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Design and Operation of Stable rf-Biased Superconducting Point-Contact Quantum Devices, and a Note on the Properties of Perfectly Clean Metal Contacts

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J. E. Zimmerman, Paul Thiene, and J. T. Harding field. The axis of the induced currents is tilted in a direction such as to tend to minimize the Lorentz forces (magnetic pressure) over most of the volume of the cylinder. The tilted pattern of circulation generates an axial magnetization, hence, modifies the existing configuration of flux along this direction. In the two situations we have just described, it appears that the tendency to relieve the Lorentz forces is paramount over the tendency to maintain the existing configuration of flux as large induced or conduction currents are made to flow in hysteretic type-II superconductors. As a consequence, macroscopic electric currents arising in hysteretic type-II superconductors can, under certain circumstances, adopt intricate trajectories which are not entirely dictated by the direction of the impressed or induced electric field.

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Design and Operation of Stable rf-Biased Superconducting Point-Contact Quantum Devices, and a Note on the Properties of Perfectly Clean Metal Contacts*

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Point-contact devices are described which have exhibited long-term stability and reliability. A particular mode of operation of the devices as rf-biased low-frequency detectors is described in detail, including a description of how the device drives a resonant circuit to which it is coupled. In this mode of operation the sensitivity of the devices to low-frequency fields is of the order of 10^{-9} G per root cycle bandwidth. Perfectly clean contacts were made by breaking a notched niobium member at 4.2°K and then remaking contact at the break. Quantum behavior of such contacts is identical to that of ordinary contacts, but effects of microscopic multiple connections at the contact were not observed.

INTRODUCTION

Superconducting quantum devices utilizing point contacts have been used extensively both in fundamental studies and in applications such as magnetometry and high-frequency radiation sensing.[1] This came about because contacts with the requisite physical characteristics can be made by the most naive and straightforward methods, as in the original experiment in which a pair of crossed wires, off the shelf, were pressed lightly together.[2] On the other hand, such methods will usually result in contacts which are extremely sensitive to shock and vibration, and quite unpredictable after thermal cycling to room temperature and back. In the above experiment for example, the contact was "adjusted" by rapping the side of the cryostat with a pencil. For this reason, it is common practice to provide a mechanism for readjusting the contact each time it is used (or oftener). The adjusting mechanism may itself be a source of microphonics unless carefully designed. An approach which we have used to avoid this problem is to mechanically disengage the adjusting mechanism from the device after adjustment. For most applications, however, it would be desirable to design the device for long-term stability with respect to the thermal and mechanical stresses encountered in normal operation and handling, so that the adjustment need be made one time only.

Besides being mechanically delicate, point contacts usually exhibit unpredictable critical-current oscillations as a function of applied magnetic field, an effect which is interpreted as quantum interference between various microscopic conduction paths produced by surface irregularities within the macroscopic contact area. Because of this, the response of single-[3] or double-contact[2] loop structures to an applied dc field frequently is multiply periodic. A loop with an area of .01 cm^2, for example, whose main period is about 20 μG, may also exhibit a much larger amplitude response with a period of the order of a gauss, owing to asperities a few microns apart within the macroscopic contact. Thus the operating bias levels required to display the 20-μG periodicity in the neighborhood of zero ambient field may be quite inappropriate for displaying the same 20-μG periodicity in the neighborhood of 1-G ambient field. Such a device would not be suitable as a wide-range digital magnetometer unless the contact itself is shielded from the applied field. This latter is not difficult to accomplish, but it is nonetheless an inconvenience. Furthermore, a certain amount of the ambient field will be trapped in the superconducting material when the device is cooled through its transition temperature. Thus the critical current of the contact may vary with the orientation of the device in the ambient field during the cooling process. This effect can be mistaken for a change in critical current due to thermal stress, but the two effects are clearly distinguishable through the use of certain obvious tests; for example, temperature cycling the device at a fixed orientation in a fixed ambient field. For both conceptual and operational simplicity, it is clearly desirable to make nonmultiple (microscopically simply connected) point contacts.

In this paper we describe the design of reasonably stable and reliable rf-biased point-contact loop devices requiring one-time-only adjustment, thus satisfying the first desideratum given above, and we describe briefly a method of making "perfectly clean" metal-to-metal contacts which may, to a considerable extent, satisfy the second. Also, we will discuss in some detail how such a device drives a resonant circuit to which it is loosely coupled.

