Design and fabrication of cryogenic probe for penetration depth measurements down to 1.8 K

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Abstract. We describe the design and fabrication of a cryogenic probe for measurements of magnetic penetration depth ($\lambda$) down to 1.8 K. Penetration depth provides fundamental information about the nature of superconductivity and sets the length scale for vortex dynamics. Our probe employs the single coil self inductance technique at radio frequencies, in which the coil configuration along with the temperature stabilized tunnel diode oscillator enable the measurement of $\lambda$ for thin film samples. There is also a provision for studying modulation of $\lambda$ in the presence of small magnetic fields generated from an inbuilt coaxial superconducting coil. We present the performance of this probe in controlled sustenance of temperatures below 4.2 K and attainment of a signal-to-noise ratio of $\sim 10^5$, while measuring superconducting transition of a foil of indium.

1. Introduction

The magnetic penetration depth ($\lambda$) is a probe of the superconducting condensate density ($n_s$), and is particularly sensitive to the changes in $n_s$ induced by external magnetic fields. It further determines the length scales for Vortex motion which is fundamental for understanding the statistics and dynamics of strongly interacting vortices subjected to thermal and structural disorders. The regime of sub liquid Helium temperatures where thermal fluctuations are sufficiently suppressed is required for detection of small changes in the penetration depth.

The technological importance of the penetration depth studies has driven the development of various microwave techniques for measurement of $\lambda$. The widely used traditional techniques are parallel plate resonator[1], superconducting cavity resonator[2], and dielectric resonator[3].

Here we have employed the technique of lowering of boiling point of liquid helium by gradual decrease in vapor pressure over liquid surface to reach low temperatures. The probe design provides a fine control over liquid helium flow and pumping rate to facilitate a slow approach to $T < 4.2$ K. For the $\lambda$ measurements, we have used radio-frequency (rf) self inductance technique in which the coil (L) with the sample inside, forms part of an oscillator circuit. The change in the effective area available to magnetic flux inside the coil due to flux expulsion from the sample in Meissner state changes the inductance and thus the resonant frequency of the circuit which is directly related to the change in $\lambda$ through a proportionality constant.

2. Operating Principle

The underlying principle involved in attainment of temperatures lower than boiling point of liquid helium is the following. The boiling point corresponds to the temperature at which the
vapor pressure of the liquid equals the surrounding environmental pressure. Thus with lower surrounding pressure more energetic molecules escape to vapor phase, leading to a decrease in liquid temperature. The vapor pressure of liquid helium versus temperature has been studied in detail and is indicative of the temperatures attainable with pumping on its surface[4].

Penetration depth (\(\lambda\)) measurement technique employed here involves placement of the sample in a coil which forms part of an LC circuit of resonant frequency “f” in the radio frequency (rf) range. This circuit is driven by a tunnel diode oscillator of low power and highly stable frequency, given by \(f = \frac{1}{2\pi\sqrt{LC}}\), where the inductance \(L\) of the coil is directly proportional to the area offered to magnetic flux to pass through it. At \(T < T_c\), the sample is in the Meissner state, and with \(H < H_{c1}\), a complete flux expulsion occurs from the sample which minimizes the area containing flux. A Change in temperature changes the Meissner screening and thus this area. This leads to a shift in resonant frequency which can be measured by a stable frequency counter. Schawlow and Devlin,\[5\] gave the basic expression \(d\lambda = - G df\), where \(G\) is a geometric parameter. Absolute measurement of the penetration depth and hence \(n_s\) requires a knowledge of this geometrical factor.

To ensure small perturbation and hence application of linear theories of vortex dynamics, operation at low rf field “\(H_f\)” and hence small induced currents “\(J_f\)” is done. Techniques based on this general principle have been used previously to measure superconducting transition and mixed state properties of low\[5, 6\] and high \(T_c\) superconductors\[7, 8\].

3. Experimental Setup

3.1. Temperature attainment and sustenance

The probe as shown in the detailed layout presented in Fig.1 consists of two coaxial thin wall stainless steel pipes. Thinner pipe is connected to a copper pot where as the outer one to a SS cylinder. Both these vessels can be evacuated with vacuum pumps. Liquid helium to the pot is supplied from a storage dewar through a stainless steel capillary. A needle valve as shown is Fig. 2 regulates the flow of helium through the capillary. The vacuum jacket between the inner pot and outer SS cylinder supplemented with Miller radiation shield isolates the inner pot from the outer 4.2 K Helium reservoir. The heat load to the sample stage is minimized by thermal anchoring of the low thermal conductivity brass wires and composite radiation shield inside the inner steel pipes. The probable creeping up of the superfluid liquid helium below lambda point (2.17 K) is prevented by very narrow opening of the inner pot to the inner steel pipe (Not shown here). A Cernox temperature sensor (mounted on sample stage) coupled with Lakeshore temperature controller has been used to monitor and regulate the temperature.

