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SUPERCONDUCTIVE DEVICES

The performance, reliability, and importance of superconductive devices have developed rapidly since the middle 1960's. This growth has been stimulated largely by the Josephson effects. Despite the fact that these devices must be operated at liquid helium temperatures, usually 4.2 K or lower, they are now used for a variety of purposes both in and away from the low temperature physics laboratory. This article briefly describes the more important devices.

Superconducting Quantum Interference Devices. The most highly developed and widely used Josephson devices are Superconducting QUantum Interference Devices (SQUIDs). The two varieties of SQUID, the dc SQUID and the rf SQUID, are the most sensitive devices available to measure magnetic fields, magnetic field gradients, magnetic susceptibilities, and voltages. The dc SQUID consists of two Josephson junctions mounted on a superconducting loop [Fig. 1(a)]. The device shown in Fig. 2(a) is constructed of thin film; each of the two Nb-NbOx-Pb junctions is resistively shunted by a gold strip to eliminate hysteresis in the current-voltage (I-V) characteristic. A constant current greater than the critical current (maximum zero-voltage current) of the two junctions biases the SQUID at a non-zero voltage. The critical current and the voltage across the SQUID are periodic in the external magnetic flux, Φ_e, applied to the loop, with a period of one flux quantum, Φ_o. A change in flux, $\Delta\Phi_e$, that is much smaller than Φ_o can be detected with the flux-locked SQUID shown in Fig. 1(a). The feedback circuit generates a current in a coil inserted in the SQUID so that the flux in the SQUID is maintained at a constant value. The voltage, V_o, across the resistor, R_o, is proportional to $\Delta\Phi_e$.

The rf SQUID consists of a single Josephson junction on a superconducting ring that is inductively coupled to the coil of a cooled tank circuit. The tank circuit is excited at its resonant frequency, typically 30 MHz. The rf voltage across the tank circuit is amplified and rectified to produce a voltage that is periodic in Φ_e. The rf SQUID is then used in a flux-locked loop in a way similar to that of the dc SQUID. Several types of rf SQUID are commercially available; two examples are shown in Figs. 2(b) and (c).

The dynamic range of both rf and dc SQUIDs is typically 10^6 in a 1 Hz bandwidth, the frequency response is typically 0 to 50 kHz, and the flux resolution is typically 10^{-5} to 10^{-4} Φ_o $\mathrm{Hz}^{-\frac{1}{2}}$ for a SQUID inductance of 1 nH.

SQUIDs are frequently used in conjunction with a superconducting flux transformer, for example, the gradiometer shown in Fig. 1(a). A change in the magnetic field gradient $\partial H_z/\partial z$ produces a supercurrent in the transformer and hence a voltage at the output of the flux-locked SQUID, whereas a change in the uniform magnetic field produces no response, provided the two loops are balanced. A typical sensitivity is $10^{-13}\,\mathrm{Tm}^{-1}$ $\mathrm{Hz}^{-\frac{1}{2}}$. Other configurations can be used to measure $\partial H_z/\partial x$ or $\partial^2 H_z/\partial z^2$. A flux transformer with a single pick-up loop is a vector magnetometer with a sensitivity that can be as high as $10^{-15}\,\mathrm{THz}^{-\frac{1}{2}}$. One can use a configuration similar to that in Fig. 1(a) to measure magnetic susceptibility, by placing the sample in one of the pick-up loops. The application of a magnetic field H_z produces an output from the flux-locked SQUID that is proportional to the susceptibility of the sample. A sensitivity of 10^{-9} mks m^{-3} for a 10^3 mm^3 sample in a field of 10^{-2} T is typical. The configuration of Fig. 1(b) is voltmeter; in practice, the feedback current is usually applied to the resistor R. The voltage resolution is usually limited by Johnson noise in the resistor: For example, for a resistor of 10^{-8} Ω at 4 K, the resolution is about 10^{-15} VHz$^{-\frac{1}{2}}$.

SQUIDs have been used for laboratory measurements for over a decade. More recently, SQUIDs have been used as magnetometers and gradiometers at sites far removed from the low-temperature laboratory. These applications have been made possible by the development of portable fiberglass cryostats that use no liquid nitrogen, and that boil off 1 ℓ or less of liquid helium per day. Applications include magnetocardiography, magnetoencephalography, geophysical surveying, and gravity wave detection.

