Wanlass's CMOS circuit

For the record

June 18, 1963: Frank Wanlass applies for a patent on complementary field-effect transistor circuitry that reduces the standby power consumption of digital logic by six orders of magnitude

Most people remember the '60s as the era of the Beatles, the Vietnam War, Woodstock, and 35-cent-a-gallon gasoline. But electronics engineers of a certain age remember them as the days of free-wheeling experimentation when—at some companies, at least—bright young Ph.D.s were given latitude to see what they could create without interference from corporate managers.

One bright young Ph.D. of that time was Frank Wanlass, who this February received the 1991 IEEE Solid-State Circuits Award for his invention of complementary-MOS (CMOS) logic circuitry.

Wanlass's interest in MOS technology dates to 1962, when he was still studying for his doctorate in solid-state physics at the University of Utah in Salt Lake City. Upon reading about the Radio Corporation of America's work with thin-film cadmium sulfide field-effect transistors (FETs), he became intrigued by the simple structure of the devices, which he thought would make it easy to design fairly complex integrated circuits. But the devices were unstable. When left on a shelf for just a few hours, their electrical parameters changed dramatically.

Wanlass believed that making the FETs in silicon would solve the problem. After all, Fairchild Semiconductor Research and Development had made some very stable and reliable bipolar transistors in silicon using its planar process, so why not use the same material to make stable MOSFETs?

So he went to work for the Fairchild Semiconductor subsidiary of Fairchild Camera and Instrument Co. in Palo Alto, Calif., in August 1962, unaware that other researchers were already working on silicon MOSFETs at both RCA and Bell Laboratories. A few months later, he made his first p-channel silicon MOSFETs, which, like all early MOSFETs, were a great disappointment. At 10–20 volts, their threshold voltages were very high and very unstable. They were no better than RCA's CdS devices.

Wanlass speculated that the aluminum gate electrode was diffusing into the gate oxide. If that were the case, the use of a more inert metal would solve the problem.

Michael J. Riezenman Contributing Editor

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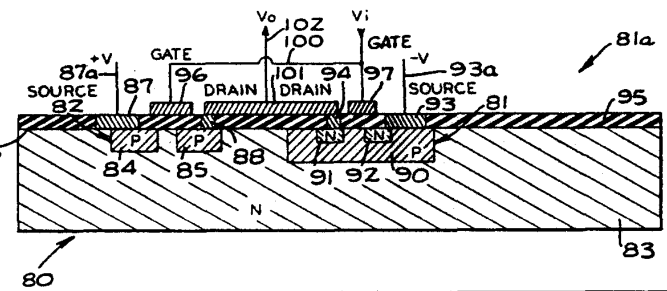
LOW STAND-BY POWER COMPLEMENTARY FIELD EFFECT CIRCUITRY

Filed June 18, 1963 5 Sheets-Sheet 5



Wanlass's patent portrayed an integrated CMOS inverter.

While investigating that possibility, he found to his surprise that aluminum electrodes deposited by an electron beam evaporation machine yielded quite stable devices. The problem, he began to suspect, was not aluminum diffusion after all, but contamination.

The usual way to deposit aluminum in those days was to evaporate it by placing an aluminum wire in contact with a heated tungsten filament. Wanlass reasoned that the process was introducing positive ions into the aluminum and thence the gate oxide.

Further investigation inculpated sodium contamination from both the tungsten and the aluminum. Electron beam evaporation solved the problem because the electron-beam apparatus had a shutter mechanism that protected the silicon wafers from a carbon crucible of molten aluminum until the aluminum was at evaporation temperature. The sodium, having a much lower boiling point, boiled away before the shutter opened.

Wanlass next had the idea for CMOS. "It occurred to me," he told *IEEE Spectrum* in a recent interview, "that a complementary circuit of NMOS and PMOS devices, if it could be made, would use very little power. In standby, it would draw practically nothing—just the leakage current."

His boss Gordon Moore, now the chairman of Intel Corp., gave him a free hand to pursue his idea. At first, Wanlass tried to build a CMOS circuit monolithically, but that was so difficult he decided to prove the concept with discrete p-channel and n-channel MOSFETs instead. Because only p-channel devices were available, he had to start by building an n-channel silicon MOSFET.

The CMOS concept requires that both of its transistors be enhancement-mode devices. But whereas PMOS transistors were inherently of that type, the n-channel MOSFET was not. It would be years before MOS surface physics was well enough understood to permit the fabrication of such devices. Consequently, Wanlass made depletion-mode n-channel MOSFETs and back-biased their bodies negative with respect to their sources to turn them into enhancement-mode units.

The concept worked. The first demonstration circuit, a two-transistor inverter, consumed just a few nanowatts of standby power. Equivalent bipolar and PMOS gates consumed milliwatts of power even in standby. CMOS shrank the standby power consumption by six orders of magnitude!

The speed was impressive enough, too. Propagation delay times were on the order of 100 nanoseconds—about half the speed of bipolar, but almost an order of magnitude faster than PMOS.

On June 18, 1963, Frank Wanlass applied for patent protection for his CMOS concept, and in due course, was granted U.S. patent no. 3 356 858, the rights to which became part of Fairchild's patent portfolio. That patent described the overall concept and three specific circuits—an inverter, a NOR gate, and a NAND gate—from which any digital function can be built. In addition to the discrete implementations that were actually built, the patent includes the representation of an integrated CMOS inverter shown here. (Wanlass's laboratory notebooks, with his original drawings, were lost, probably when Fairchild Semiconductor was taken over by National Semiconductor Corp. in 1987.)

Neither Wanlass nor Fairchild Semiconductor grew rich from the invention. In those days companies traded the rights to their patent portfolios. Still, the integrated CMOS inverter shown, although never built, is the progenitor of all CMOS ICs today. ◆

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