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John Clarke

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SQUID - Superconducting Quantum Interference Devices and Their Applications, H. D. Hahlbohm and H. Lübbig, Eds. (Walter de Gruyter, Berlin - New York, 1977) to be published.

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CURRENT PERFORMANCE OF SUPERCONDUCTING QUANTUM INTERFERENCE DEVICES*

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This article briefly surveys the performance of SQUIDs as low frequency detectors, and discusses how improvements in sensitivity might be achieved. The paper summarizes an extended review[1] to be published in the proceedings of the NATO Advanced Study Institute on Small Scale Superconducting Devices, Lago di Garda, Italy, September 1-10, 1976.

DC SQUID

Principles

In the dc SQUID[2], two Josephson[3] junctions are mounted on a superconducting ring of inductance L. The critical current, I_m, of the two junctions is periodic in the external magnetic flux applied to the ring, Φ_e, with a period Φ_o. The SQUID can be used to detect small changes in Φ_e ($<< \Phi_o$) by measuring the corresponding change in I_m.

An order-of-magnitude estimate of the flux resolution may be made as follows. In the limit $\beta = LI_m/\Phi_o >> 1$, the critical current modulation depth $\Delta I_m = I_m[n\Phi_o] - I_m[(n + \frac{1}{2})\Phi_o] \rightarrow \Phi_o/L$. However, most SQUIDs are operated with $\beta \approx 1$, for which value[4] $\Delta I_m \approx \Phi_o/2L$. If $L \approx 10^{-9}$ H, $\Delta I_m \approx 1\ \mu A$. We assume that each junction can be represented by a resistively shunted tunnel junction[5] with $\beta_c = 2\pi I_c R^2 C/\Phi_o \leq 1$, so that the current-voltage characteristic is non-hysteretic. Here I_c, C, and R are the critical current, capacitance, and shunt resistance of each junction. The current-voltage (I-V) characteristic of the SQUID is also periodic in Φ_e, provided that the Josephson frequency is not much greater than the characteristic frequency of the ring, $(2R/L)/2\pi$. If $R \approx 1\ \Omega$ and $L \approx 1$ nH, $R/\pi L$ is about 0.3 GHz, corresponding to a voltage $\Phi_o R/\pi L$ of roughly 1 μV. If the SQUID is biased with a constant current I_o near this voltage, the voltage modulation depth is $\Delta V \approx \Phi_o R/4L$. The transfer function is

$$(1) \quad \left(\frac{\partial V}{\partial \Phi_e}\right)_{I_o} \approx \frac{R/2}{L} ,$$

about 0.5 $\mu V \, \Phi_o^{-1}$. Equation (1) is a measure of the signal available from the SQUID.

The intrinsic noise of the SQUID can be approximated by the Johnson noise in the resistive shunts (for a more detailed treatment, see ref. 4). The power spectrum of the voltage noise is

$$(2) \quad S_v(f) \approx 4k_B T(R/2) ,$$

where T is the temperature of the SQUID. The power spectrum, S_Φ, of the flux noise is readily obtained from Eqs. (1) and (2):

$$(3) \quad S_\Phi \approx 8k_B TL^2/R .$$

The energy resolution is

$$(4) \quad \frac{S_\Phi}{2L} \approx \frac{2k_B T}{(R/2L)} .$$

Equation (4) indicates that the energy resolution of the SQUID per unit bandwidth is essentially $k_B T$ divided by the characteristic frequency or "sampling frequency" of the SQUID, R/2L. For $R = 1\ \Omega$, $L = 10^{-9}$ H, and $T = 4$ K, $S_\Phi^{1/2} \approx 10^{-5}\ \Phi_o\ \mathrm{Hz}^{-1/2}$, and $S_\Phi/2L \approx 2 \times 10^{-31}\ \mathrm{JHz}^{-1}$. A more detailed calculation[4] shows that Eq. (4) should be multiplied by a dimensionless factor that is a complicated function of I_o, R, L, and T. For the parameter values given, the detailed theory indicates that $S_\Phi^{1/2}$ is a factor of about 3 higher than these estimates.

For most applications, the SQUID is coupled to a superconducting flux transformer. The appropriate figure of merit in the zero frequency limit is the energy resolution per Hz referred to the input coil of inductance L_i coupled to the SQUID[1,6]:

$$(5) \quad \frac{S_\Phi}{2M_i^2/L_i} = \frac{S_\Phi}{2\alpha^2 L} ,$$

where $M_i^2 = \alpha^2 LL_i$.

Practical Device

The most sensitive dc SQUID is that of Clarke, Goubau, and Ketchen[7]. The configuration is shown in Fig. 1. The substrate is a fused quartz tube 20 mm long with an outside diameter of 3 mm. A band of Pb/In alloy (∿ 10% wt. In) about 11 mm wide and 0.3 μm thick is evaporated around the tube. A 250 μm wide, 75 nm-thick Au film is then evaporated: this film is the shunt for the tunnel junctions. Next, two 150 μm-wide, 0.3 μm-thick Nb films, separated by 1.2 mm, are dc sputtered onto the cylinder, making low resistance contacts with the Au film and, at low temperatures, superconducting contacts with the Pb/In band. The Nb is thermally oxidized, and immediately afterwards, a 0.3 μm-thick Pb/In tee is deposited. The cross bar of the tee overlaps the niobium strips to form two tunnel junctions, each with an area of about 10^{-2} mm^2. Next, the Pb/In band is scribed midway between the Nb strips. Two In pellets are pressed on as contacts, one on the base of the tee, and the other on the Pb/In band. The entire sensor is coated with a thin insulating layer of Duco cement. Finally, a 0.3 μm-thick Pb/In ground plane (not shown in Fig. 1) is evaporated over the slit in the Pb/In band and the strips that form the junctions to mini-