Detectors of Microwave and Submillimeter Radiation. Several superconducting devices have been developed to detect electromagnetic radiation at microwave and submillimeter wavelengths. Josephson junction detectors have been operated in several different modes, of which the most promising appear to be the mixer and the parametric amplifier. Point contact junctions, Dayem bridges, and tunnel junctions have all been used as mixers. The non-linearity of the I-V characteristic is used to mix the signal frequency, f_S, with the local oscillator frequency, f_{LO}, to obtain an intermediate frequency $f_{IF} = |f_S - f_{LO}|$. The voltage oscillations across the current-biased junction at a frequency f_{IF} are amplified with a low noise IF amplifier. Mixers of this type have been operated at signal frequencies as high as 300 GHz. Higher-order mixing processes in which $f_{IF} = |pf_S - qf_{LO}|$ (p and q are integers) also occur, and are potentially important for frequency comparison. The parametric amplifiers make use of the non-linear inductance exhibited by a Josephson junction. The most successful devices have been operated with zero static current bias, and with $2f_P = f_S + f_I$, where the external pump frequency, f_P, signal frequency, f_S, and idler frequency, f_I, are all approximately equal. Point contacts and arrays of Dayem bridges and tunnel junctions have been operated as amplifiers at 10 GHz, 33 GHz, and 36 GHz. Gains in excess of 10 dB have been observed.

The super-Schottky diode, consisting of a superconductor-semiconductor junction, is a non-Josephson device that is the best available x-band mixer. The non-linear I-V characteristic, which has the form $I = I_o \exp(eV/k_BT)$, is used to mix the two signals. The Josephson mixer and parametric amplifier and the super-Schottky mixer have been operated successfully in the microwave region. However, these devices have not yet been operated extensively at millimeter and submillimeter wavelengths, where there is the greatest need for improved detectors, and considerable effort will be required to extend the low-noise performance of the devices into this range.

The superconducting bolometer shown in Fig. 3 is the most sensitive broadband far infrared detector currently available. The temperature-sensitive element is an aluminum film evaporated onto a 4 × 4 × 0.05 mm single-crystal sapphire substrate that is supported by indium-coated nylon threads inside a vacuum can. The reverse side of the substrate is coated with a bismuth film that absorbs approximately 50% of the incident far infrared radiation. The temperature of the device is adjusted to be close to the midpoint of the resistive superconducting transition of the aluminum film, about 1.2 K. When far infrared radiation is absorbed by the bolometer, the temperature rise produces an increase in the resistance of the film, which is then measured. The noise equivalent power of the bolometer is typically $2 \times 10^{-15}\,\mathrm{WHz}^{-\frac{1}{2}}$, a value that is within a factor of two of the fundamental limit imposed by energy fluctuations in the bolometer. This device has considerable potential in far infrared astronomy and in laboratory far infrared experiments that require detectors with a high sensitivity.

Computer Elements. One of the most spectacular *potential* applications of the Josephson effect is in ultra-fast computers. The Josephson devices offer not only very fast switching speeds, but also very low dissipation. The low dissipation enables one to achieve a high packing density of junctions, and to minimize transit times between junctions. A number of storage and logic devices have already been successfully operated by workers at IBM. One type of memory cell [Fig. 4(a)] consists of a superconducting loop containing two Josephson tunnel junctions with hysteretic I-V characteristics. The experimental configuration of the cell is shown in Fig. 5. A "1" or a "0" is represented by a persistent supercurrent in the clockwise or anti-clockwise direction respectively, and is written in the cell by applying appropriate current pulses to the word and bit lines to drive one of the junctions momentarily into the non-zero voltage state. When the pulses are removed, a persistent supercurrent of the required polarity remains in the ring. Thus, storage requires no external currents and is non-dissipative. The contents of the cell can be read non-destructively by applying suitable currents to the word and sense lines. These cells are suitable for operation in an array. The smallest cell yet made has an area of about 900 μm^2, a writing time of less than 80 ps, and a power-delay product of less than 10^{-16} J per writing cycle.