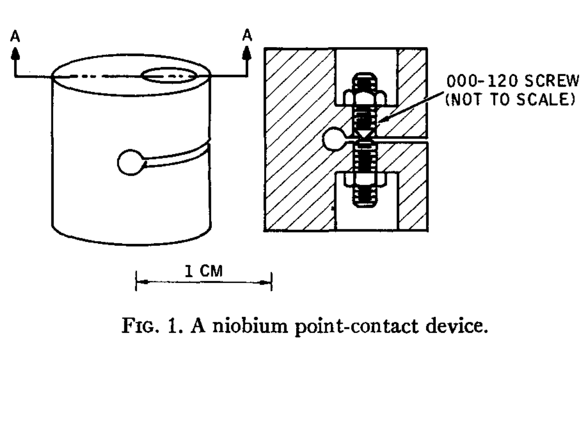
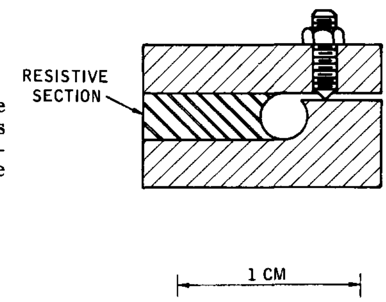


FIG. 1. A niobium point-contact device.

FIG. 2. A resistive device. Material is niobium with a copper alloy resistive section.



THE DEVICES

It is obvious that the mechanical stability of a very small contact is highly dependent on the stability of the external supporting structure, in contrast to the case of a thin-film tunnel junction where the insulating medium through which tunneling takes place is also the supporting structure which holds the two pieces of superconductor in precise relative position. In the design of a stable structure, the following possibilities, at least, should be given consideration:

(1) Mechanical vibration and shock.

(2) Structural distortion due to temperature inhomogeneities during heating and cooling (thermal shock).

(3) Structural distortion during heating and cooling due to inhomogeneity of the thermal-expansion coefficient.

(4) Atmospheric corrosion of the contact during storage at room temperature.

(5) Distortion due to moisture condensation on or near the contact, with subsequent freezing.

(6) Changes within the contact due to room temperature annealing and related effects such as grain growth, stress relaxation, etc.

(7) Burnout of the contact by electrical transients.

Items (4) and (5) can be taken care of by encapsulating the device or sealing off some part of the apparatus including the device with a helium atmosphere for heat transfer. Encapsulation also tends to cushion the device against thermal shock (item 2), and, in addition, it provides an opportunity for mechanical shock mounting (item 1). Our experience supports the contention that sealing the device from the atmosphere is essential for long-term stability.

Room-temperature annealing effects (item 6) are likely to be serious with soft materials like tin and lead. All of our experience has been with niobium or niobium alloys as the contact material, for which room-temperature annealing is probably quite negligible.

Point contacts, thin-film bridges, and tunnel junctions are all subject to damage by electrical transients or overloads (item 7). However, when the weak link is shunted by a low-inductance ($<10^{-9}$ H) loop, as in the devices we are considering here, such damage

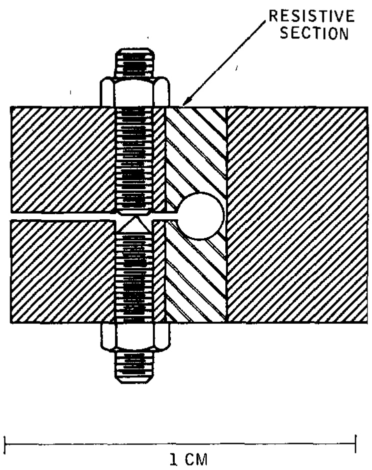


FIG. 3. Temperature-compensated resistive device.

becomes rather improbable and to our knowledge has never occurred.

Our superconducting loop devices were made mechanically rugged to minimize the effects of mechanical vibration and shock (item 1), and were made entirely of one material to eliminate differential thermal expansion (item 2). The first device to which these ideas were applied was made as shown in Fig. 1. It consists essentially of a C-shaped niobium block, the jaws of the C being bridged by a small-area contact. The two opposing members of the contact are 000–120 niobium screws, one flat on the end, one pointed. The point was formed on a jeweler's lathe and was honed to microscopic sharpness. Since the required contact area is exceedingly small, probably no more than a few-hundred Angstrom units across, it is obvious that the contact itself does not contribute to the strength or rigidity of the whole structure, and any relative motion whatever of the contacting members will deform the contact and make it unreliable.

One cause of relative motion is mechanical shock or vibration, resulting in tuning-fork vibrations of the C-shaped structure. The magnitude of such motion is minimized by making the structure fairly massive, and by placing the contact as far in toward the center hole as possible. It is not easy to carry out an exact analysis of vibrational modes of the structure, but a rough estimate indicates that a shock load of 100 G might produce a tuning-fork vibration with amplitude of the order of 10 Å at the contact. For a contact 1000 Å across, vibration of this amplitude might have a degrading effect. Experimentally we have found that severely shocking the device, as by rapping it with a screwdriver, does indeed change the contact characteristics. However, devices which have been mounted inside a probe assembly and thus protected from any direct physical shock have been highly reliable on this score, even though the assembly itself was roughly handled on some occasions.

A second cause of relative motion is thermal deformation of the structure resulting from temperature gradients. Deformation also will occur due to differential expansion if the structure itself is inhomogeneous. The coefficient of thermal expansion of Nb is $7\times10^{-6}/°C$ at room temperature. Thus a temperature difference of only 1°C between the left and right half of the device (Fig. 1) will produce a relative deformation of more than 100 Å. Presumably such a device at room temperature should not be directly immersed in a cryogenic liquid if one hopes for reproducible operation. Such treatment is likely to be detrimental for another reason, namely that moisture condensation in the slot and on the contact will contribute to differential expansion effects. The moisture may also corrode the contact.

