# Mr. SQUID* Goes to School

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## Introduction

The discovery of high-temperature superconductivity enables the development of SQUIDs (Superconducting QUantum Interference Devices)[1] and other superconducting devices that can be operated routinely in liquid nitrogen, and thus used in situations that were impracticable when superconductors required liquid helium. In particular, there is a great opportunity to use SQUIDs as an educational tool for students in universities and even in high schools. We designed Mr. SQUID expressly for this purpose. Thus, Mr. SQUID is both simple to use and difficult to destroy while selling for a price within the reach of most educational institutions. The student can observe for himself or herself the basic functions of the dc SQUID, namely the VI (voltage-current) characteristics and its periodic modulation by an external magnetic field. In more advanced experiments, the student can observe the resistive transition of the SQUID and the ac Josephson effect. He or she can incorporate Mr. SQUID into a home-built flux-locked loop, build a voltmeter, and observe the magnetic transition of a superconductor. We should emphasize, however, that Mr. SQUID is *not* intended to give state-of-the-art sensitivity, and, in particular, does not have a superconducting input coil or low-noise electronics. Such refinements, essential for technological applications, would have put the cost of the system beyond the reach of most educational institutions.

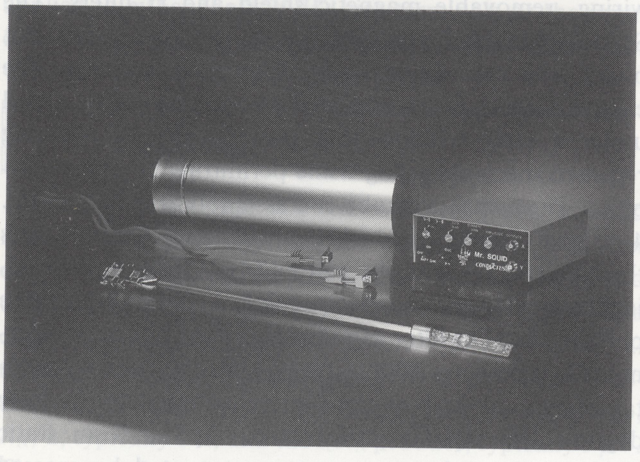



Fig. 1 The Mr. SQUID system showing the probe, electronics package, cable and dewar.

*Nickname of Superconducting Quantum Interference Device applied high $T_c$ superconducting YBCO thin film.

Mr. SQUID is a complete system containing the SQUID chip mounted on a sealed, magnetically-shielded probe, a battery-operated electronic control box containing the circuitry needed to operate the SQUID, a cable to connect the two, and a dewar to hold liquid nitrogen (Fig. 1). An extensive user's guide provides background information on SQUID technology, details the operation of Mr. SQUID and describes a series of advanced experiments.

## The SQUID in Mr. SQUID

The first active device[2] to be made from thin films of the high transition temperature ($T_c$) superconductors was a dc SQUID. The two Josephson junctions consisted of boundaries between randomly oriented grains of $YBa_2Cu_3O_7$ (YBCO). Within a short time, many groups in the U.S., Japan and Europe had made similar grain boundary SQUIDs. Although the yield of these early high $T_c$ devices was low, nonetheless some SQUIDs exhibited the classic behavior that had been observed for a quarter of a century in low $T_c$ devices. Subsequently, there was a worldwide effort to develop more reproducible Josephson junctions, and many types have been produced. Some of these involve more controlled grain boundary junctions, made, for example, from films deposited across a step in the substrate[3] or on a bicrystal substrate[4] in which the two halves of the substrate had been cut and fused together at a predetermined misorientation angle that was mimicked by the epitaxial growth of the YBCO film. Conductus developed a process for fabricating Josephson junctions that is inherently extendable to wafer-scale integration and that yields devices with good performance characteristics. We call these junctions "bi-epitaxial" grain boundary junctions in analogy to the bicrystal grain boundary junctions that inspired their development.