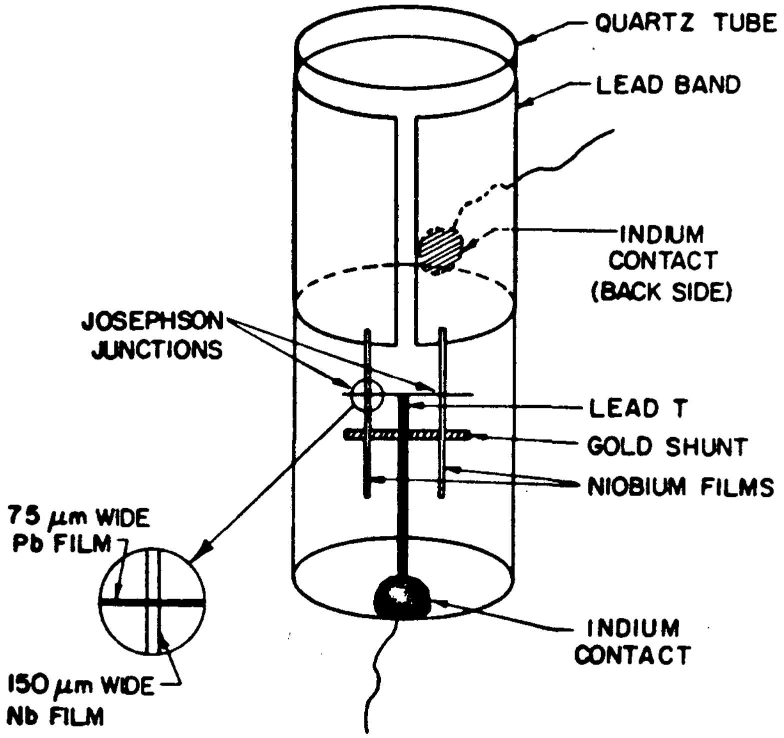

Fig. 1. Thin film tunnel junction dc SQUID

mize the parasitic inductances. A 50-nm film of Ag deposited over the ground plane protects it from oxidation.

Typical parameters for the sensor are: capacitance per junction, 200 pF; total critical current, 1 to 5 μA; parallel shunt resistance, 0.5 Ω; and total inductance, about 1.25 nH (∿ 0.75 nH for the cylinder, and ∿ 0.5 nH for the Nb and Pb/In strips). For testing, and for use in conjunction with a flux transformer, the SQUID is enclosed in a superconducting tube to screen out fluctuations in the external magnetic field. The tube acts as a ground plane that reduces the inductance of the SQUID cylinder to about 0.5 nH. The total SQUID inductance is thus about 1 nH.

The SQUID is invariably operated in a feedback mode. The SQUID is biased at a constant current I_o greater than the critical current, and a 100 kHz-modulation flux of peak-to-peak amplitude $\Phi_o/2$ is applied by means of a coil inside the SQUID. The ac voltage appearing across the SQUID is amplified with a cooled tank circuit ($Q \sim 100$) or by a cooled transformer with a gain of about 300. After further amplification with a FET preamplifier, the signal is lock-in detected, using a 100 kHz reference. The output of the lock-in is zero when $\Phi_e = n\Phi_o/2$, and a maximum or minimum when $\Phi_e = (n \pm \frac{1}{4})\Phi_o$. The output of the lock-in is further amplified, integrated, and fed back as a current into the coil in the SQUID.

Performance

For the case in which the SQUID is matched to the preamplifier with a transformer, typical performance parameters for the SQUID in the feedback mode are: dynamic range, $\pm 3 \times 10^6$ in a 1 Hz bandwith; frequency response 0 to 50 kHz; and slewing rate, $2.5 \times 10^5\ \Phi_o s^{-1}$. The noise and drift of the SQUID were measured with a 24-turn superconducting coil wound on the outside of the Pb/In cylinder. The energy resolution $S_\Phi/2\alpha^2L$ referred to the input coil is plotted in Fig. 2, and the relevant parameters are given in Table 1. The roll-off above 200 Hz is due to filtering in the electronics. The resolution is about $7 \times 10^{-30}\ \mathrm{JHz}^{-1}$ in the white noise region, corresponding to a rms flux noise of about $3.5 \times 10^{-5}\ \Phi_o \mathrm{Hz}^{-\frac{1}{2}}$. We estimate $\alpha^2 \approx 0.5$, so that the energy resolution referred to the SQUID is about $3 \times 10^{-30}\ \mathrm{JHz}^{-1}$.

The long term drift of the SQUID in a helium bath whose temperature was regulated to ±50 μK was $\leq 2 \times 10^{-5} \Phi_0 h^{-1}$.