![Figure 1. Detailed schematic diagram of the probe.](image-url)
3.2. Sample mount arrangement

As shown in Fig.3, the sample mounting arrangement consists of a sapphire rod whose one end is glued to the sample and the other clamped onto the inner pot end. Sapphire has been used because of its insulating character and greater thermal conductivity. The sample along with the sapphire rod is inserted into the coaxial coil, whose inner coil made of copper forms the inductor L of the oscillator circuit and the outer NbTi wire coil forms the superconducting magnet for generation of small dc fields.

![Figure 2. Composite Needle valve and capillary arrangement for liquid helium flow control.](image1)

![Figure 3. Schematic diagram of the sample stage showing the coaxial coil and sapphire rod sample mounting arrangement.](image2)

3.3. Electronic circuitry

Sustained and stable oscillations of any oscillator circuit depend on the nature of regenerative feedback which compensates for the energy losses in the system. Tunnel diodes are one of the best candidates to provide this positive feedback i.e. negative resistance to the circuit. Here we have used a Germanium Power Devices BD2 tunnel diode, chosen because of its low peak point current so that the ac field is negligibly small compared to the dc field. Low terminal capacity and series inductance, typically 6 pF and 1.5 nH, respectively, make it suitable for high frequency applications. As for other elements of the circuit, optimum performance was realized for the following set of components: \( C_1 = 120 \text{ pF}, C = 680 \text{ pF}, R_0 = 47 \Omega, C_B = 330 \text{ pF}, \) choke \( = 0.1 \text{ mH}. \)

![Figure 4. Tunnel diode oscillator circuit with L being the inductance of the coil with sample inside.](image3)

The shift in frequency is measured with HP 53131A frequency counter which has an inbuilt oven time base for resolution of the order of 1 Hz in \( 10^{10} \text{ Hz}. \)
4. Probe performance
After stabilizing the system at 4.2 K the pot is continuously pumped and the needle valve is
opened to start filling the pot with liquid helium. With sufficient helium inside the pot the
needle valve is throttled to start decreasing the pressure on liquid surface. In this manner the
temperature of the sample stage can be lowered down to 1.97 K. With the use of sample heater,
it is also possible to control the temperature between the lowest point and 4.2 K as is indicated
in Fig.5.

![Figure 5](image1.png)  ![Figure 6](image2.png)

**Figure 5.** Controlled attainment and stabilization of temperature. The temperature ramp is 0.1
K/min.

**Figure 6.** Temperature dependence of the resonant frequency (f) and the standard deviation with indium foil as sample.

We have checked the temperature stability and the performance of the LC circuit by
measuring the response of a thin foil of Indium. Fig.6 shows the temperature dependence of the resonant frequency for In sample. The data clearly show normal to superconducting state transition at $T_c \sim 3.4$ K. The transition width $\Delta T_c$ is only $\approx 0.1$ K. This matches very well with the reported values in literature. The variation of standard deviation of the resonant frequency is also plotted over here. This is a clear signature of good stability of the oscillator circuit.

5. Conclusions
In conclusion, we have fabricated and tested a cryogenic probe for penetration depth measurements in the temperature range of 1.8 - 4.2 K. The stability and response of the $\lambda$ measurement probe and circuitry have been checked by measuring the transition of a thin Indium foil. A frequency stability of $\Delta f/f \approx 10^5$ and temperature stability of $\pm 0.01$ K have been achieved.

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[1] Taber R C 1990 Rev. Sci. Inst. 61 2200-2206.
[2] Sridhar S and Mercereau J E 1986 Phys. Rev. B. 34 203-216.
[3] Mazierska J 1997 J. Supercond. 10 73.
[4] Dijk H van and Shoenberg D 1949 Nature 164 151-151.
[5] Schawlow A L and Devlin G E 1939 Phys. Rev. 113 120-126.
[6] Sridhar S, Maheswaran B, Willemsen B A, Wu Dong-Ho and Haddon R C, 1992 Phys. Rev. Lett. 68 2220-2223.
[7] Patnaik S, Singh Kanwaljeet and Budhani R C 1999 Rev. Sci. Inst. 70 1494-1500.
[8] Sridhar S, Wu Dong-Ho and Kennedy W 1989 Phys. Rev. Lett. 63 1873-1876.