The bi-epitaxial process, which uses standard photolithographic processing, produces an essentially planar structure that can be easily incorporated into multilayer integrated circuits. The grain boundary junction is formed by underlying "seed layers": a YBCO film

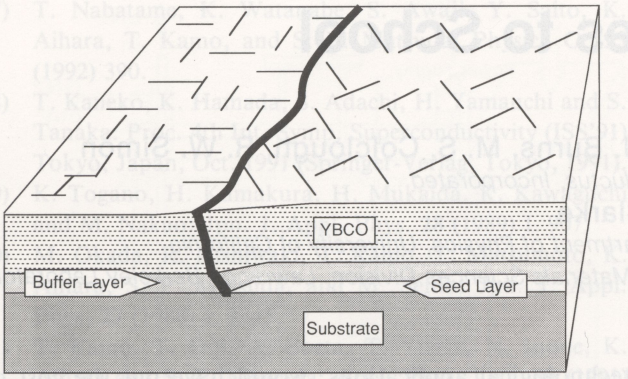



Fig. 2 Cross-sectional diagram of bi-epitaxial Josephson junction showing the constituent substrate, seed, and buffer layers that form the grain boundary.

growing epitaxially over a specific seed layer will have a different in-plane orientation than a YBCO film without the seed layer. Appropriate patterning of the seed layer and YBCO yields grain boundaries (and hence, Josephson junctions) in the YBCO film wherever the YBCO film crosses the edge of the seed layer. The buffer layer film grows in two different orientations separated by a 45° grain boundary as a result of its different eptaxial relationships with the seed layer and the substrate layer. The YBCO layer on top grows epitaxially everywhere and thereby reproduces the grain boundary in the buffer layer (Fig. 2). SQUIDs such as those in the Mr. SQUID chip are defined by conventional photolithographic patterning of the YBCO layer. This process has been described in publications[5] and the general class of structures has been awarded a United States patent.

## The SQUID Chip

A dc SQUID consists of a superconducting ring broken in two places by "weak links", of which the bi-epitaxial junctions are an example. Electrical contacts are made on opposite sides of the weak links. In the square washer geometry of Mr. SQUID (Fig. 3), there is a slit running from the central hole to the outside, where the weak links are located. The edge of the seed layer crosses this slit, defining the two bi-epitaxial junctions. This geometry ensures that a magnetic flux generated by a flat spiral coil laid on top of the washer is forced, by the superconducting nature of the washer material, to thread through the central hole in the washer and thus to couple strongly to the SQUID. In the case of Mr. SQUID, there are two single-turn coils laid on top of, but electrically insulated from, the washer. The coils are made from metallic silver and are thus not superconducting. One of the coils is connected to the Mr. SQUID control electronics and the other is made available for the user to apply external signals.

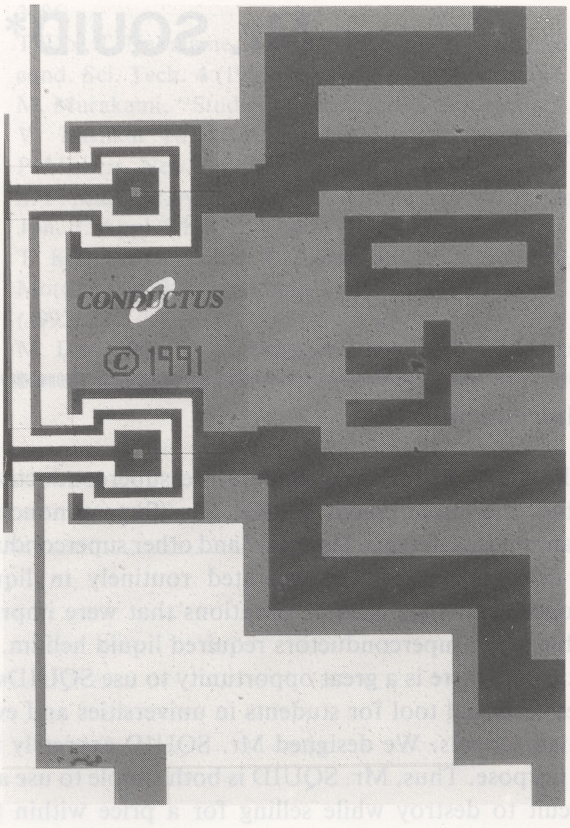



Fig. 3 The Mr. SQUID chip showing two SQUIDs with their silver modulation and coupling coils.