These considerations led to the concept of mounting the device in a sealed probe, which at the same time protects the device from (a) direct mechanical shock, (b) severe thermal stress, and (c) chemical action by moisture and other atmospheric condensates. The outer wall of the probe was $\frac{1}{2}$-in. thin-wall stainless steel which served also as the outer conductor of the coaxial line coupling the device to the preamplifier at room temperature. The probe was filled with helium gas at low pressure for heat transfer. The success of this concept is indicated by the fact that two probes which were assembled early in Jan. 1968, have since been operated many times with no apparent change of critical current or other characteristics. One of these has been temperature cycled more than sixty times between 4.2° and 300°K.

Construction of resistive devices involves the use of two different materials, and so differential expansion is a serious problem. A cross section of a device is given in Fig. 2. With this design, differential expansion between the niobium part of the structure and

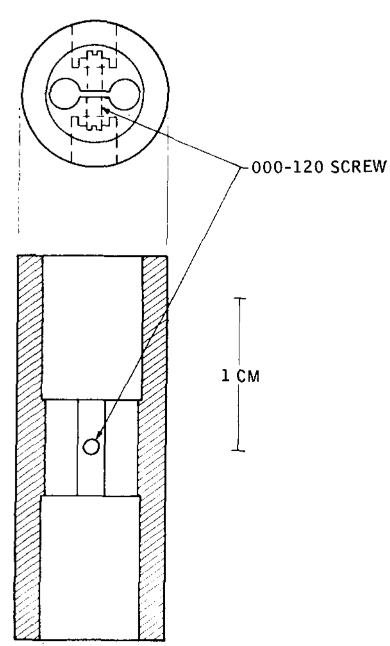


FIG. 4. An inherently stable symmetric structure for a niobium point-contact device.

the resistive part (a dilute copper–germanium alloy) amounts to 2 or 3 μ, so it was not surprising to find that the contact opened completely upon warming the device from 4.2°K to room temperature. A design which in principle compensates for the effects of differential expansion is shown in Fig. 3. By dividing the resistive section into two identical parts, symmetrically arranged, the thermal-expansion integral around the loop vanishes to a first approximation. Several such devices were constructed. The resistive material was copper with up to 10 at. % germanium to increase the resistivity. The resistive alloy was bonded to the niobium by induction melting it in a pure helium atmosphere. One technique was to mill a slot in a block of niobium, place a slab of the alloy in the slot, and then heat the block to a temperature well above the melting point of the alloy. Very good, bubble-free bonds were obtained if the helium atmosphere was sufficiently pure and the metal parts were well cleaned. The device was machined from the composite block. So far as long-term reliability is concerned this design was only marginally successful. A device with a 0.15-mm thick resistive section was temperature cycled 14 times in 45 days with no appreciable change of characteristics, but several devices with 1.5-mm thick resistive sections survived no more than a few temperature cycles, the contact generally getting weaker with each cycle.

Experience with the superconducting loop devices (Fig. 1) demonstrates that point-contact structures can exhibit long-term reliability. Nevertheless, as indicated above, the C-shaped structure is susceptible to severe mechanical or thermal shock. A very much better device, on both accounts, is the symmetric structure shown in Fig. 4. This type of device is presently being used in a number of investigations in magnetometry and high-frequency detection. Owing to its particular geometry and topology, it differs from the previous device in its response to applied time-varying magnetic fields. The total flux within the two holes of the device is constant in time ("trapped") and is not a function of applied field. The quantum interference phenomenon is observed by modulating flux from one hole to the other, which is accomplished by means of a coil inserted in one or the other of the two holes, or by applying the appropriate component of field gradient to the device. If the trapped flux in the device is nonzero, inserting a magnetic material in one hole will also shift flux from one hole to the other, so the device is useful as a self-contained susceptibility bridge. A *uniform* applied field gives no shift or change of flux, and hence no response. To use it as a magnetometer requires a superconducting "flux transformer". The use of this device as a detector element, in conjunction with a flux transformer as a coupling element to the external field, permits great flexibility in design and application.

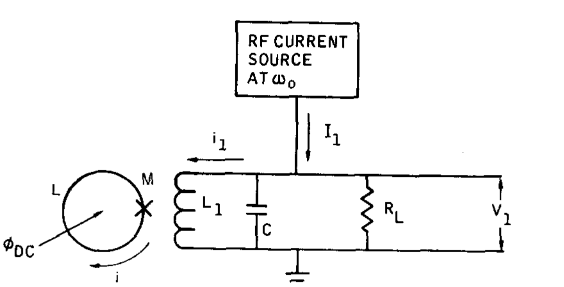


FIG. 5. Schematic representation of a point-contact loop coupled to a resonant circuit driven by a current source I_1 at ω_0.

