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ABSTRACT

The dc and ac Josephson effects and the behavior of the current-voltage characteristics of Josephson junctions are briefly reviewed. The Josephson junction cryotron is described. Two cryotrons have been incorporated into a NDRO memory cell with a switching time of 80ps, a power-delay product of 10^{-16}J, and an area of 900μm^2. DRO memory cells involving the storage of a single flux quantum have estimated switching speeds of 50ps and a dissipation in continuous operation of 40nW. Latching logic elements with a switching time of 200ps and a power-delay product of 5fJ have been built. Non-latching devices and the flux shuttle are described. The use of dc and rf SQUIDs in conjunction with flux transformers for magnetic measurements is discussed. Presently achieved sensitivities are: magnetic field, 10^{-15}THz$^{-\frac{1}{2}}$, magnetic field gradient, 10^{-13}Tm^{-1}Hz$^{-\frac{1}{2}}$; magnetic susceptibility, 2×10^{-11}e.m.u. for 1cm^3 at 10^{-1}T; voltage, 10^{-15}VHz$^{-\frac{1}{2}}$. The highest energy resolution reported for a SQUID-transformer combination is 8×10^{-30}JHz^{-1} in a frequency range from 2×10^{-2}Hz to 1kHz. At lower frequencies the noise power spectrum is 1/f. The performance of the computer and measuring devices is compared with that of conventional (non-superconducting) devices.

INTRODUCTION

In this article I shall briefly review the use of Josephson junctions as computer elements and as magnetometers for the measurement of magnetic fields, magnetic field gradients, magnetic susceptibilities, and voltages. These two areas of application are at very different stages of development. A variety of ingenious and elegant Josephson devices have been operated as computer storage and logic elements, and their very high speed and very low power dissipation have been clearly demonstrated. The potential of these devices in future computers seems to me to be extremely promising, but of course (to my knowledge) no superconducting computer has yet been built. Thus this field is still in a state of rapid development and innovation. I have tried to list most of the important devices that have appeared in the literature and to give a reasonably complete set of references. On the other hand, Josephson junction magnetometers are well-established instruments, and are commercially available. The literature on this subject is vast, and I have confined the references to a representative selection that should enable the interested reader to find his way into the field.

JOSEPHSON JUNCTIONS

The classic Josephson tunnel junction[1,2,3] consists of two superconductors separated by an insulating barrier typically 20Å to 30Å thick through which both single ("normal") and paired ("superconducting") electrons can tunnel. Junctions are fabricated by evaporating or sputtering a strip of superconductor onto an insulating substrate, oxidizing the strip, and depositing a second film of superconductor [Fig. 1(a)]. In most practical applications it is desirable for the transition temperature, T_c, of the superconductor to be a factor of two or more higher than the boiling temperature of liquid helium, 4.2K. At 4.2K the energy gap, Δ, of the superconductor is then close to its zero temperature value (about 1.4mV in Pb), and is relatively independent of temperature. A typical current-voltage (I-V) characteristic is shown in Fig. 1(b) for $T \lesssim T_c/2$. As the current I through the junction is increased from zero, no voltage is developed for $I < I_m$, the critical current. In this zero voltage regime, the current is carried by superfluid electron pairs that tunnel through the barrier. At $I = I_m$ the voltage jumps discontinuously to a value of approximately $2\Delta/e$. As I is increased and then reduced again, the voltage does not return to zero at $I = I_m$, but remains at approximately $2\Delta/e$ until a transition occurs at a relatively small value of current.[4-6] The amount of hysteresis is determined by the value of the parameter $\beta_c = 2\pi I_m R^2 C/\phi_o$ (R is the normal state resistance of the junction, C is the junction capacitance, and $\phi_o = h/2e \approx 2\text{x}10^{-15}$ Wb is the flux quantum). If the junction is resistively shunted so that $\beta_c \lesssim 1$, the hysteresis vanishes, and the I-V characteristic of Fig. 1(c) is obtained.

For $T \lesssim T_c/2$, $I_m = \alpha\pi\Delta/2eR$[7], where α is usually between 0.5 and 1.0. Critical current densities as high as 30kAcm^{-2} have been reported.[8] If a magnetic field H is applied parallel to one of the strips in Fig. 1(a), the critical current is modulated according to the relation[3] $I_m(H) = I_m(0)\left|\sin(\pi\phi/\phi_o)/(\pi\phi/\phi_o)\right|$, provided the width of the strip w is small compared with the Josephson penetration depth[1,2] $\lambda_j = [\phi_o/2\pi\mu_o(2\lambda + d)j_m]^{\frac{1}{2}}$. Here, λ is the penetration depth of the superconductor (~500Å), d is the barrier thickness, j_m is the critical current density, and $\phi = Hw(2\lambda + d)$. In the limit $\lambda_j \ll w$, the tunneling supercurrent no longer flows uniformly through the junction but is confined to a region of width $\sim\lambda_j$ near the edges of the junction. The junction is said to be "self field limited." In the same way, an external magnetic field is screened by supercurrents flowing in the Josephson penetration depth. As we shall see later, the modulation effects of the magnetic field are considerably modified.