A simple logic circuit is shown schematically in Fig. 4(b). A Josephson tunnel junction is connected to two superconducting strip-lines terminated with a matching resistor. The junction is overlaid with three superconducting control lines, A, B, and C, and is biased in the zero voltage state with a constant current I_o. When a current pulse with the same polarity as the current I_o is applied to any one of the control lines, the junction switches to a non-zero voltage, and a current is established in the strip line. This process represents the logical OR operation. The logical AND operation is performed by simultaneously applying current pulses with a polarity opposite to that of I_o to all three control lines, thereby switching the junction into the non-zero voltage state; pulses with this polarity applied to one or two of the lines do not switch the junction. The logic element can also be used to perform the INVERT and CARRY functions. In practical circuits, a logic delay of less than 200 ps and a power-delay product of about 5×10^{-15} J have been achieved. These logic elements have been incorporated into a one-bit adder, a four-bit multiplier, and an eight-bit shift register.

The switching speed is an order of magnitude faster than, and the dissipation several orders of magnitude smaller than semiconducting computer elements. Storage and logic elements that involve the transfer of a single flux quantum are now being investigated, and may be the devices ultimately to be incorporated into a superconducting computer. Within the next few years one may hope to see an ultra-fast superconducting computer with a largest dimension of not much more than 0.1 m.

Standards. The Josephson effects are being used increasingly in standards laboratories. The most important applications have been the measurement of the fundamental constant ratio e/h, and the maintenance of the standard volt. When a Josephson junction is irradiated with microwaves at frequency f, constant-voltage steps are induced on the I-V characteristic at voltages $V_n = nhf/2e$ $(n = \pm 1, 2, \ldots)$. In 1965, Parker and coworkers measured V_n and f to high precision, and determined a value of e/h that differed significantly from the previously accepted value. The new value of e/h was used in a least squares adjustment of the fundamental constants that resulted in substantial changes in the values of several constants. The standard volt at the National Bureau of Standards and at several national laboratories overseas is now maintained by Josephson junctions. Since frequency can be measured very accurately, it is a simple procedure for different laboratories to compare their standard volts. It should be noted, however, that the standard volt is not *defined* by the Josephson effect.

The Josephson effect has been used in two ways to measure temperatures in the range 1 mK to 1 K. In the first, a junction shunted with a resistance R is biased at a voltage V_o by a stable current. The Johnson noise voltage across the resistor causes the Josephson frequency to fluctuate with an rms bandwidth $\widetilde{\Delta\nu} = 4\pi k_B TR/\Phi_o^2$. Thus, by measuring $\widetilde{\Delta\nu}$, one can determine the absolute temperature, T. In the second method, a superconducting loop containing a resistance R is coupled to a flux-locked SQUID [see Fig. 1(a)]. One determines T by measuring the spectral density of the Johnson noise currents in the loop, $S(f) = 4k_B TR/(R^2 + 4\pi^2 f^2 L^2)$.

SQUIDs can be used as current comparators to compare two static currents to very high precision, and, in a non-feedback mode, to calibrate rf attenuators over a wide range of frequencies.

Phonon Generators and Detectors. Quasiparticle tunnel junctions have been used to generate and detect phonons. When a quasiparticle is tunnel-injected into a superconductor, it is most likely to make a transition to the gap edge, where it recombines with another quasiparticle to from a Cooper pair, emitting a phonon of energy approximately 2Δ (Δ is the energy gap). The spectrum of phonons emitted thus peaks around 2Δ. The junction can also be used to detect phonons with energies greater than 2Δ. These phonons break pairs to form quasiparticles that increase the tunneling current at a given voltage bias. These techniques are of particular interest in the 10^{11} to 10^{12} Hz range. Some degree of tuning can be achieved by varying the energy gap with a magnetic field.

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Figure Captions

Fig. 1. (a) Flux-locked dc SQUID used as gradiometer; (b) flux-locked rf SQUID used as voltmeter.

Fig. 2. (a) Tunnel junction dc SQUID; (b) Dayem bridge rf SQUID; (c) point-contact toroidal rf SQUID.

Fig. 3. Superconducting transition edge bolometer.

Fig. 4. (a) Memory cell (bit and sense films overlay the nearby films of the cell); (b) logic element (control films, A, B, and C, overlay the film containing the junction).

Fig. 5. Photograph of prototype memory cell (courtesy of J. Matisoo, IBM).

