New Kind of Energy Barrier

Transistors, such as bipolar types in which voltage to a "base" terminal controls the flow of current from an "emitter" terminal to a "collector" terminal, are used as a kind of electronic valve to regulate current or to switch it on and off, depending on the type of circuit application. In conventional silicon transistors, physical barriers of semiconductor material (P-N junctions and depletion layers whose ability to conduct electricity changes with applied voltage) are raised and lowered by varying the voltage applied to the base terminal, allowing current to flow from the emitter to collector.

In quantum effect devices, the different discrete energy levels that are characteristic to the different materials in the base and emitter and collector act as barriers to current flow. Current flows only when voltage applied to the transistor base is modulated so that these energy levels become precisely matched and electrons can resonate, enabling them to "tunnel" across the base, and thus provide current flow from emitter to collector.

"The key technical breakthrough in developing the quantum effect transistor," explains Dr. Reed, "was in being able for the first time to directly control tunneling current by modulating the voltage potential inside the quantum-well, or base. Previous approaches to contacting and controlling the potential inside a quantum-well base have failed to address the basic problem of keeping the base isolated from the collector and emitter. Fabrication difficulties are secondary." In the Texas Instruments device, the voltage potential in the quantum well base is modulated by putting charge into the quantum well at an energy level or band below and separated from the energy levels, known as conduction bands, in which the working current tunnels across the base from emitter to collector.

The resonant tunneling transistor, Dr. Reed explains, is only an intermediary laboratory development on the road to a unipolar quantum transistor in which electrons will be confined to quantum proportions in all three dimensions. Nevertheless, the bipolar device, fabricated in gallium arsenide, aluminum gallium arsenide, and indium gallium arsenide, exhibits promising performance. Robert Bate, manager of advanced concepts in the Systems Component Laboratory of TI's Central Research Laboratories, notes that current gains at room temperature typically measure about 50, and that gains as high as 450 have been observed. Transit speeds, the speeds at which electrons tunnel from emitter to collector, are so fast that they're difficult to measure with today's technology, but are estimated to be on the order of femtoseconds (quadrillionths of a second).

Significant Developmental Hurdles Remain

"Although the quantum effect transistor marks a critical milestone toward what many people are calling 'nanoelectronics,' much developmental work remains to be done," Bate cautions. "Manufacturing and interconnecting such small structures reliably in production quantities demand techniques that have yet to be developed. Another impact of their minute size is that whole new circuit architectures will have to be devised."

Researchers in TI's Central Research laboratories have worked with quantum effect devices and architectures since 1982. Early work on resonant tunneling was supported by the Office of Naval Research and the U.S. Army Research Office. The first quantum effect transistor was realized under a contract awarded to TI by the Air Force Wright Aeronautical Laboratories. Similar work is continuing under a contract funded by the Defense Advanced Research Projects Agency (DARPA), a branch of the U.S. Department of Defense.

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