The size of the Mr. SQUID square washer is $250 \times 250$ $\mu m^2$, with a $20 \times 20$ $\mu m^2$ hole in the center. The $2.5 \times 2.5$ $mm^2$ chip actually contains two complete SQUIDs; during testing the better one is selected and connected to the wiring in the probe.

## Probe and Dewar

The cryogenic probe contains the YBCO SQUID chip, wiring, removable magnetic shield and rf filters. The SQUID chip itself is mounted on a custom printed circuit board with connections made by ribbon bonding. The chip and surrounding area of the board are encapsulated under a clear window that protects the chip during repeated thermal cycling while permitting complete visibility. The complete probe-end assembly is shown in Fig. 4. Signals are carried through twisted copper pairs through the metal probe rod and terminate in a metal-jacketed nine-pin connector linked to a removable pi-filter unit. The filter and shielding eliminate most external rf interference. Without such shielding, environmental rf sources such as cordless telephones significantly degrade the SQUID performance. Spikes from static discharges or other sources are attenuated by crossed diodes in the probe. Magnetic shielding is provided by a (removable) mu-metal cylinder surrounding the probe bottom. The metal-encased glass dewar provided will

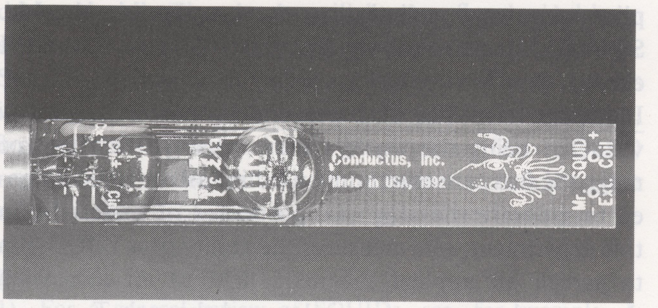



Fig. 4 The Mr. SQUID probe end assembly showing the encapsulated SQUID chip bonded to the circuit board.

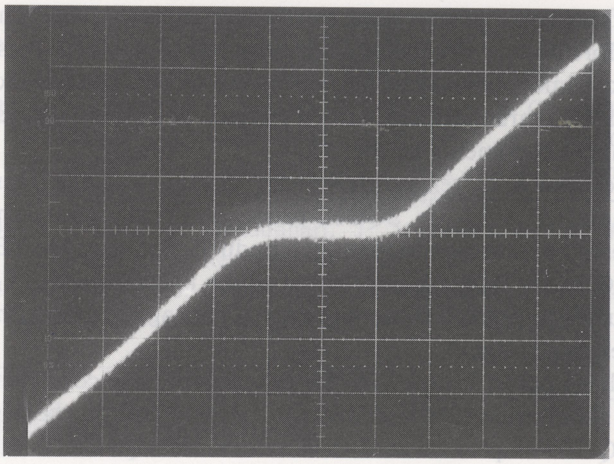


Fig. 5 The V-I curve of Mr. SQUID as an output from the Mr. SQUID electronics package.

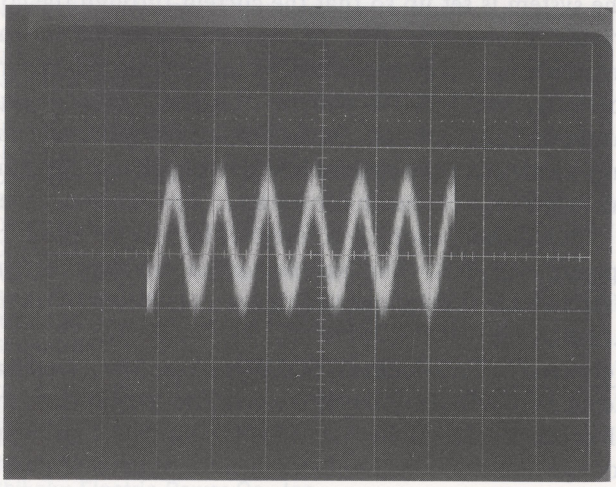


Fig. 6 The V-$\Phi$ curve of Mr. SQUID as an output from the Mr. SQUID electronics package. Typical modulation depth is greater than 1 $\mu$V.

hold one liter of liquid nitrogen for most of a day.