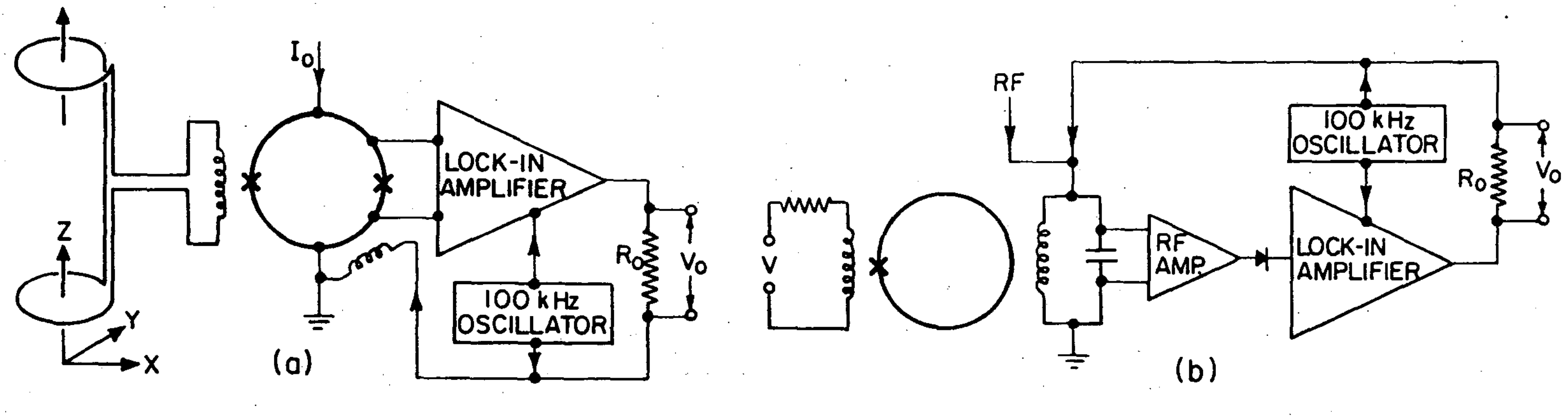

Fig. 1

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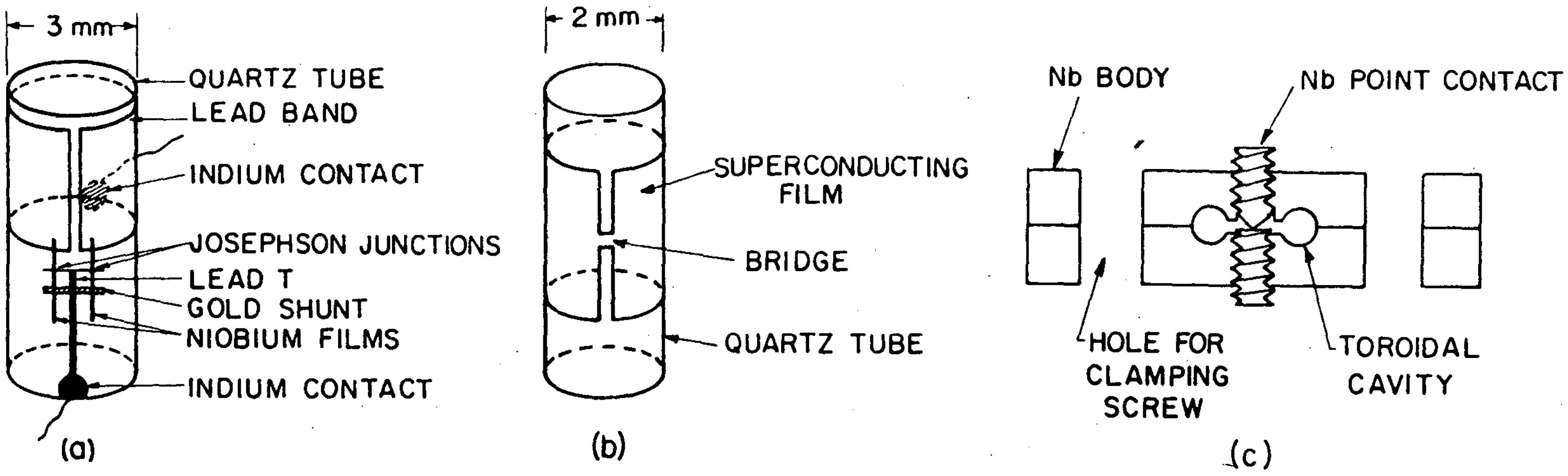