At non-zero voltages, the supercurrent oscillates at a frequency[1] $f = V/\phi_0$. This oscillation persists out to voltages of at least $2\Delta/e \sim 10^{12}$ Hz in lead or niobium at 4.2K. One of the manifestations of the ac Josephson effect is the presence of constant voltage current steps[9] on the I-V characteristic. These steps occur when the frequency of the Josephson current matches the frequency of one at the electromagnetic modes of the cavity formed by the junction. The lower limit for frequencies that can propagate is the plasma frequency[1] $\omega_j = (2\pi j_m d/\phi_0 \varepsilon)^{\frac{1}{2}}$ (ε is the barrier dielectric constant).

The materials most commonly used for practical devices are a lead alloy ($T_c \sim 7$K to 8K) and niobium ($T_c \approx 9.5$K). Sophisticated techniques for fabricating Pb-PbOx-Pb junctions have been developed in which the oxide barrier is grown by an rf discharge in oxygen.[10-13] Nb-NbOx-Pb[14] and Nb-NbOx-Nb[15] junctions have also been made, while Van Duzer and co-workers have successfully fabricated Pb-Te-Pb[16] and Pb-Si-Pb[17] junctions. Photoresist techniques[18] have been used to produce evaporated lead strips with widths of about 1μm. The stability of these junctions during prolonged storage at room temperature and thermal cycling between room and helium temperatures is reported to be excellent. All of the devices for computer applications have utilized tunnel junctions. Magnetometers currently use tunnel junctions, point contacts, or bridges. The point contact[19] consists of a sharp niobium point pressed against a niobium block. In the Anderson-Dayem bridge[20] [Fig. 1(d)], a bridge of submicron dimensions is fabricated in a film of superconductor. In one version[21], the bridge is "weakened" by a normal metal underlay or overlay that lowers its transition temperature.

COMPUTER APPLICATIONS

The possibility of using a Josephson junction as a cryotron for high speed low dissipation storage and logic computer elements was first suggested by Matisoo.[22] Subsequently Anacker[23] designed a random access memory module based on these devices with non-destructive readout. Anderson[24] and McCumber[25] proposed the use of junctions for the control and movement of single flux quanta. After describing experiments to determine the switching speed of a Josephson junction I will discuss the principle of the cryotron, and its use as a memory cell and logic element. I will then briefly describe devices based on single flux quanta.

Matisoo[22,26] measured the risetime of transitions from the zero voltage state to the single-particle tunneling state [Fig. 1(b)] using 125μm square and 250μm square junctions, and found an upper bound of 800ps. Subsequently Zappe and Grebe[27] measured risetimes of 60ps using 100x125μm junctions. Jutzi *et al.*[28] estimated a risetime of less than 24ps in a 8.5x20μm junction. This time was probably limited by the reactances of the test chip. The theoretical risetime in the limit $2\Delta \ll I_m R_j e$, approximately[28] $C\Delta/eI_m$, was about 6ps (R_j is the subgap tunneling resistance). It would appear that switching times on the order of a few ps will eventually be obtainable. However, as we shall see, the junction switching time is not the limiting time in logic devices fabricated so far.

A junction may be used as an in-line cryotron[22,23] [Fig. 2(a)], in which a given control current I_c switches a larger gate current I_g. A superconducting ground plane is deposited on a substrate, followed by an insulating layer. The in-line junction is fabricated on the insulator, and coated with a second insulating film. Finally a control line is evaporated over the junction. The length of the junction ℓ (the overlap of the two superconducting films) is larger than λ_j, so that the junction is self-field limited. The variation of junction critical current I_m with control current in the upper film is then asymmetrical as shown in Fig. 2(b). The self-field generated by the gate current significantly depresses the critical current of the junction. If the control and gate currents flow in opposite directions there is a value of control current for which the field in the junction is zero, and for which the critical current is a maximum. The curve shown in Fig. 2(b) represents a "skewed" version of the central peak of the diffraction pattern for the non-self-field limited junction, and in practice higher order maxima are also observed. The shape of the I_m-I_c curve has been investigated in great detail.[29]

If the values of I_g and I_c are chosen to be inside the curve in Fig. 2(b), the junction will be in the zero voltage state; if they are outside, the the junction will be in the finite voltage state. Suppose that the junction is initially in the zero voltage state ("a") with a gate current I and $I_c = 0$. If a control current I_{c1} is now applied, the critical current of the junction will fall below I, and the junction will switch to a finite voltage ("b"). If instead a control current $-I_{c1}$ is applied, the junction remains in the zero voltage state ("c").