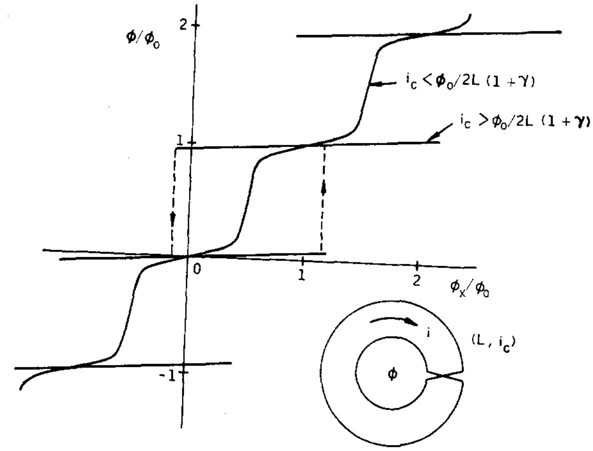


FIG. 6. Static flux ϕ in a weakly superconducting loop as a function of applied flux ϕ_x for two values of critical current i_c.

Finally, it might be pointed out that the symmetric structure is particularly convenient for microwave detection or mixing experiments. The two holes connected by a narrow slot form a capacitively loaded waveguide with a cutoff wavelength of the order of a few cm, depending on the slot width. Microwave radiation from a rectangular waveguide can therefore be fed into the end of the device through a transition section or funnel, to travel down the slot and impinge on the contact. The dominant mode of propagation is also the one giving maximum coupling to the current through the contact.

Our experience has shown that the response of these single-point-contact devices to an rf bias field and a quasistatic or dc field, as shown in Figs. 8, 10, and 11, is highly reproducible from one device to another provided the contact can be preset so that the critical current lies within a certain limited range. It is quite difficult to set the critical current exactly to some preordained value, but fortunately, as discussed in the following section, the amplitude of the quantum effects does not depend upon the critical current within this limited range, and so there is no need to set the critical current precisely. The least reproducible feature of point contacts is the multiple-contact effect mentioned in the introduction, which is recognized operationally as a gross change of critical current with large

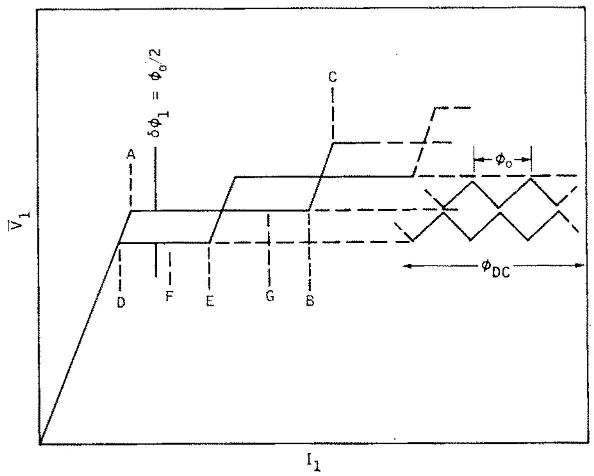


FIG. 7. Expected rf voltage amplitude $\bar{V}_1$ as a function of rf current I_1 and of static field ϕ_{dc}.

changes ($\sim$1 G) of ambient field. Probably more than half of our niobium contacts show this effect. The final section of this paper discloses a possible technique for making contacts with little probability of multiplicity, or if multiplicity is present it is on a much finer scale so that variation of critical current with field occurs, if at all, only at much higher fields.

MECHANISM OF OPERATION OF rf-BIASED DEVICES

In this section we will describe in some detail how a device interacts with a resonant circuit to which it is inductively coupled and which is driven by a constant-current rf bias, as indicated in Fig. 5. The groundwork for this discussion has been given previously by Silver and Zimmerman,[3] who showed that the dynamic behavior of the device can be derived from a quantum-periodic magnetic-response function, Fig. 6, which is either continuous and reversible or discontinuous and hysteretic, depending upon whether the critical current i_c of the contact is less than or greater than $\phi_0/2L(1+\gamma)$. Here γ is a dimensionless parameter which in practical devices is small compared to unity. For i_c greater but not *much* greater than $\phi_0/2L(1+\gamma)$, transitions between the disconnected states obey a selection rule $\Delta n = \pm 1$; that is, transitions take place only between adjacent states. Transitions are assumed to take place in a short time compared to one period of the rf-bias signal. The physical process of the transition will involve the shock excitation of the microwave modes of the structure (see Shin and Schwartz[4]) damped by the normal conductance of the contact. This will be discussed in more detail in a later paper. What we will consider here is the practical case where i_c is greater than $\phi_0/2L(1+\gamma)$ and where the rf-bias frequency ω_0 is set equal to the low-level resonant frequency of system. At low levels the device looks like a shorted turn in the field of the coil, therefore ω_0 is higher than the resonant frequency of tank circuit in the absence of the device, or with the contact open, or at high bias levels. The rf voltage across the tank circuit V_1 is a linear function of the rf-bias current I_1 as long as the total peak current in the superconducting loop is less than i_c. For the case where the dc applied field is