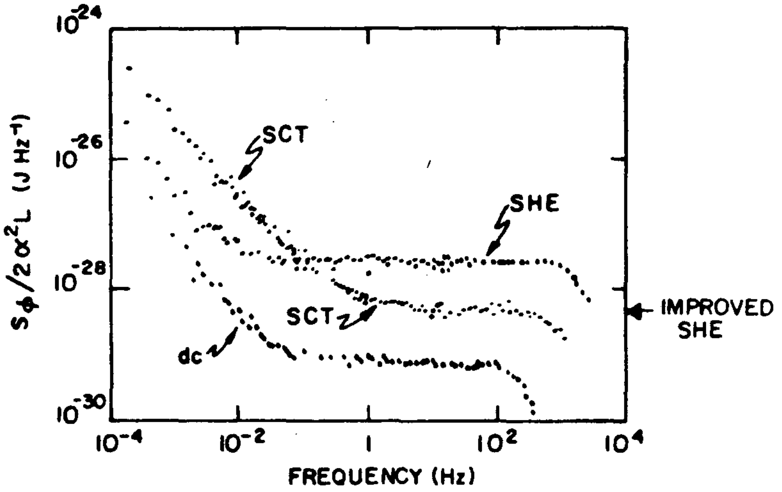

Fig. 2. Noise power spectra (plotted as energy resolution) for tunnel junction dc SQUID and S.C.T. and S.H.E. toroidal rf SQUIDs (Summer 1975). Subsequently, the white noise of the S.H.E. SQUID was improved to the level shown.

SQUID	S_Φ ($\Phi_0 Hz^{-1}$)	M_i (nH)	L_i (nH)	$S_\Phi/2\alpha^2L$ ($10^{-30} JHz^{-1}$)
dc (Clarke *et al.*[7])	1.2×10^{-9}	11.5	356	7
rf (S.H.E.[16]) 19 MHz	5×10^{-9}	20	2×10^3	50
rf (S.C.T.[17]) 30 MHz	6.6×10^{-10}	3	360	50
rf (Pierce *et al.*[18]) 10 GHz	1×10^{-10}	8	500	2

Table 1. Flux noise power spectrum (S_Φ), mutual inductance with input coil (M_i), inductance of input coil (L_i), and figure of merit ($S_\Phi/2\alpha^2L$) for several SQUIDs.

Future Developments

At measurement frequencies above 2×10^{-2} Hz, the resolution of the tunnel-junction dc SQUID at 4 K is limited by its intrinsic noise. From Eq. (4), we see that at a fixed temperature, the performance can be improved by increasing the sampling frequency R/L. This increase is subject to the constraints $\beta_c = 2\pi I_c R^2 C/\Phi_o \le 1$ and, as can be deduced from the more detailed theory, $\beta \sim 1$. A reduction in L improves the energy resolution only if the coupling efficiency to the input coil is not also reduced. The alternative means of improving the resolution is to increase R, simultaneously decreasing C to maintain $\beta_c \le 1$. It should be possible to reduce the junction area by four orders of magnitude to $\sim 1 \times 1\,\mu m$ (a size attainable by photoresist techniques) maintaining the critical current at $\sim 1\,\mu A$ (the critical current density required, $\sim 10^2\,A\,cm^{-2}$, is easily attainable). C would be decreased by four orders of magnitude, and the shunt resistance of each junction could then be increased to $\sim 100\,\Omega$ without introducing hysteresis. If L is maintained at 10^{-9} H, this procedure should decrease $S_\Phi/2\alpha^2 L$ by two orders of magnitude to a value of 10^{-31} JHz^{-1} or less.

RF SQUID

Principles

The rf SQUID consists of a single Josephson junction mounted on a superconducting ring[8,9], with $LI_c \sim \Phi_o$. The ring is coupled to the coil of a LC-resonant circuit that is excited by a sinusoidal current, I_{rf}, at its resonant frequency (typically 30 MHz). The rf voltage, V_T, developed across the tank circuit is amplified, and detected with a diode (for example). If one plots V_T (vertically) versus I_{rf} (horizontally), one obtains a series of "steps" and "risers". On the steps, V_T is nearly independent of I_{rf}. If Φ_e is slowly changed, the voltages at which the steps appear oscillate with period Φ_o. It can be shown[1,8] that the transfer function referred to the tank circuit is

$$(6)\quad \left(\frac{\partial V_T}{\partial \Phi_e}\right)_{I_{rf}} \approx \frac{\omega L_T}{M} ,$$

where $\omega/2\pi$ is the rf frequency, L_T is the tank circuit inductance, and $M = K(LL_T)^{\frac{1}{2}}$. The value of M cannot be reduced indefinitely, since the influence of the SQUID on the tank circuit would become insignificant. An approximate lower limit on M is set by requiring that the dissipation in the SQUID be no smaller than the dissipation in the tank circuit. A straightforward analysis[1] shows that this requirement is equivalent to

$$(7)\quad K^2 Q \ge 1 ,$$

where Q is the quality factor of the tank circuit. If $Q \sim 100$, $K \geq 0.1$. Taking the values $\omega/2\pi \approx 30$ MHz, $L_T \approx 100$ nH, $L \approx 1$ nH, $K \approx 0.1$, and $M \approx K(LL_T)^{\frac{1}{2}} \approx 1$ nH, we find $(\partial V_T/\partial\Phi_e)_{I_{rf}} \approx 40\ \mu V\Phi_o^{-1}$.