Two cryotrons can be used to make a memory cell cell[23] (Fig. 3) that has nondestructive readout and that can be incorporated into a random access memory. The two cryotrons or word gates (WG), which ideally have identical characteristics, are mounted symmetrically on a superconducting loop to which a word line is connected. A bit line overlays the two junctions. A "1" or a "0" is stored respectively as a clockwise or anticlockwise persistent circulating supercurrent . Suppose that initially there are no circulating or applied currents, and that one wishes to write a "0". A current pulse I_w is applied to the word line so that, because of symmetry, a current $I_w/2$ flows through each junction. I_w is below the critical current $I_m(o)$ of either junction. Simultaneously a bit current pulse I_b is applied to the bit line in the left-to-right direction. The magnetic fields generated by $I_w/2$ and I_b cancel at WG1 but add at WG0 so that its critical current is reduced to below $I_w/2$. WG0 thus makes a transition into the resistive state. The current that was carried by WG0 is transferred to the left hand arm of the cell until the current flowing through WG0 falls below the value required for the junction to return to the zero voltage state. The cell becomes superconducting again with $I_r \approx 0$ and $I_\ell \approx I_w$. When the bit and word currents are removed, the flux trapped in the cell, approximately $(L/2)I_w$, is conserved. Thus a circulating supercurrent of about $I_w/2$ is established in an anticlockwise direction to represent a stored "0".

Suppose a subsequent attempt is made to write a "0". The word current establishes currents $I_\ell \approx I_w$ and $I_r \approx 0$. The field generated by the application of I_b is insufficient to drive either junction out of the zero voltage state, and on removing the word and bit currents, the "0" remains. On the other hand, suppose that one wishes to write a "1". A bit current in the right-to-left direction causes WG1 to make a transition into the resistive state, while

WGO remains in the zero voltage state. The word current is thus transferred into the right arm of the cell. Upon removal of the bit and word pulses, a clockwise supercurrent of approximately $I_w/2$ remains, representing a "1". It is important to realize that no transitions occur unless the word and bit currents are applied simultaneously. Thus a single cell may be addressed from a large array of memory cells with common word and bit lines.

Circulating currents in the memory cell are control currents for the sense gate (SG). A current pulse I_s is applied to the sense line. In the absence of a word current pulse, a circulating current ($\sim I_w/2$) of either polarity generates insufficient field for SG to switch to the resistive state. However suppose that a word current pulse is applied simultaneously with I_s. If the cell contains a "0", $I_r \approx 0$ and the SG remains in the zero voltage state. On the other hand, if the cell contains a "1", $I_r \approx I_w$, the critical current of SG is exceeded, and the resultant voltage is detected. The sense operation does not affect the current stored in the cell, so that readout is non-destructive. It is evident that the sensing operation can be readily performed in an array.

To make a working memory cell, there are a number of practical problems that must be overcome. For example, self-induced steps[9] can disrupt the switching process. It is important that the LCR circuit formed by one junction and the superconducting loop during the switching process not be underdamped.[6,30,31] Zappe[6] has shown that critical damping occurs when $2R_j = (L/C)^{\frac{1}{2}}$, and has discussed the choice of the various circuit parameters and their tolerances. Zappe[32] has operated cells with junctions of size 110x85μm with $C \approx 220pF$, $R_j \approx 0.25\Omega$, and $L \approx 37pH$, and achieved a writing time of 600ps with a repetition rate of 1GHz. The energy dissipated during each write cycle was less than 2×10^{-15}J. Broom <u>et al</u>.[8] have operated a considerably smaller cell with junctions of size 4x5μm and an overall cell size of about 900μm^2. They achieved a writing time of less than 80ps and an energy dissipation of less than 10^{-16}J per writing cycle.

Logic circuits based on the cryotron have been demonstrated by Henkels[33] and Herrell.[34] A circuit for AND, OR, INVERT, and CARRY functions is illustrated in Fig. 4(a). The tunneling gate is connected to two superconducting strip lines of characteristic impedance Z_o terminated by a matching resistor $R = 2Z_o$. Thus when the junction is switched to a

Fi. 4

voltage 2Δ,a current $2\Delta/eR$ is established in the strip line, and can be read by a sense junction (not shown). The gate junction has three control lines A, B, and C. In operation, the junction is biased with a current I in the zero voltage state at "a" in Fig. 4(b). The application of a current i in the same direction as I to any one of the control lines A, B, or C causes the junction to switch to a non-zero voltage state ("b"). This is the OR function. A current i opposed to I in one or two of the control lines will not switch the gate ("c" or "d"), but in all three lines will switch the junction to the resistive state ("e"): This is the AND operation.

Henkels[33] and Herrell[34] have reported a logic delay of less than 200ps and a power-delay product of about 5fJ, representing a power dissipation of about 20μW. More sophisticated circuits have also been operated. Herrell has reported a one-bit adder[35] with a 500ps delay time, and four-bit multiplier[36] with a multiplication time of 27ns, and Yao and Herrell[37] have built an eight-bit shift register.