Fig. 2

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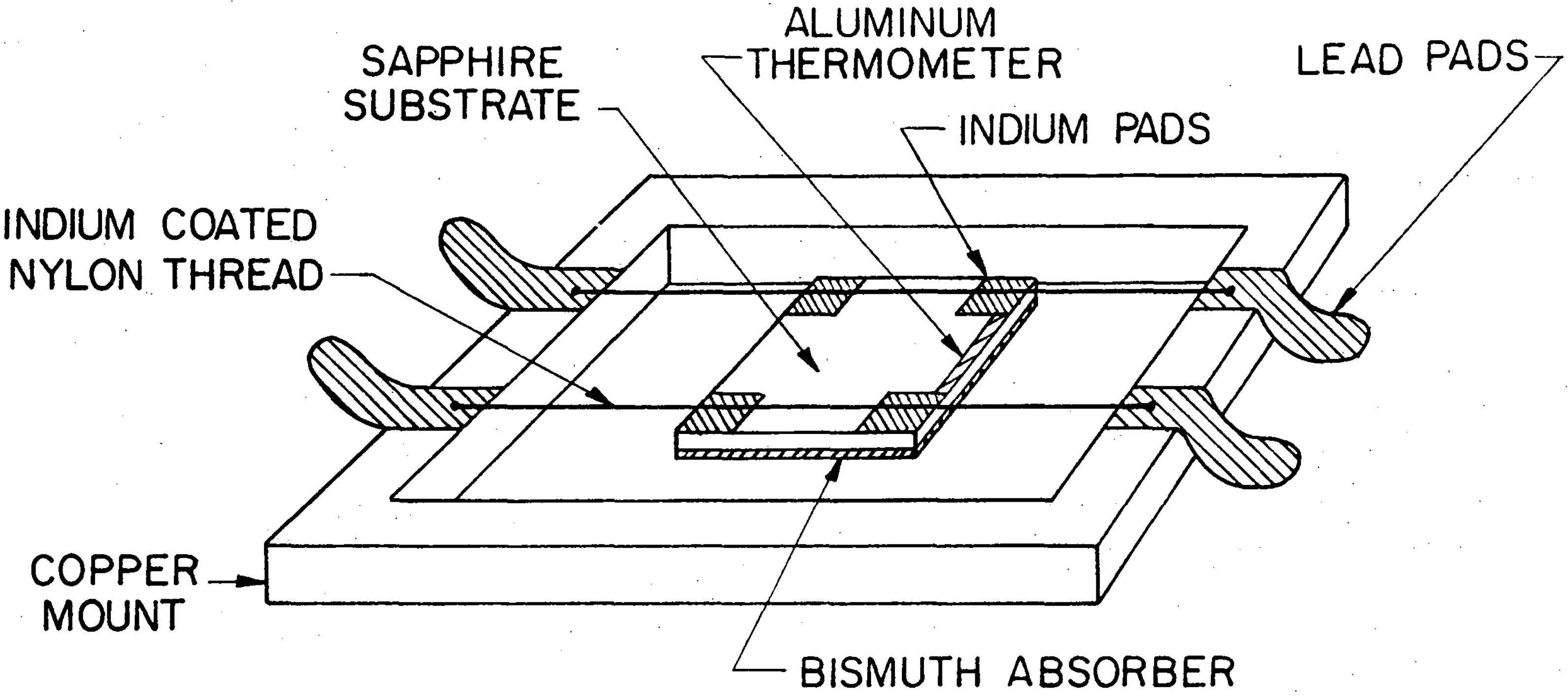