The rf SQUID is usually operated in a feedback circuit. A flux modulation ($\Phi_o/2$ peak-to-peak and typically at 100 kHz) is applied to the SQUID; after rf detection, the 100 kHz signal is lock-in detected and the smoothed output is fed back to the tank circuit coil.

The three sources of noise in the rf SQUID, intrinsic noise, tank circuit noise, and preamplifier noise have been reviewed in detail by Jackel and Buhrman[10]. The intrinsic flux noise has a power spectrum[10,11]

$$(8) \qquad S_\Phi^{(i)} \approx \frac{\pi\varepsilon^2\Phi_o^2}{\omega} ,$$

where ε (assumed to be $<< 1$) is the ratio of the voltage rise along a step in the V_T-I_{rf} characteristic to the separation in voltage of successive steps. The tank circuit Johnson noise gives rise to an equivalent flux noise with a power spectrum[1,10,12]

$$(9) \qquad S_\Phi^{(tc)} \approx \frac{4\pi\varepsilon^2 k_B T_e L}{\omega} ,$$

where T_e is the effective temperature of the tank circuit. We have assumed $LI_c \approx \Phi_o$. The equivalent flux noise of the preamplifier has a power spectrum found by dividing the power spectrum, $S_V^{(p)}$, of the voltage noise by $(\partial V_T/\partial\Phi_e)^2_{I_{rf}}$:

$$(10) \qquad S_\Phi^{(P)} \approx \frac{M^2 S_V^{(p)}}{\omega^2 L_T^2} .$$

This result may be written in a convenient form by defining a noise temperature, $T_N^{(p)}$, for the preamplifier through the relation

$$(11) \qquad S_V^{(p)} = 4k_B T_N^{(p)} \varepsilon R_T .$$

Here, R_T is the resistance of the tank circuit on resonance in the absence of the SQUID, and εR_T is thus the approximate dynamic resistance on a step in the presence of the SQUID. If we insert Eq. (11) in Eq. (10) and set $K^2Q = 1$ with $Q = R_T/\omega L_T$, we find

$$(12) \qquad S_\Phi^{(p)} \approx \frac{4\varepsilon k_B T_N^{(p)} L}{\omega} .$$

Notice from Eq. (11) that $T_N^{(p)} \propto 1/\omega$ if Q and ε remain constant, so that $S_\Phi^{(p)}$ is proportional to $1/\omega^2$.

The overall energy resolution is found from Eqs. (8), (9), and (12):

$$(13) \qquad \frac{S_\Phi}{2L} \approx \frac{\pi\varepsilon^2\Phi_o^2}{2\omega L} + \frac{2\pi\varepsilon^2 k_B T_e}{\omega} + \frac{2\varepsilon k_B T_N^{(p)}}{\omega} .$$

This expression assumes that $LI_c \approx \Phi_o$ and $K^2Q \approx 1$. The intrinsic energy resolution is proportional to the energy available per cycle, $\sim \Phi_o^2/L$, divided by ω. The second and third terms represent the thermal energies of the tank circuit ($k_B T_e$) and preamplifier ($k_B T_N^{(p)}$) divided by ω. It should be emphasized that these expressions are approximate, and are accurate only to within factors of 2 or 3.

It is instructive to make estimates for the three contributions. If we take as typical values $\varepsilon \approx 0.2$, $L \approx 1$ nH, $\omega/2\pi \approx 30$ MHz, $T_e \approx 200$ K, and $T_N^{(p)} \approx 50$ K, we find $S_\Phi^{(i)}/2L \approx 10^{-30}\,\mathrm{JHz}^{-1}$, $S_\Phi^{(tc)}/2L \approx 4 \times 10^{-30}\,\mathrm{JHz}^{-1}$, $S_\Phi^{(p)}/2L \approx 2 \times 10^{-30}\,\mathrm{JHz}^{-1}$, and $S_\Phi/2L \approx 10^{-29}\,\mathrm{JHz}^{-1}$. The total rms flux noise is $\sim 7 \times 10^{-5}\,\Phi_o\,\mathrm{Hz}^{-1/2}$. As is usually the case for the rf SQUID, the intrinsic noise is relatively insignificant.

Practical Devices

A selection of rf SQUIDs is shown in Fig. 3. These include the point contact SQUID (a) of Zimmerman et al.[8], the thin film SQUID (b) of Mercereau and co-workers[9], the two-hole SQUID (c)[8,13], and the toroidal SQUID (d)[14]. Another ingeneous point contact device (not shown) is the fractional-turn SQUID of Zimmerman[15]. Each device has an inductance of 1 nH or less, and a critical current $\sim \Phi_o/L$. Most devices are operated at 20 to 30 MHz. However, much higher frequencies have been used in order to improve the resolution.