$$\phi_{dc} = 0 \text{ (or } n\phi_0\text{)},$$

the critical current i_c is reached at the flux level (taking $\gamma \sim 0$)

$$\phi_c = Li_c.$$

The rf flux ϕ_1 applied to the device is

$$\phi_1 = Mi_1 = V_1 M/\omega_0 L_1,$$

where i_1 is the current in the tank coil whose inductance is L_1, and M is the mutual inductance. Hence

$$\phi_1 = \phi_c \quad \text{when} \quad V_1 M/\omega_0 L_1 = Li_c.$$

Denoting this value of V_1 by V_{1c}, and the corresponding value of I_1 by I_{1c}, we have

$$V_{1c} = \omega_0 L_1 L i_c / M = I_{1c} R_t. \tag{1}$$

At this bias level (Fig. 7, Part A) a transition to one of the two adjacent states and back will take place. Thus the tank-circuit energy is abruptly reduced by the area of one hysteresis loop, that is

$$\Delta E = 2\phi_0 i_c - \phi_0^2/L. \tag{2}$$

This is equivalent to shock-exciting the tank out-of-phase with the driven oscillation. No further transitions can take place until the shock excitation dies out, that is, until the oscillation level again builds up to the critical level. Consequently, the system undergoes a low-frequency, low-amplitude saw-tooth modulation in time.[5] As the bias current I_1 is further increased above the critical value, the buildup of the oscillation level V_1 is more rapid and the saw-tooth modulation frequency increases; however, the modulation amplitude and the average oscillation level $\bar{V}_1$ remain fixed, the former being proportional to ΔE and the

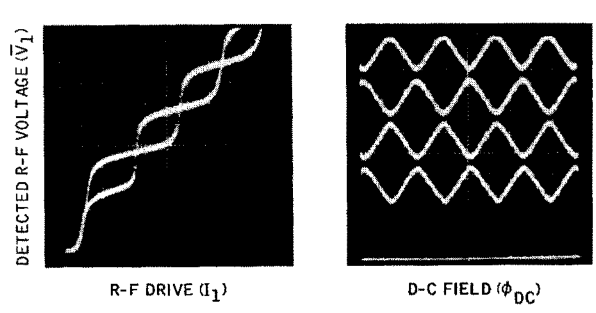


FIG. 8. Observed rf *VI* curves and dc field patterns for point-contact device of Fig. 4.

latter being essentially equal to V_{1c} minus half the modulation amplitude. Both ΔE and V_{1c} are fixed parameters of the system. Thus $\bar{V}_1$ is limited at this level until two hysteresis loops, one above and one below the dc field level ϕ_{dc}, are traversed on every rf cycle. At this point (Fig. 7, B), $\bar{V}_1$ again increases until the second pair of hysteresis loops is encountered, at which point (Fig. 7, C) $\bar{V}_1$ is again limited by mechanism described above. The total response may be described as a linear rise in $\bar{V}_1$ interrupted by an equally spaced series of plateaus.

This model predicts that if an average-reading detector is used one should see a spike (not shown in Fig. 7; see below) at the leading edge of each plateau, the height of which is half the peak-to-peak modulation amplitude. The modulation amplitude[5] is given by

$$\frac{\Delta V_1}{V_1} \cong \frac{1}{2}\frac{\Delta E}{E} = \frac{\phi_0 i_c - \phi_0^2/2L}{C(\omega_0 L_1 L i_c/M)^2}$$

or

$$\Delta V_1 \cong \frac{(2\phi_0 i_c - \phi_0^2/L)M}{\omega_0 L_1 L i_c C},$$

where E is the tank-circuit energy. This is particularly simple if i_c is considerably greater than ϕ_0/L, then,

$$\Delta V_1 \cong 2\phi_0\omega_0 M/L, \quad \text{for} \quad i_c \gg \phi_0/L.$$

The spike height is therefore $\Delta_s \cong \phi_0\omega_0 M/L$.

For the case where ϕ_{dc}/ϕ_0 is an odd half-integer,

$$\phi_{dc} = (n+\tfrac{1}{2})\phi_0,$$

then the first plateau comes near

$$V_{1c} = \omega_0(L i_c - \phi_0/2) L_1/M. \tag{3}$$

In this case limiting is effected by one hysteresis loop rather than two, so the first plateau (Fig. 7, D–E) is half as long as succeeding ones.

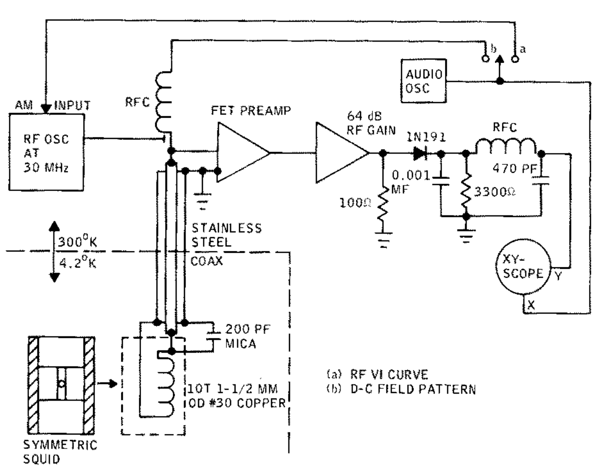


FIG. 9. Block diagram of cryogenic and electronic system used for observations of quantum properties of loop devices.