## Electronics Package

The electronic controller enables the user to observe and measure several characteristic properties of the SQUID and is self-contained and battery powered. The output is displayed on either an oscilloscope or an X-Y recorder.

The controller contains three current sources and a voltage amplifier, along with a multiple-pole mode switch which changes the interconnections of these circuit blocks. The voltage amplifier has a differential input and a gain of 10,000 with a passband from dc to 2.8 kHz. The input noise is less than 5 nV/$\sqrt{\text{Hz}}$, sufficiently low that a SQUID modulation depth of 1 $\mu$V can be easily seen on an oscilloscope.

Two of the current sources, adjusted by knobs on the control panel, provide bias current to the SQUID and current in the input coil of the SQUID, thus applying a constant magnetic flux. The third current source is driven by a triangle-wave oscillator, at 15 Hz for an oscilloscope display or at 0.08 Hz for an x-y recorder; the user can adjust the amplitude from the front panel. Depending on the position of the mode switch, the oscillating current is applied to either the SQUID bias terminals or the input coil, thus displaying the current-voltage characteristic or voltage-flux characteristic, respectively.

## Basic Experiments

To operate Mr. SQUID, one cools the probe in liquid nitrogen and then connects the control box. The first observation is of the V-I curve, illustrated in Fig. 5, and of its modulation by a magnetic field created by passing a current through the modulation coil. From these observations, one determines the critical current of the two junctions, $2I_c$ typically 10 $\mu$A, the resistance at high currents, $R_N/2$, typically 1 $\Omega$, and the $I_cR_N$ product, typically 5 $\mu$V. The current $I_m$ in the modulation coil required to produce one flux quantum, $\Phi_0=h/2e$, in the SQUID yields the mutual inductance $M=\Phi_0/I_m$ between the coil and the SQUID, about 75 pH. Since the coil consists of a single tightly coupled turn, to a good approximation $M$ is equal to $L$, the SQUID inductance.

In the second operational mode of the control box, one plots the voltage across the SQUID vs. magnetic flux, maximizing the peak-to-peak value $\Delta V$, typically 1 to 2 $\mu$V, by adjusting the static bias current (Fig. 6). In common with most other high-$T_c$ SQUIDs at 77 K, $\Delta V$ is rather smaller than predicted theoretically, due, possibly, to the non-sinusoidal nature of the current-phase relation of the Josephson junctions.

## Advanced Experiments

The User's Guide details more advanced experiments using Mr. SQUID that demonstrate a variety of superconductive phenomena as well as showing how SQUIDs are used in practical applications. The advanced experiments require various additional pieces of equipment and, often, some assembly of simple electronic circuits. The effort and experimental skills required to perform these experiments should be well within the scope of an advanced undergraduate laboratory course. We briefly discuss these experiments below.

Resistance vs temperature: By adding a diode thermometer to the Mr. SQUID probe, users can observe the resistive transition to the superconducting state of the YBCO in the SQUID chip as the probe is cooled. The V-I curve output from the electronics package provides the resistance signal.

Flux-Locked Loop: In this experiment, one constructs a simple circuit that allows the external coil on the Mr. SQUID chip to be used to flux-lock the SQUID. In this mode, one biases the SQUID with a constant current so that the voltage across it is periodic with the applied flux. One then amplifies this voltage response and uses the resultant signal to drive current through the external coil. The system is set up so that the current through the coil creates a magnetic flux of opposite polarity to the unknown flux to be measured. If one sets up the system correctly, the SQUID will be "locked" into a zero magnetic flux condition. In the flux-locked state, one has only to measure the current being fed back to determine the magnitude of the unknown flux. This scheme, called a "flux-locked loop", is almost invariably used to operate SQUIDs. The simple circuit outlined in the User's Guide enables one to achieve a sensitivity of about $0.01\Phi_0/\sqrt{Hz}$.