These logic devices are latching: The gate junction cannot be returned to the zero voltage state by removing or reversing the control current, but only by momentarily switching off the junction bias current. This may be a serious disadvantage. However, Chan *et al.*[38] have proposed a logic gate that automatically unlatches after each operation. Baechtold *et al.*[39,40] have reported a non-latching circuit involving two junction gates that has a switching time of 60ps and a dissipation of about 17μW. Zappe[41] has operated a three-junction logic device that can be operated in both latching and non-latching modes. With hysteretic junctions, the device operates in a latching mode in essentially the same way as the single-junction logic element. However, by resistively shunting the junctions, Zappe[41] eliminated the hysteresis and obtained non-latching operation with a logic delay of 235ps and a power dissipation of <40nW in continuous operation.

The idea[24,25] of using a single flux quantum ϕ_0 in memory and logic elements was first exploited by Fulton and co-workers in the flux shuttle.[42-44] Two basic configurations are possible. In one, a self-field limited junction ($\ell \gg \lambda_J$) supports one (or more) ϕ_0 [Fig. 5(a)] by means of circulating supercurrents.[1,2,45,46] In the other, a flux quantum is stored in a superconducting ring containing two junctions.[42,43,47,48]

The flux shuttle of Fulton and Dunkleberger[44] [Fig. 5(b)] consists of a film with crossarms evaporated onto a wider oxidized film to form a long tunnel junction. Suppose a current is passed between leads 4 and 5 (for example). The current generates a field in the junction that attracts (repels) flux quanta of the same(opposite) field sense, thus providing a potential well(hill). A shift register was operated in the following mode. Pairs of leads attached to 6-7, 5-6, 4-5, and 3-4 were each fed a sinusoidal current with relative phases 0°, 140°, 270°, and 360°. A flux quantum that originated in the well 6-7 when that well was deepest was then transferred successively to wells 5-6, 4-5, and 3-4 in one clock cycle. The flux quantum was written when the well at 6-7 was deepest by applying a short pulse to leads 7-9, the current in lead 7 opposing the clock current. The pulse introduced several flux quanta into the wells 6-9. The pulse amplitude was chosen so that when the pulse ended a single ϕ_0 remained in well 6-7. This quantum was then successively shifted along the register to well 3-4. As the clock advanced further, the well at 4-5 became a potential hill, while the well depth at 3-4 became zero. The flux quantum was thus expelled towards A. A bias current I was applied to leads 1-A whose magnitude was somewhat below the critical current of the junction formed by the overlap of crossarm 1 and the lower strip. The arrival of the flux quantum lowered the critical current below I, and a detectable voltage appeared across the junction.

The flux shuttle has been tested only at 300-700Hz. However, it is believed that operation at frequencies approaching the Josephson plasma frequency (10^{10}Hz to 10^{11}Hz) should be possible. The energy dissipation per shift is of order $I_c\phi_0 \sim 10^{-18}$J for $I \sim 1$mA.

Gueret[48,49] has operated a single self-field limited junction as a memory cell in which a "0" and a "1" are represented by the absence and presence of one flux quantum respectively. A ring containing two junctions has been used as a single flux quantum memory cell.[47,48] Zappe[47] obtained an estimated switching time of about 50ps. The single quantum cells have destructive readout.

Tab I

The performances of a number of Josephson memory and logic elements are summarized in Table I. For comparison, approximate values for several semiconductor devices are included in the table. The Josephson devices offer the combined advantages of high speed and low dissipation. For example, a buffer memory with a density of 10^4 NDRO Josephson cells[8] per cm^2 would have a dissipation of only

10mW cm^{-2} even if all cells were in continuous operation; this heat load can be easily handled by liquid helium.

MAGNETIC MEASUREMENTS

The basic device for the measurement of magnetic fields is the SQUID (Superconducting QUantum Interference Device). There are two versions: The dc SQUID and the rf SQUID. The dc SQUID was the first to be developed, but subsequently the rf SQUID became the more popular, and is now available commercially from several companies. There are several review articles that describe both types of SQUID in detail.[50-53]

Fig. 6

The dc SQUID[54] consists of a superconducting ring on which are mounted two junctions [Fig. 6(a)] with non-hysteretic I-V characteristics. A dc current I_o biases the SQUID at a non-zero voltage [Fig. 6(b)]. As the magnetic flux threading the ring is slowly changed, the critical current of the two junctions I_m oscillates with a period ϕ_o [Fig. 6(c)], being a maximum for $\phi = n\phi_o$ and a minimum for $\phi = (n + \frac{1}{2})\phi_o$ (n is an integer). The voltage across the SQUID at a constant current bias is correspondingly periodic in the applied flux. The most sensitive dc SQUID is that of Clarke, Goubau, and Ketchen.[55] Their SQUID has a cylindrical geometry and involves two shunted Nb-NbOx-Pb junctions evaporated on a 3mm o.d. quartz tube. Typical parameters are: SQUID inductance ~1nH; parallel resistance of shunts 0.4Ω; $I_m \approx 5\mu A$ (both junctions); $\beta_c \approx 0.5$; voltage modulation depth, $V[(n + \frac{1}{2})\phi_o] - V[n\phi_o]$, ~0.5μV.