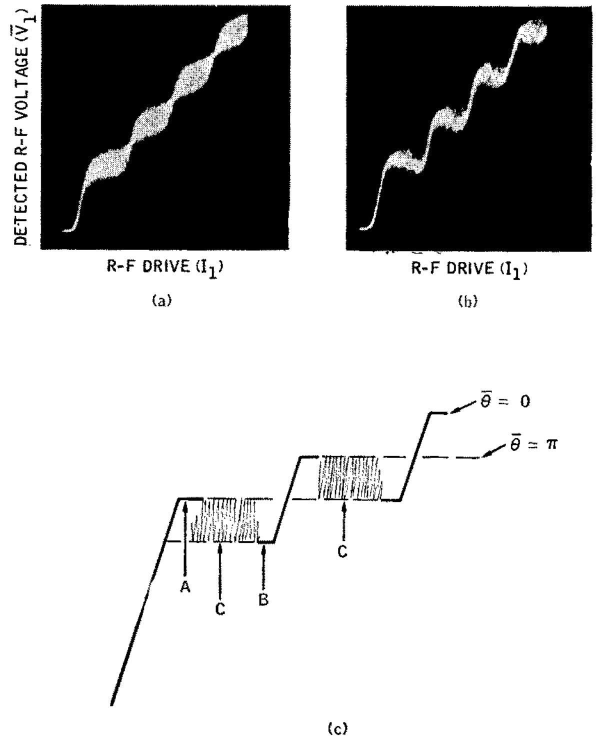


FIG. 10. rf VI curves for a resistive loop device with same geometry as superconducting device used in obtaining Fig. 8.

Finally, it is easy to show by extension of these arguments that for a particular rf bias level (Fig. 7, F, for example), $\bar{V}_1$ decreases linearly in the regions $n < \phi_{dc}/\phi_0 < (n+\frac{1}{2})$ and increases linearly in the regions $(n-\frac{1}{2}) < \phi_{dc}/\phi_0 < n$. That is, the response as a function of dc field is a triangular wave, furthermore the wave reverses phase as the rf level is increased so as to encompass the next adjacent pair of hysteresis loops, or so that the rf flux amplitude at the superconducting loop increases by $\phi_0/2$ (Fig. 7, G). These conclusions were already anticipated by qualitative arguments in an earlier paper (page 334, Ref. 3).

The vertical separation of the plateaus in $\bar{V}_1$, that is, the peak-to-peak variation of the response *vs* ϕ_{dc}, is given by the difference of Eqs. (3) and (1)

$$\Delta = \tfrac{1}{2}\omega_0\phi_0 L_1/M. \tag{4}$$

The height of the spike at the leading edge of each plateau was given above, $\Delta_s = \omega_0\phi_0 M/L$. In practice we have $M \ll (LL_1)^{1/2}$, from which it follows that $\Delta_s \ll \Delta$. Thus the spikes are very small and are not shown in Fig. 7. In fact they have not been seen experimentally, probably for at least two reasons: (1) we generally use a diode peak detector so that what we measure corresponds more closely to the peak value of V_1 than to $\bar{V}_1$, and (2) high-frequency thermal fluctuations superimposed on the applied rf flux causes premature triggering of quantum transitions, so that the edges of each plateau are actually rounded

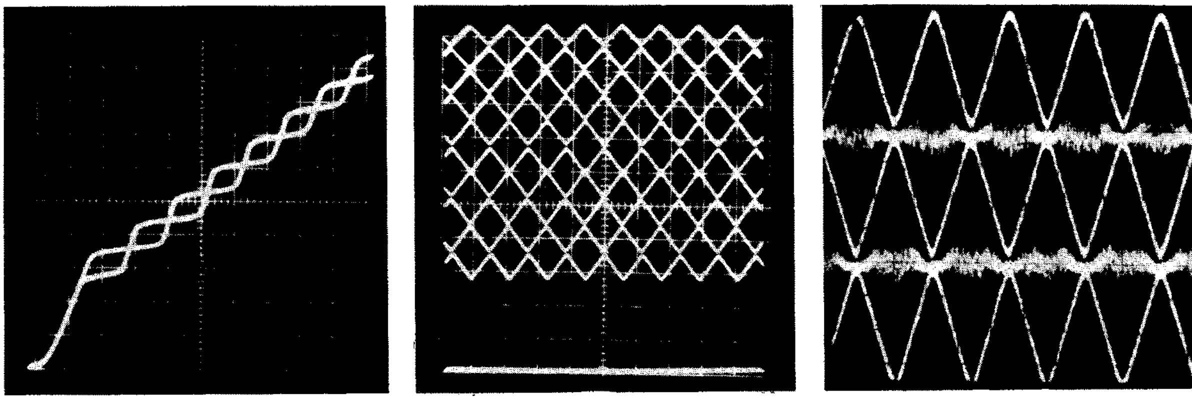


FIG. 11. rf VI curves (a) and dc field patterns (b) for superconducting device with perfectly clean contact. A portion of the dc field pattern is shown (c) with gain settings approximately the same as for the patterns of Fig. 8.

off. The difference between $\bar{V}_1$ and the peak value of V_1 is in any case very small.