Performance

In the feedback mode, typical performance parameters are: dynamic range, $\pm 10^6$ in a 1 Hz bandwidth; frequency response, 0 to a few kHz; slewing

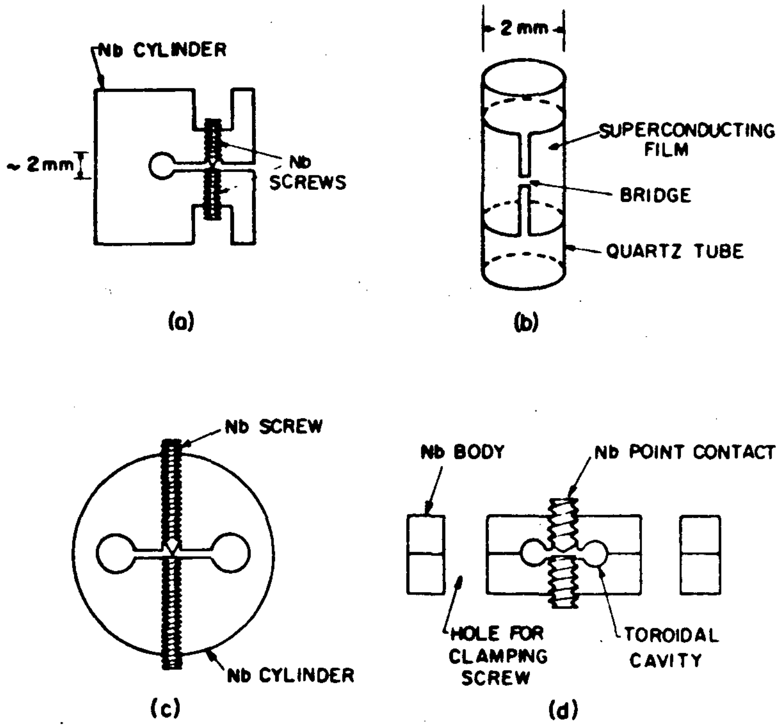

Fig. 3. Selection of rf SQUIDs: (a) point-contact rf SQUID, machined from niobium; (b) thin-film rf SQUID evaporated on quartz tube; (c) two-hole point-contact rf SQUID, machined from niobium; (d) toroidal point-contact rf SQUID, machined from niobium.

rate, 10^5 to 10^6 $\Phi_o s^{-1}$; and rms flux noise, 10^{-4} Φ_o $\mathrm{Hz}^{-\frac{1}{2}}$ (in the white noise region). The flux resolution is in quite good agreement with the value calculated earlier. At Berkeley, in the Summer of 1975, we measured the noise power spectra of the toroidal rf SQUIDs of S.C.T.[16] and S.H.E.[17]. The power spectra obtained, plotted as $S_\Phi/2\alpha^2L$, are shown in Fig. 2. Since these spectra were obtained, the white noise of the S.H.E. device has been improved to about $5 \times 10^{-29}\,\mathrm{JHz}^{-1}$. The values of S_Φ, M_1, L_i, and $S_\Phi/2\alpha^2L$ (in the white noise region) are presented in Table 1 for three rf SQUIDs (in the case of the S.H.E. device, the new value of S_Φ has been used).

Numerous workers have attempted to achieve better flux resolution by working at higher frequencies. For example, Pierce et al.[18] operated a thin film cylindrical SQUID at 10 GHz, and obtained a flux noise of about $10^{-5}\Phi_o\,\mathrm{Hz}^{-\frac{1}{2}}$, and an energy resolution of $2 \times 10^{-30}\,\mathrm{JHz}^{-1}$ at frequencies above a few kHz (see Table 1). The noise increased substantially at lower frequencies. The best flux resolution is probably that obtained by Gaerttner[19],

$7 \times 10^{-6}\Phi_0\ \mathrm{Hz}^{-\frac{1}{2}}$, using a 440 MHz point contact SQUID. Unfortunately, the parameters required to calculate $S_\Phi/2\alpha^2 L$ appear to be unavailable.

Future Improvements

Jackel and Buhrman[10] have given a detailed discussion of the optimization of the flux resolution of the rf SQUID. In all present versions, the intrinsic noise is insignificant, and the preamplifier and tank circuit contributions dominate. Optimization usually involves making these two contributions equal[10]. The best 30 MHz-SQUIDs are well-optimized, and no further improvement in performance is likely at this frequency. As is evident from Eqs. (8)-(10), the intrinsic and tank circuit contributions to the energy resolution vary as $1/\omega$, while the preamplifier contribution varies as $1/\omega^2$, provided that $S_V^{(p)}$ is independent of ω; unfortunately, the voltage noise of conventional FET preamplifiers tends to increase with increasing frequency. For example, suppose that $\omega/2\pi = 10$ GHz, $\varepsilon = 0.2$ (this may be a low estimate at 10 GHz), $L = 1$ nH, $T_e = 200$ K, and $T_N^{(p)} = 500$ K. From Eq. (13), we find $S_\Phi^{(i)}/2L \approx 4 \times 10^{-33}\ \mathrm{JHz}^{-1}$, $S^{(tc)}/2L \approx 10^{-32}\ \mathrm{JHz}^{-1}$, and $S_\Phi^{(p)}/2L \approx 5 \times 10^{-32}\ \mathrm{JHz}^{-1}$. The noise is dominated by preamplifier noise. This result is an order of magnitude smaller than the experimental value of Pierce _et_ _al_.[18], indicating that their preamplifier had a noise temperature higher than 500 K, and, probably, that ε was greater than 0.2.

It is clear that high frequency preamplifiers with lower noise are necessary to reduce the preamplifier contribution to the flux noise. The most promising development appears to be the use of cooled FET preamplifiers[19], which can have lower noise temperatures than room temperature preamplifiers. A cooled preamplifier may have the additional advantage of reducing T_e substantially, thereby reducing $S_\Phi^{(tc)}$.