In practice, a flux change of much less than ϕ_o can be detected by using the SQUID as a flux null detector in a feedback circuit. A 100kHz flux modulation is superimposed on the quasistatic flux ϕ in the SQUID. The amplitude of the 100kHz voltage across the SQUID is then periodic in ϕ. This voltage is amplified by an LC resonant circuit with a superconducting coil, further amplified by conventional (room temperature) electronics, and lock-in detected. The output of the lock-in is also periodic in the applied flux. This output is fed back as a current into a coil inside the SQUID to produce a flux that cancels any flux applied to the SQUID. The feedback current is proportional to the flux change applied to the SQUID. The dynamic range of the closed-loop system is $\sim 10^6 \phi_o$, and the maximum slewing rate is $\sim 10^5 \phi_o \sec^{-1}$. Noise and drift measurements were made with the SQUID in a superconducting shield that screened out external magnetic field fluctuations. The noise power spectrum is white from $2x10^{-2}$Hz to about 2kHz, with an rms value of typically $3.5x10^{-5}\phi_o Hz^{-1}$, corresponding to a magnetic field resolution of about $10^{-14}THz^{-1/2}$. This noise limit is set by the Johnson noise in the junction shunts. Below $2x10^{-2}$Hz, the noise power spectrum is approximately 1/f. The long term drift is typically $2x10^{-5}\phi_o h^{-1}$.

Fig 7

The rf SQUID[56,57] [Fig. 7(a)] consists of a single Josephson junction on a superconducting ring. The ring is coupled to the inductor of a tank circuit whose resonant frequency is typically 30MHz. An ac current at the resonant frequency is applied to the tank circuit, and adjusted to the appropriate amplitude. The amplitude of the 30MHz voltage across the tank circuit is periodic in the flux ϕ applied to the SQUID, the period again being ϕ_o. The 30MHz signal is amplified and demodulated to produce a quasistatic voltage that is periodic in the flux. A second, lower frequency flux (typically 100kHz) modulates the flux in the SQUID which is then used in a feedback circuit in much the same way as the dc SQUID. Zimmerman and co-workers,[56] have pioneered the use of point contacts in a variety of rf SQUIDs machined from niobium cylinders. The first version [Fig. 7(b)] consisted of a niobium tube with a slit down one side connected by an adjustable niobium screw.[56] A later version [Fig. 7(c)] contained two holes and a single point contact.[51,56] Zimmerman[58] has also operated a "fractional turn" rf SQUID, while more recently point contact rf SQUIDS with a toroidal geometry have become commercially available.[59,60] An alternative rf SQUID design was evolved by Mercereau and co-workers.[57] A superconducting film is evaporated around a quartz tube, and a single bridge is fabricated in the film. This type of SQUID is also commercially available.[60,61]

The noise in rf SQUIDs has been extensively investigated.[62] In practice, rf SQUIDs with an inductance $\lesssim 10^{-9}$H and an rf frequency of 30MHz have a resolution of about $10^{-4}\phi_o Hz^{-\frac{1}{2}}$ in the white noise region. The intrinsic noise is proportional to (rf frequency)$^{-\frac{1}{2}}$, and a lower intrinsic noise has been observed in rf SQUIDS operated at higher frequencies. Gaertner (unpublished) has achieved a resolution of $7x10^{-6}\phi_o Hz^{-\frac{1}{2}}$ in a SQUID of unspecified inductance with an rf frequency of 440MHz.

To make magnetic measurements, it is often convenient to use a superconducting flux transformer in conjunction with a dc or rf SQUID that is itself shielded from external magnetic fields [Fig. 8(a)].

Fig [illegible]

A magnetic field applied to the pick-up loop generates a persistent supercurrent that in turn produces a flux in the flux-locked SQUID. The diameter of the pick-up loop is typically 50mm, while the secondary coil coupled to the SQUID usually has several turns so that its inductance is equal to that of the pick-up loop. With proper design,[58,63] the flux transformer can enhance the sensitivity of a SQUID by an order of magnitude,[58] although in practice the noise limitation is set by fluctuations in the earth's magnetic field. The flux transformer may also be used as a gradiometer[64] [Fig. 8(b)]. The two pick-up coils are carefully balanced so that a uniform magnetic field induces no supercurrent. A gradient $\partial H_z/\partial z$ induces a flux in the SQUID. A resolution approaching $10^{-13}\mathrm{Tm}^{-1}\mathrm{Hz}^{-\frac{1}{2}}$ is possible. Transformers measuring off-diagonal gradients ($\partial H_x/\partial y$ etc.) and second-derivatives ($\partial^2 H_z/\partial z^2$) have also been operated.[65,66] The magnetic field resolution of SQUIDs is appreciably higher than that obtainable using other instruments: The fluxgate and proton precession magnetometers have sensitivities of about $10^{-10}\mathrm{T\ Hz}^{-\frac{1}{2}}$, while the pumped cesium vapor magnetometer has a sensitivity of about $10^{-11}\mathrm{T\ Hz}^{-\frac{1}{2}}$.[67]

