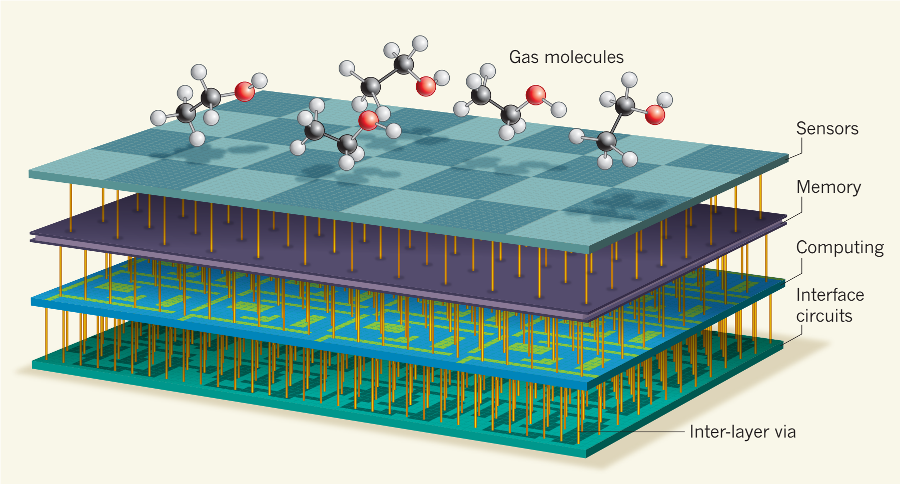

Figure 1 | A prototype 3D integrated circuit. Shulaker *et al.*[1] have constructed a 3D integrated circuit that can sense and classify ambient gases and vapours. Their integrated circuit contains four device layers that are joined by electrical connections called inter-layer vias. The top layer consists of carbon-nanotube transistors (electronic switches) that act as gas sensors. The next layer comprises memory cells that store the signals generated by the sensors. The third layer down hosts computational circuits made of carbon-nanotube transistors that use machine-learning techniques to identify the gas or vapour. And the bottom layer contains circuits made of standard silicon transistors that interface with the other layers to perform several required operations. The authors' prototype 3D integrated circuit demonstrates how emerging device technologies could be implemented in next-generation computing systems.

RRAM cells to identify the gas or vapour. The identification is achieved using a machine-learning technique called support vector machines, in which data are classified on the basis of the results of previous training[8]. Finally, the bottom layer contains conventional silicon-based circuits that interface with the other layers to perform several required operations, such as reading data from the RRAM cells and steering these data to the computational circuits.

The authors' integrated-circuit design provides a path forward to address some of the hardest technological challenges in computing: namely, maximizing energy efficiency, scalability and communication bandwidth. The CNFETs used for the computations are considered to be some of the most promising low-power alternatives to existing silicon-based transistors[9]. The monolithic 3D integration circumvents the inherent physical limitations of scaling in 2D. The use of inter-layer vias, rather than through-silicon vias, provides a tremendous increase in communication bandwidth, which enhances performance and saves power. The non-volatile RRAM cells eliminate the need for an external memory system, improving both energy efficiency and scalability. Finally, the monolithic integration of sensors could lead to a new realm of computing applications.

Nevertheless, Shulaker and colleagues' fabrication process has room for improvement. For instance, the lithography technique that the authors used to fabricate their integrated circuit is based on a 1-micrometre technology node — the minimum feature size of the transistors is 1 μm — and requires an operating voltage of 3 volts. The technique therefore lags far behind state-of-the-art commercial integrated circuits that use 10- to 14-nm technology nodes and voltages of less than 1 V (see go.nature.com/2tngik1). Scaling the present system to use state-of-the-art fabrication technology could bring substantial improvements in integration density, connectivity, performance and power consumption. However, this scaling might be limited by physical and economic challenges[3]. The physical challenges arise from the increased temperatures generated when multiple device layers are operated in a relatively small volume. To alleviate this problem, 3D integrated circuits should incorporate cooling elements in the stack, such as thermally conductive heat-spreading structures or layers of convective microfluidic cooling channels.

A more practical limitation is yield, which is defined as the fraction of integrated circuits that are fully functional in a fabricated sample. As more layers are monolithically integrated, the probability of a defect in a particular integrated circuit increases, limiting the number of fabricated layers[10]. To mitigate this challenge, 3D integrated circuits will probably contain more redundant structures than conventional integrated circuits to compensate for defects. Nevertheless, unlocking the potential of monolithic 3D integration could usher in many applications that blend sensors, memory and computing. These applications include embedded smart cameras that have high-performance artificial-intelligence capabilities, intelligent robots that swim and deliver drugs through the bloodstream, and artificial retinas. ■

NATURE

50 Years Ago

While the causes of clear air turbulence remain obscure, it is clear that it is often associated with temperature gradients in the atmosphere. Recent work at Oxford and Reading Universities may offer a way of detecting the gradients, and, by inference, the turbulence. If this can be detected far enough ahead of aircraft, evasive action can be taken … Dr J. T. Houghton of the Clarendon Laboratory at Oxford and … Dr S. D. Smith of the Department of Physics at Reading … have developed a radiometer which detects the infra-red radiation from carbon dioxide in the atmosphere … intended to provide a world-wide survey of the temperature of the atmosphere up to about 30 miles. At different heights in the atmosphere, the carbon dioxide band occurs at different wavelengths, so that by choosing a certain wavelength a certain height can be studied by the instrument in the orbiting satellite.

From *Nature* 8 July 1967

100 Years Ago

Efficient protection of the eyes from glare is a subject of considerable importance at the present time, but unfortunately a great deal of misconception has arisen in regard to it. Most glare protectors are designed for conditions of unusually strong illumination; generally speaking, for daylight … A great deal of experimental work has been done recently on the physiological effects of ultra-violet radiation in the eye, a quartz-mercury lamp being used as a source, which is especially rich in its emission of the shorter wave-lengths. The results … are that with long-continued exposure serious harm may result from the absorption of these shorter waves … but with low intensities of radiation regular exposures produce no permanent effect.

From *Nature* 5 July 1917