Jackel and Buhrman[10] have shown that a non-sinusoidal current-phase relation in the weak link gives rise to a substantially higher noise than a sinusoidal current-phase relation. This result should be borne in mind when one chooses a weak link. For example, long microbridges tend to have highly non-sinusoidal current-phase relations, and are consequently undesirable in applications where the best noise performance is required.

Buhrman and Jackel[20] have found that the ultimate intrinsic energy resolution of the rf SQUID is of order $4k_BT/\omega_{opt}$, where $\omega_{opt} = R/L$. Apart from possible numerical factors, this is essentially the same result as that for the dc SQUID, Eq. (14). If we choose $\omega/2\pi \approx 10$ GHz, and $L \approx 1$ nH, we require $R \approx 60\ \Omega$. Thus, both dc and rf SQUIDs require junctions with the highest possible resistance to achieve the best flux resolution. This requirement, and the need for a sinusoidal current-phase relation, imply that the use of small area shunted tunnel junctions in SQUIDs should receive serious consideration.

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SUMMARY AND CONCLUSIONS

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In his rather elegant talk on high frequency detectors, Paul Richards likened his survey to visiting cages in a zoo: one had to make brief inspections of many different animals. In retrospect, I think his problem was much simpler than mine because his zoo was merely 1-dimensional. As I looked over the program for this conference, and wondered how I could possibly summarize such a diversity of topics, I realized that my own zoo was 8-dimensional! Rather than visit in turn each cage of this enormous zoo, I decided that I would try to summarize the conference in a general way. Therefore, I shall refer to very few specific papers, and, instead, try to give an overview of the present status of Josephson junctions and devices, and to speculate on future prospects. I have divided the summary into two parts: first, I will briefly discuss the junctions that are the building blocks of devices, and second, I will talk about the devices themselves.

The three basic configurations currently used as Josephson devices are the tunnel junction (oxide barrier or semiconductor barrier), the microbridge (constant thickness, variable thickness, or proximity effect), and the point contact. The properties of a point contact can be close to those of a tunnel junction, close to those of a microbridge, or lie somewhere between, depending on how the contact is made. I shall confine myself to a brief discussion of the tunnel junction and the microbridge, since it seems to me that, ultimately, Josephson devices will use thin film technology. How well do we understand the behavior of tunnel junctions and microbridges? - that is, to what extent do present theories have any correspondence with the properties of the real junctions? In the case of tunnel-junctions, the theory is well understood. The critical current can be accurately predicted from the junction resistance. If the junction is shunted, the resistively shunted junction model makes an excellent prediction of the shape of the current-voltage characteristic and whether or not it is hysteretic. In the case of microbridges, the situation is very much less clear. My own understanding of the theory of microbridges is in a rather confused state. We have heard a number of theoretical discussions on microbridges based on either GL or TDGL theories. To some extent these models explain some features of some types of microbridges. However, there are many additional factors to be considered, some of which may need to be included in a more successful description, for example: heating, nonlinear quasiparticle conductance, quasiparticle relaxation processes (there are several to choose from!), gap relaxation processes, vortices, and non-uniform current distribution. It remains to be shown which of these factors are essential in a proper description. As evidenced by the many papers at this conference, this area of research is very active at present, and hopefully we shall see a resolution of these problems in the next two or three years. However, one important point seems to be generally agreed upon: to obtain a sinusoidal current-phase relationship, one must make the length of the bridge shorter than the coherence length.

Let me turn to junction fabrication. The most reproducible tunnel junctions are undoubtedly the lead (alloy)-oxide-lead (alloy) junctions produced by IBM. Niobium-oxide-lead and particularly niobium-oxide-niobium tunnel junctions are also very reliable, and are attractive for devices. The barrier is grown by thermal oxidation or by a plasma discharge in oxygen. Junctions with semiconductor barriers are also a very promising development. With the aid of mechanically machined masks, one can obtain junction dimensions down to perhaps 25 μm. Photolithographic techniques enable one to achieve dimensions of about 1 μm. In the case of microbridges, the favored materials are niobium, tantalum, tin, and indium. We have heard about very sophisticated electron beam-lithographic and ion-milling techniques that can achieve dimensions of 0.2 μm or even less. The technology of microbridge fabrication seems to be in good shape, although it is certainly very expensive.

The reproducibility and reliability of tunnel junctions are excellent. Microbridges are reproducible if the appropriate technology is available, and for the hard superconductors, at least, the reliability is excellent. On the other hand, microbridges made of soft superconductors tend to burn out rather easily.

What are desirable properties for junctions? For SQUIDs and high frequency detectors, I_cR should be as large as possible, and RC (i.e. C) should be as low as possible (I_c, R, and C are the critical current, resistance, and capacitance). The current-voltage characteristic should be non-hysteretic ($2\pi I_c R^2 C/\Phi_o \lesssim 1$). It is desirable for the junctions to operate well below the transition temperature without developing large critical currents, and for dI_c/dT to be small. In the case of high frequency detectors, one wants the junction to couple as efficiently as possible to rf radiation. The computer memories and logic circuits developed so far have used tunnel junctions with hysteretic current-voltage characteristics ($2\pi I_c R^2 C/\Phi_o >> 1$). The main requirement is to achieve the highest possible value of I_cR.