The magnetic susceptibility of a sample may be measured by placing it in the pick-up loop of a flux transformer, or in one of the loops of a gradiometer, and applying a magnetic field to it. In order to obtain a sufficiently stable magnetic field, it is necessary to use a superconducting magnet in a persistent field mode and to stabilize the field with a superconducting shield.[68] Systems in which the sample temperature can be varied from 4.2K to 300K or higher have been operated.[59,69] A susceptibility resolution of 10^{-10}e.m.u. for a 1cm^3 sample in a field of 10^{-2}T was achieved by Cukauskas *et al.*,[68] and of 2x10^{-11} e.m.u. for a 1 cm^3 sample in a field of 10^{-1} T has been achieved commercially.[60] The limit on these measurements is set by vibration and temperature drifts rather than by SQUID noise. By way of comparison, Foner[70] has reported a resolution of 10^{-13} e.m.u.g^{-1} at 1T using a vibrating sample magetometer, and a resolution of 10^{-11} e.m.u.g^{-1} at 10T has been achieved commercially using a Faraday balance.[71] The resolution of the SQUID system could probably be much improved if the filling factor of the sample in the pick-up coil were increased, and/or if the vibration of the sample could be reduced so that a larger magnetic field could be used.

The SQUID can be used as a voltmeter[51,72-74] by connecting a voltage source in series with a known resistor and a superconducting coil coupled to the SQUID. At 4.2K, the voltage resolution can be limited by Johnson noise in the resistor for values of resistance less than a few ohms. For example, for a resistance of $10^{-8}\Omega$, the resolution is $\sim 10^{-15}$ VHz$^{-\frac{1}{2}}$.

To conclude, I shall comment on the figure of merit[63] used to compare SQUIDs. The sensitivity is often quoted in flux Hz$^{-\frac{1}{2}}$, but this is insufficient information to properly characterize the SQUID. Consider a coil (the secondary of a flux transformer) of inductance L_c coupled to the SQUID with mutual inductance M_c. If the SQUID mean square flux resolution is $\langle\phi_N^2\rangle$(per Hz$^{\frac{1}{2}}$), the current resolution in the coil is $\langle I_N^2\rangle = \phi_N^2/M_c^2$, corresponding to an energy resolution $L_c\langle I_N^2\rangle/2 = \langle \phi_N^2\rangle/(2M_c^2/L_c)$. This quantity is an appropriate figure of merit for all SQUID applications[63] in the limit of very low frequency. The smallest energy resolution reported is that of Clarke et al.[55], 8×10^{-30} JHz^{-1}.

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Device	Switching speed (ps)	Power x delay (J)
NDRO memory[8]	80	10^{-16}
Single ϕ_o memory[47]	50	10^{-18}
Latching logic[34]	200	5×10^{-15}
N-L complementary[39]	60	10^{-15}
N-L 3-jn.[41]	235	10^{-17}
Flux shuttle[43] (expected)	10-100	$\sim 10^{-18}$
TTL	10^4	10^{-10}
EFL	3,000	3×10^{-12}
n-MOS	10^5	10^{-11}
IIL	10^4	10^{-13}

Table I Approximate switching times and power-delay products for Josephson and semiconductor devices (semiconductor values from ref. 34 and T. van Duzer, private communication. N-L = non-latching).