The above description of events is good only if the tank circuit is fairly high Q, and the mutual inductance M is large enough that the inherent energy loss per cycle $2\pi V_1^2/\omega_0 R_L$ is considerably smaller than the area of a hysteresis loop.

Experimental evidence obtained under these conditions lends strong support to this detailed description. Figure 8 is typical of patterns obtained with devices of the types shown in Fig. 4, with a tank circuit $Q\sim100$, $M/(LL_1)^{1/2}\sim0.2$, $L\sim4\times10^{-10}$ H, an overall system bandwidth of 10^5 Hz, a tank-circuit capacitance $C\sim2\times10^{-10}$ F, and $\omega_0/2\pi=30$ MHz. The tank coil, a ten-turn coil of #30 copper about $1\frac{1}{2}$-mm o.d. was inserted directly in one hole of the device. The peak-to-peak amplitude of the patterns of Fig. 8(b) is about 14 μV referred to the preamplifier input (see Fig. 9).

The close quantitative relationship between superconducting loop and partly resistive loop devices has already been emphasized[6] in the literature and will not be repeated here. The essence of the relationship is that a resistive loop responds to rf fields in precisely the same way as a superconducting loop of the same geometry, with the additional feature that the phase of the response precesses in time at a rate which is the Josephson frequency, that is

$$d\theta/dt=V_0\phi_0,$$

where V_0 is the total voltage across the resistive section from all sources (Johnson noise, thermal emf, and IR drop for example).

Figure 10(a) is the rf response $\bar{V}_1$ vs I_1 for a resistive (18 $\mu\Omega$) loop device of nearly identical geometry and critical current replacing the superconducting device relating to Fig. 7. The same tank circuit and electronic components were used with no change of settings. Owing to a slight temperature gradient across the resistive loop and consequent thermal emf of $\sim10^{-11}$ V, a Josephson oscillation at a few kHz caused a corresponding amplitude modulation of $\bar{V}_1$. The envelope of the modulation can be represented quite accurately by the curves of Fig. 8(a) for the superconducting loop.

By applying a dc current bias to the resistive loop of a magnitude to exactly cancel the thermal emf, the curve of Fig. 10(b) was obtained. Some implications of this curve are rather interesting. Burgess[7] has shown that a tunnel junction in a resistive loop (in the absence of ac fields) fluctuates around the position of minimum Josephson coupling energy, namely around zero current i and zero phase shift $\theta(i=i_c\sin\theta$, where θ is the gauge-invariant quantum-phase shift across the junction). The total fluctuations in phase are small compared to unity if $kT\ll\phi_0^2/L$. Figure 10(b) shows that the same situation obtains under the application of an rf field, up to the point where quantum transitions begin to take place [Fig. 10(c), point A]. At higher rf bias [Figure 10(c), point B] the system shifts to a state corresponding to an average phase shift π across the contact, rather than zero. At intermediate bias levels (neighborhood of point C) large fluctuations take place, and in this region, as we show experimentally in another paper,[8] random walk of the phase takes place, analogous to the Brownian motion of a free particle in one dimension. An analytical description of the alternation of phase shift from zero to π as a function of bias amplitude is also given in that paper.

The particular regime of operation for point-contact devices described in this section does not necessarily provide best signal to noise. Nisenoff, using thin-film bridge devices, has made a careful study of the effect of varying the coupling. He finds that the pattern amplitudes (Fig. 7) vary inversely with the mutual inductance M, as implied by Eqs. (1) and (3), in the regime of tight coupling. With very weak coupling, however, although the rf bias levels must be increased, the dc field patterns [Fig. 8(b)] spread apart, decrease in amplitude and vanish as they must at zero coupling. It seems plausible that optimum coupling obtains when the area of a hysteresis loop is comparable to the energy dissipated per cycle in R_L. The latter is a function of M since the required rf-bias level varies as $1/M$.

The rms noise level apparent in the patterns of Fig. 8(b) is something less than a microvolt, or about 10^{-9} V per root cycle, referred to the preamplifier input. The system (Fig. 9) was used as a lock-on magnetometer[3] by replacing the oscilloscope with a Princeton Applied Research phase-locked detector and feeding its output back into a field coil coupled to one hole of the symmetric device (Fig. 4). With the loop gain and integration time adjusted for a response time of one second, the rms fluctuation in the output, expressed as flux through the device, was $\phi_0/6000$, or 10^{-9} G. With a trapped field in the device of $\sim\frac{1}{2}$ G (the earth field) and a superconducting shield enclosing it, no drift greater than $\phi_0/6000$ was observed over a period of several hours.