I would like to make some suggestions on junctions. If you are in the business of making tunnel junctions or microbridges (or point contacts for that matter), it is obviously important to state the value of I_cR that is achieved. However, in addition, one would like to know the range over which I_c and R can be varied. For example, in a microbridge it might be relatively straightforward to obtain $I_c \sim 10$ mA and $R \sim 0.1\ \Omega$ so that $I_cR \sim 1$ mV. But can one also achieve $I_cR \sim 1$ mV with $I_c \sim 1\ \mu$A and $R \sim 1\ k\Omega$, the values one would like to use in a SQUID? Another important parameter to report is the maximum frequency at which one can obtain a response from the junction: a useful criterion is the highest voltage at which a microwave-induced step can be observed. A final suggestion is for those who have developed these beautiful techniques for producing very small microbridges. I would like to see someone make an earnest attempt to fabricate tunnel junctions with dimensions 1 × 1 μm or (preferably!) less, and to test these out in SQUIDs and high frequency detectors. (IBM has made junctions of this size, but, as far as I know, has used them only in computer elements.) A tunnel junction with dimensions 1 × 1 μm would have a capacitance of about 0.03 pF. One could then make $I_c \sim 1\ \mu$A (the critical current density, 10^2 A cm^{-2}, is easily achievable), and use a shunt resistance of 100 Ω without having hysteresis. SQUIDs made with these junctions should be exceedingly sensitive. For high frequency detectors, one would probably want to use a somewhat higher critical current, and a correspondingly lower resistance. In my opinion, small area tunnel junctions are likely to have a considerable impact on the device technology.

For the second part of the summary, I will review the three main areas of application covered by the conference: high frequency detection, computer elements, and SQUIDs. Paul Richards reviewed high frequency detectors, and I will just repeat the list of cages in his zoo. He began with the video or square law Josephson detector. The sensitivity of this device compares somewhat unfavorably with the superconducting transition edge bolometer, the best semiconductor bolometers, and the super-Schottky diode, and is unlikely to be used very much (except, possibly, when a very rapid response time is essential). The Josephson mixer can be used with either an internal local oscillator (that is, the Josephson self-oscillator) or an external local oscillator. Of these, the mixer with an external local oscillator seems to be the more promising, but is subject to strong competition from the super-Schottky diode mixer. Lastly there are the Josephson parametric amplifiers, either internally or externally pumped; the externally pumped parametric amplifier in a doubly degenerate mode with zero bias current has the best performance.

All of these devices have been made with point contacts. In addition, the externally pumped parametric amplifier has been made recently with an array of microbridges. The arrays have considerable promise as high frequency detectors, although the junctions in an array appear to be coherent only at low frequencies. Coherence is not necessary for externally pumped devices but is essential for internally pumped devices. This is an application in which small area tunnel junctions could have a considerable impact, since arrays could be made with a high degree of reproducibility and stability.

It is by no means obvious which of the Josephson high frequency detectors will finally have the best performance. It is also not clear that any of the Josephson detectors is vastly superior to the competition. It seems that a better microscopic understanding of the properties of junctions is required in order to achieve successful operation at the higher frequencies (above, say, 50 GHz) where improved performance is most urgently needed. One may hope for steady progress over the next two or three years.

At present, computer elements are the most rapidly developing application of Josephson devices. As far as I know, nobody has yet made a superconducting computer, but the potential of Josephson junctions for high speed computers seems enormous. This work has been largely dominated by IBM. Memory cells with writing times of less than 100 ps and several types of latching and non-latching logic circuits have been successfully operated. One of the most important aspects of the Josephson devices is their extremely low power dissipation, as a result of which one can obtain a very high packing density. It is essential to have closely spaced elements and consequently short transit times if one is to take advantage of the very fast switching times of these devices. I find it impossible to make any predictions of developments in this field over the next couple of years. I would just make a plea to IBM that they keep us informed of progress!

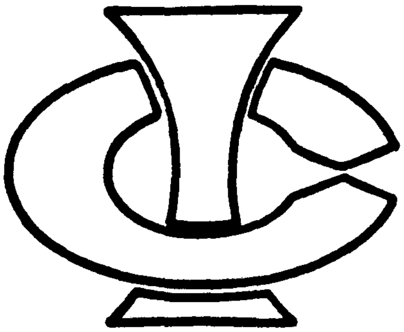
The main topic of this conference was SQUIDs. This is one area in which one can safely say that the Josephson devices are clearly superior to the competition. Numerous applications were described at this meeting: measurements of susceptibility, flux creep, thermopower, rf power, and ion-current, a precision resistance comparator, current stabilization, calorimetry, and even submarine communications. (Two major areas that for some reason were not mentioned here are geophysics and medical physics.) The steady growth in the applications is due at least in part to the commercial availability of reliable SQUIDs. Thinking back over the conference, I realize that there has been relatively little development in SQUID hardware over the last couple of years. The reason for this static situation is probably that the devices have had a performance that was at least adequate (and in many situations much more than adequate) for the applications in hand. However, there are now at least two applications in which more sensitivity is required, namely gradiometers and gravity-wave detectors. I suspect that the next two years will see a substantial improvement in the sensitivity of SQUIDs.