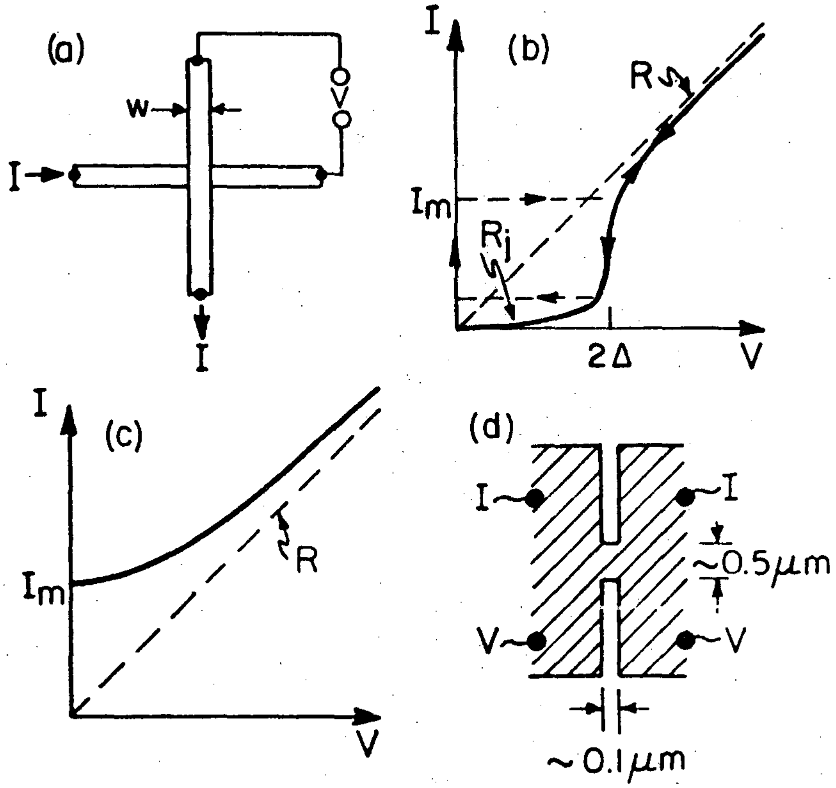


Fig. 1 (a) Tunnel junction; (b) I-V characteristic of tunnel junction with identical superconductors; (c) I-V characteristic of shunted tunnel junction; (d) Anderson-Dayem bridge.

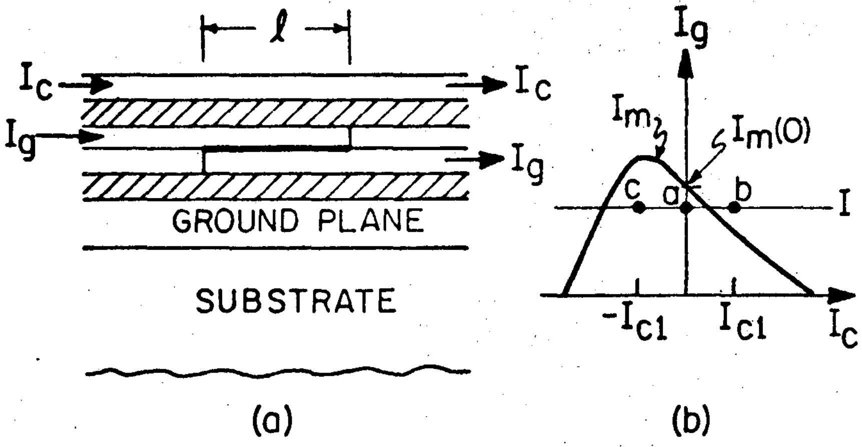


Fig. 2 (a) In line junction cryotron; (b) I_m vs. I_c for in-line cryotron.

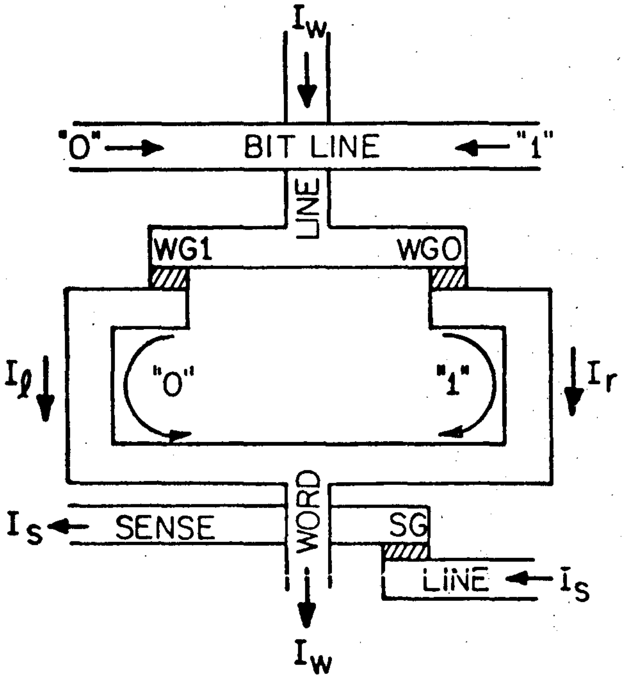


Fig. 3. Memory cell (after Zappe[32]).

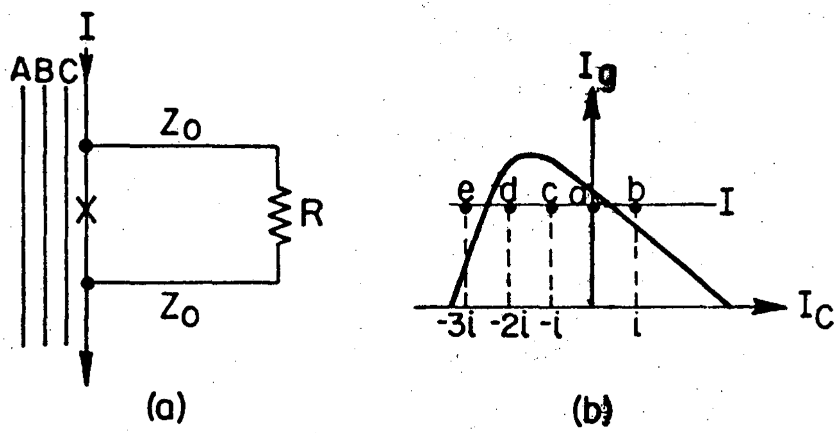


Fig. 4 (a) Logic circuit; (b) I_g vs. I_c for gate (after Herrell[34]).