The response of a device under the simultaneous application of an rf bias and a dc or low-frequency field, as shown in Fig. 8(b), for example, is a particular example of the general phenomenon of heterodyne detection. Since one input signal, ϕ_{dc}, contains only low-frequency Fourier terms, the heterodyne terms lie close to ω_0 and the total output signal (carrier plus sidebands) appears at the diode as an amplitude-modulated wave and is detected as such. The more general case, where both input signals lie at high frequencies and only a heterodyne signal at ω_0 is detected (single-sideband detection), is presented in a separate paper.[9]

QUANTUM PROPERTIES OF "PERFECTLY CLEAN" METAL CONTACTS

There seems, understandably, to be no clear-cut idea as to what a point contact really is. Some authors refer to point contacts as Josephson junctions or tunnel junctions and let it go at that, although it has been pointed out that I–V characteristics can range all the way from those of ideal thin-film tunnel junctions to those of thin metal bridges. So far as experiments on rf biased niobium point-contact loops (as discussed in this and previous papers) are concerned, it has been argued that the observed characteristics are those one would expect for metal bridges. Since the analogous experiments with tunnel functions have not been reported, and the theory of metal bridges is much more qualitative than that of tunnel junctions, one cannot so easily describe the physical nature of these contacts.

Because of this uncertainty, we are interested in carrying out an experiment where one could be almost certain that the contact was made between surfaces whose composition was that of the bulk material. This was done as follows. A device of the type shown in Fig. 1 was fitted with a single screw bridging the gap and extending all the way through the device. The screw was notched to about half its area where it crossed the gap. The lower locknut was tightened securely. The upper end of the screw, without a locknut, was attached to an adjusting rod leading up and out of the cryostat, and was spring loaded to provide good contact at the threads and to eliminate backlash. By this mechanism the screw was broken at the notch while at operating temperature 4.2°K and then contact was reestablished between some random asperities on the fracture surfaces. We assume that the usual surface contaminants are immobile at this temperature, and so the contact surfaces were perfectly clean in the sense that any impurities present were those in the bulk material rather than on its surface. The quantum behavior of this contact (Fig. 11) was identical to that displayed by contacts machined at room temperature (Fig. 8). The device of Fig. 1 had somewhat lower inductance than that of Fig. 3, so the pattern amplitudes of Fig. 11 are somewhat greater than in Fig. 8. Figure 11(c) is a portion of the dc field pattern obtained at the same gain setting as those of Fig. 8.

We conclude from this that the metal-bridge model of a point contact is perfectly adequate for interpreting the type of experiments reported here and by inference may be adequate rather generally.

In certain respects, nevertheless, the perfectly clean contact behaved quite differently from ordinary contacts. Multiple contact effects were never seen, even with critical currents as high as a 10^{-3} A ($\sim 100\,\phi_0/L$). That is to say, transverse magnetic fields of the order of a gauss had no observable effect on the critical current, such as have been widely reported for point contacts and interpreted as quantum interference between alternate conducting paths. This may be somewhat surprising in view of the way this contact was made. Microscopic examination of the fracture surface revealed a fine-grain structure typical of brittle fracture, with numerous asperities where contact might have been made. Another operational feature of the contact was that the onset and magnitude of the supercurrent were exceedingly critical functions of the screw position, so that the final adjustment of the critical current was effected by elastically distorting the device by lightly loading the adjusting rod. These observations indicate that with perfectly clean surfaces the critical current density is relatively high so that for critical currents in the appropriate range ($<10^{-4}$ A) it is improbable that more than one pair of asperities will have made contact. The sharp onset of supercurrent and its rate of change with elastic loading of the device support the view that only a very small contact area is involved and that electrical contact is coincident with mechanical contact.

Note added in proof: With regard to the nature of perfectly clean contacts, Aslamazov and Larkin[10] have argued theoretically that for contact diameter a small compared to the correlation length ξ the relation between the supercurrent and quantum phase difference θ is the same as for a tunnel junction. An additional term in the current is characterized by the normal voltage-independent contact conductance G, so that the total current is

$$i=GV+i_c\sin\theta,$$

where V is the voltage across the contact. For the experiments reported here, V is small enough that the term GV can be neglected, except during transitions between states where G plays an essential role in damping the microwave modes of the system[4] and in determining the onset of higher-order transitions.[3,6] This will be discussed in a later paper.

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1 Extensive experimental studies on point contacts are those carried out by A. H. Silver and the author, by a group at Bell Telephone Laboratories (Dayem, Grimes, Richards, and Shapiro), and by a group at Kamerlingh Onnes Laboratorium (Arnold, de Bruyn Ouboter, Guinau, Kraan, Omar, Taconis, and de Waele). A review article will be published by R. de Bruyn Ouboter and A. Th. A. M. de Waele in *Progress in Low Temperature Physics*, C. J. Gorter, (North-Holland Publishing Company, Amsterdam, 1970), Vol. VI.

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