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Fig. 3

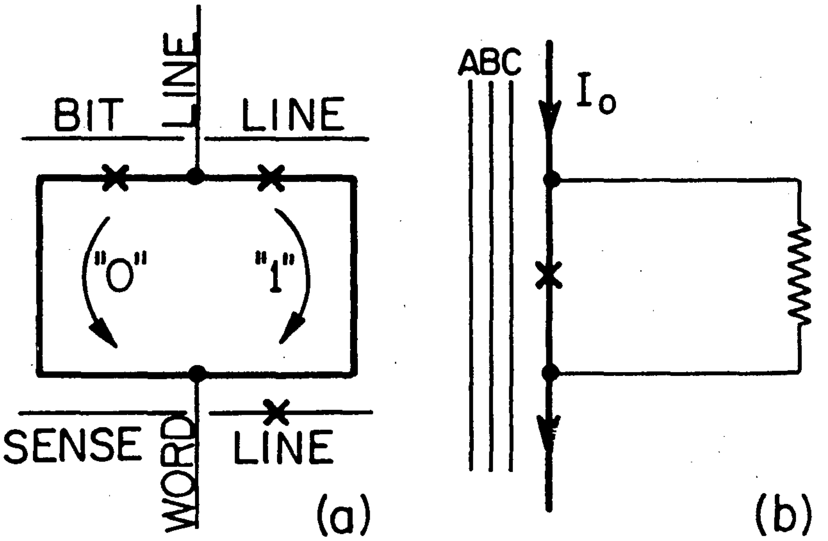

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Fig. 4

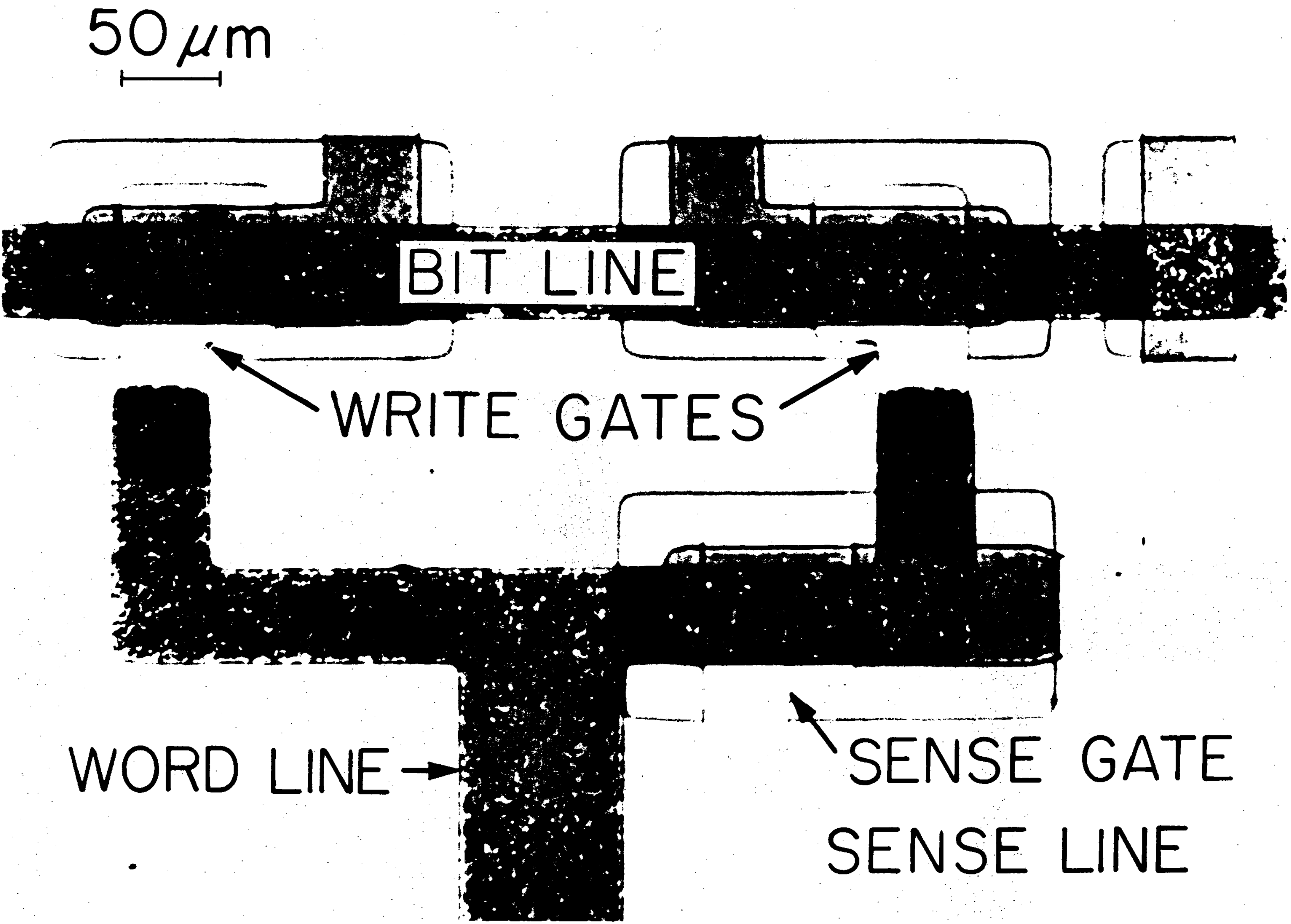

Fig. 5

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