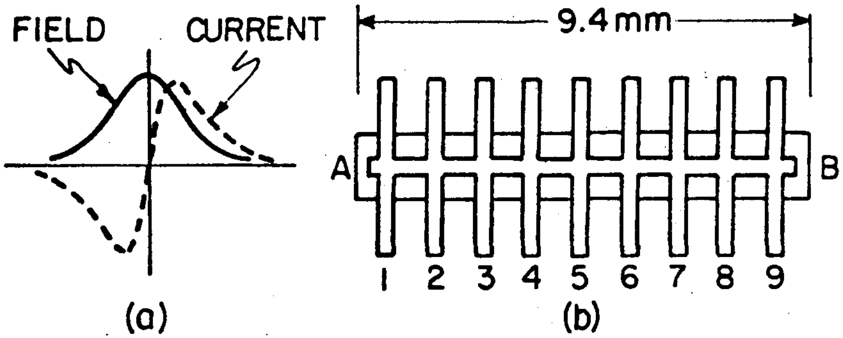
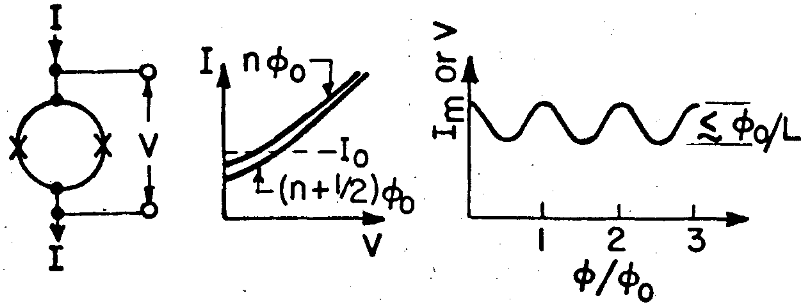


Fig. 5 (a) Magnetic field and supercurrent profiles vs. distance (in plane of junction) across vortex; (b) flux shuttle (after Fulton and Dunkleberger[44]).



(a) (b) (c)

Fig. 6 (a) Dc SQUID; (b) modulation of I-V characteristic by magnetic flux; (c) modulation of I_m or V by magnetic flux.

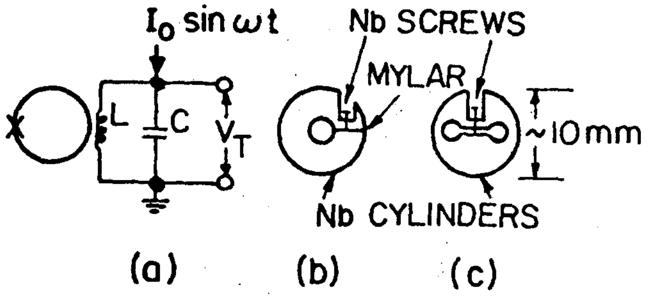


Fig. 7 (a) Rf SQUID; (b) and (c) point contact rf SQUIDs.

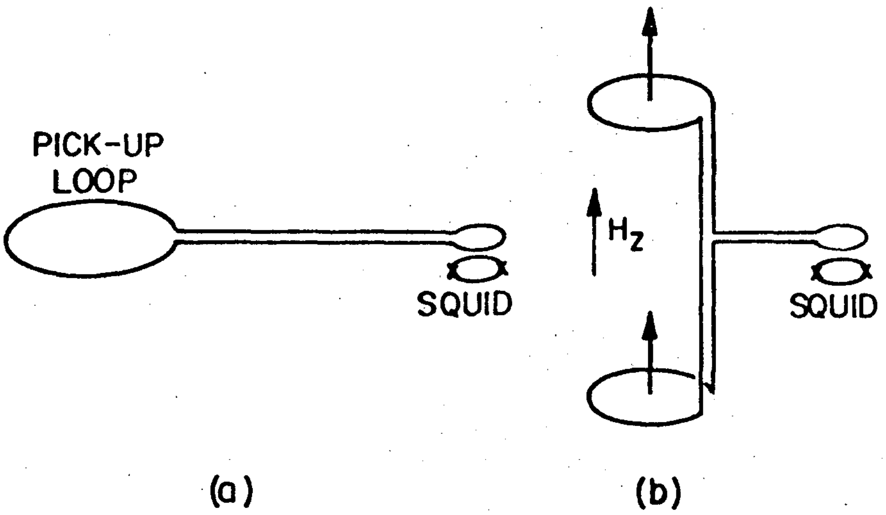


Fig. 8 (a) Flux transformer; (b) gradiometer.

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