Voltmeter: Flux-locked SQUIDs are the essential elements of SQUID picovoltmeters. The resistance of the silver external coil in Mr. SQUID limits its ultimate voltage resolution, but one can measure microvolt ($10^{-6}$) to nanovolt ($10^{-9}$) signals. The principles behind the measurement are precisely those used in the most sensitive implementations.

AC Josephson effect: When a Josephson junction is biased at a fixed voltage V, the current through it oscillates at a frequency $V/\Phi_0$. This phenomenon can be observed by placing a current-biased junction in an applied oscillating electric field. In this experiment, one applies microwave radiation to the junctions in the Mr. SQUID chip and observes characteristic steps in the V-I curve.

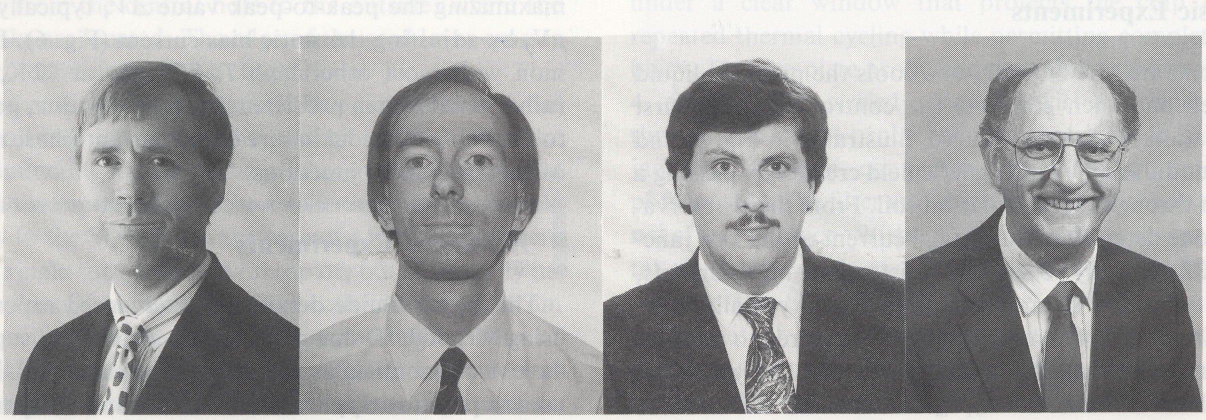
Inductive transition of superconductors: SQUIDs, by virtue of being the world's most sensitive detectors of magnetic flux, are commonly used in instruments designed to measure the magnetic properties of materials. In this experiment, one measures the ability of a YBCO film to screen an applied magnetic field to an increasing degree as the temperature is lowered through $T_c$.

## Future Developments in High $T_c$ SQUID Technology

Mr. SQUID is the first commercial system incorporating high $T_c$ SQUID technology. In order to be simple to use and affordable for the educational market, its performance is in no way competitive with established SQUID technology. Future high $T_c$ SQUID products by Conductus and by others will incorporate significant enhancements such as a useful external coupling scheme and far more sophisticated and lower-noise electronics.

One problem with high $T_c$ SQUIDs is the difficulty of making superconducting electrical connections following the high temperature processing of the superconductors. One method of circumventing this difficulty is to connect external circuits magnetically. In this scheme, a coil in the external circuit is placed against the SQUID washer, or against a coil which is in turn coupled to the SQUID. Magnetic flux generated by current in the external coil is forced, by appropriately shaped superconductors, to thread the SQUID with high efficiency, in the same way that the input coils in Mr. SQUID are strongly coupled to the SQUID washer.

The Mr. SQUID package is not intended for sensitive measurement applications, but the high $T_c$ SQUID technology on which it is based is capable of high performance in magnetic sensors. A future system under final development at Conductus will include a high $T_c$ SQUID with a large pickup coil, suitable for measuring magnetic fields, or for magnetic coupling to a still larger custom-



(from left) M. J. Burns, M. S. Colclough, R. W. Simon and J. Clarke, authors.

designed coil. The system will have a flux-locked-loop electronic controller with much lower noise than the Mr. SQUID electronics. Possible applications of such devices include sensors for non-destructive evaluation, magnetocardiography, and geophysics. Mr. SQUID represents only the first of what promises to be a long line of products enabled by high $T_c$ SQUID technology.

**References**

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