The theory of noise in both the rf and dc SQUID is now well understood, and is in good agreement with the measured noise limits. The optimum energy resolution per unit bandwidth for the dc SQUID is on the order of $k_B T/(R/L)$, where T is the device temperature, and L is the SQUID inductance. This result assumes that the noise temperature of the preamplifier is much less than T. The same result applies to the rf SQUID provided that the pump frequency, ω, is R/L; however, in this case, it is very difficult to obtain a preamplifier noise temperature that is less than the device temperature. How might one improve the performance of SQUIDs? One could obviously lower T. However, for practical reasons, it is usually convenient to run the SQUID at 4.2 K. In a few specialized applications one might operate the SQUID at a few mK, but in order to take advantage of this low temperature, one would need a cryogenic preamplifier with a very low noise temperature, probably another SQUID. In the present generation of devices, L is typically 1 nH, or somewhat less. Although a reduction in L (accompanied by an appropriate increase in ω in the case of the rf SQUID) would evidently improve the performance of the SQUID, it would most likely decrease the coupling efficiency to the signal coil, so that the energy resolution referred to the signal coil would probably not be substantially improved. Thus, the most likely way to improve performance is to increase the junction resistance, R: one would really like to have a value of 100 Ω, or more. Point contact junctions with high resistances have certainly been made, but whether they are sufficiently stable for long-term use is not altogether clear to me. It seems very difficult to produce microbridges with resistances of 100 Ω or more, unless one makes them extremely long. Unfortunately, long bridges have a very non-sinusoidal current-phase relationship, and are likely to contribute excess noise to the SQUID. Thus, one is left with small area shunted tunnel junctions as the most likely means to achieve higher performance. A properly optimized dc SQUID with a junction resistance of 100 Ω and an inductance of 1 nH should have an energy resolution per Hz approaching 10^{-32} JHz^{-1} (but still greater than $\hbar$, the ultimate limit!). An rf SQUID with the same values of R and L, and pumped at a frequency $R/2\pi L \sim 10$ GHz should have the same performance, provided that the preamplifier has a low enough noise temperature.

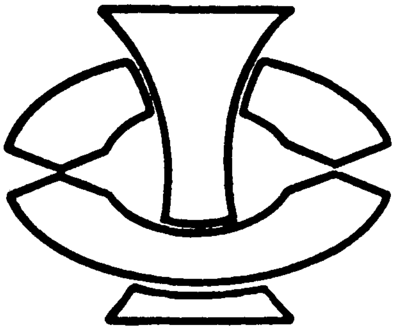
One final plea for SQUID makers. In the literature, one still occasionally finds the flux resolution quoted as a figure of merit. However, for most applications, this is not a useful quantity unless one knows the inductance, L_s, of the signal coil coupled to the SQUID, and the mutual inductance, $M = \alpha(LL_s)^{\frac{1}{2}}$ between the SQUID and the signal coil. At least in the zero frequency limit, a more useful figure of merit is $S_\Phi(f)/2\alpha^2L = S_\Phi(f)/2(M^2/L_s)$, where $S_\Phi(f)$ is the spectral density of the flux noise. (In some specialized applications, for example, a parametric amplifier coupled to a gravity wave detector, this figure of merit is also inadequate, as one needs some measure of the dissipation that occurs at a non-zero signal frequency.)

I should like to briefly refer to another paper in this conference, dealing with a topic that is of growing importance, namely refrigeration. If one is to see a widespread use of Josephson devices in applications outside the laboratory, in my opinion it will be necessary to develop a reliable type of closed-cycle refrigerator. Jim Zimmerman and his colleagues have designed a very ingenious Stirling refrigerator that presently achieves 14 K. This temperature is not yet low enough to enable one to operate the presently available devices, and there remain problems of magnetic noise generated by the refrigerator. Nevertheless, this refrigerator represents a considerable advance in low noise closed cycle refrigerators, and I believe that this is an important area for further development. Without trying to wish too much competition on Jim Zimmerman, I hope that a few other people become involved in this work.

I gather that there may well be another IC-SQUID in two or three years. I feel that this is an appropriate time scale, and I hope very much that a second conference does take place. I have a minor suggestion for the repeat performance. All of you have undoubtedly noticed the rather ingenious symbol for the conference:



The symbol obviously stands for IC, for flux, ϕ, and for an rf SQUID threaded by flux. However, if you look at the program cover, you will notice that the symbol has apparently been printed upside-down. In order to avoid any confusion at a future conference, it occurs to me that one can readily introduce some symmetry into the symbol so that one does not have to worry about which way up to print it. Thus, for the next conference, I suggest that the symbol be slightly modified to look like this:



To conclude: I should like to express my thanks, and I am sure also the thanks of everyone here, to the organizers and sponsors of this conference. IC SQUID was sponsored by the European Physical Society and the Physikalisch-Technische Bundesanstalt, to whom we are grateful for support. We should thank the program committee for their hard work in the selection of the papers and the organization of the sessions. We are also grateful to the many people behind the scenes who helped make the conference a success: those ladies and gentlemen who made sure that the projectors and loudspeaker systems worked, who supplied coffee when we needed it, and who took care of travel arrangements, visits to the PTB, and the other miscellaneous details of a scientific conference. Many of us have enjoyed the hospitality of the local scientists who have acted as our guides. Finally, our warmest thanks are due to the conference chairman, Professor Hahlbohm, who has labored for a year to make this conference a success, and who has taken overall responsibility for the organization of the meeting. Thank you very much.

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