SOME PROPERTIES OF THIN FILM ALUMINUM SUPERCONDUCTORS FOR USE AS A MEGAHERTZ SECOND SOUND DETECTOR

by

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ABSTRACT

Some properties of thin film aluminum superconductors (80-130 Å) were investigated for use as a high frequency second sound detector. The films' transition temperatures, T_c , were raised to near the lambda point of He by a surface enhancement of the BCS coupling constant. The films were useful as sensitive thermometers over the temperature range of their transition, $\Delta T_c = 0.06$ K, with a sensitivity given by the transition slope, 2-3 x 10^3 ohms/K.

The films mechanically and electrically withstood the thermal shock of five thermal cycles from room temperature to 2 K. The instability of T_c after cycling was at most 0.05 K. By increasing the bias current, T_c (the He bath temperature at the transition) could be decreased by at most 0.025 K.

The slope of the transition curve, $\frac{dR}{dT}$, increased by at most 30% upon thermal cycling and within experimental accuracy the bias current had no effect on $\frac{dR}{dR}$, for the range 2-60 μ A.

From measurements of one film's time response to thermal excitation, the time constant was found to be less than 45.5 n sec, which means that the film is capable of fully responding to second sound of frequencies of at least 3.5 MHz.

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CHAPTER I

INTRODUCTION

To detect second sound in He II within the microscopic critical region, where the wavelength of the second sound is less than the superfluid coherence length, the experimental apparatus must be capable of measuring high frequency second sound very close to the lambda point, T_{λ} . Second sound measurements have been made as close as 5×10^{-6} K below T_{λ}^{1} . For this temperature, a second sound frequency of 0.4 MHz is required to produce a thermal wavelength equal to the superfluid coherence length; higher frequency generation and detection is required for temperatures further below T_{λ} . Because of the high attenuation of second sound near the lambda point and the dc heat flow associated with operating the thermometer, this detector must have high thermal sensitivity, low operating resistance ($\langle 500 \text{ ohms} \rangle$, as well as the required low thermal time constant.

Superconducting thin films operated at their transition temperatures fulfil the stringent requirements of the needed thermometer. This thesis describes an investigation of thin film aluminum superconductors for possible use as a high frequency second sound detector.

The film properties which will be discussed are:

- a) the method of setting the transition temperature, T_c , near the lambda point of He
- b) the effect of the operating dc bias current, I_{dc} , on T_c and the slope of the transition, $\frac{dR}{dR}$
- c) the stability of T_c and dR with thermal cycling
- d) the thermal time response to heat impulses.

CHAPTER II

THEORY

A. Enhancement of T_c

A superconductor is useful as a second sound detector only over a narrow temperature range about its transition temperature, where the resistance drops from its normal value, R_n , to at most a few ohms. The transition temperature is usually defined as the temperature of the superconductor at which the material's resistance is one-half of its normal state resistance. In this investigation, we are interested in the films as detectors of thermal waves propagating in the He bath, not in the film's properties as a function of the film temperature. Therefore, for this investigation the more meaningful definition of the transition temperature, T_c , which will be used is the temperature of the He bath at which the film's resistance is one-half of its normal state resistance.

Since superconductors are useful as sensitive thermometers only over a narrow temperature range, the first problem is to prepare a film such that its sensitive temperature region is at the required temperature. Because more theoretical and experimental work has been done on shifting the transition temperatures of the elements and the simplicity of fabrication, aluminum was chosen as the thermometer material. The transition temperature of bulk aluminum is 1.175 K; a size effect enhancement phenomenon was used to raise T_c near $T_{\lambda}=2.172$ K.

An expression for T_c in bulk superconductors derived from the Bardeen-Cooper-Schrieffer (BCS) theory is the starting point of most theories predicting the enhancement of T_c .

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This expression is²:

$$kT_{c} = 1.14 \ \hbar w \exp(-1/p), \quad \text{for } p(\langle l \ (1) \rangle)$$

where w=the characteristic cutoff frequency corresponding to the Debye temperature

> p=the BCS coupling constant, which is the product of the electron density of states, N, of one spin at the Fermi surface, and the average net attractive phonon mediated electron-electron interaction, V.

From Eq. (1), it is clear that T_c can be increased by increasing either $\hbar w$ or p. Ginzberg³ has suggested that a surface enhancement of T_c may arise from increasing the specimen's BCS coupling constant, p. The effective p would be a superposition of the bulk metal electron-electron interaction in the centre volume of the specimen and the enhanced interaction at the geometrical boundaries. He also suggested that the enhanced surface interaction may be due to surface phonons and the variation of electron-nucleus screening at the surface.

Aluminum films deposited on a room temperature substrate are polycrystalline. Therefore, the surface enhancement of T_c can arise from either the film thickness, d, or the crystallite grain size, g, if either dimension is small enough to produce a large enough surface to volume ratio. If g $\langle \langle d,$ as with aluminum films deposited in a large partial pressure of oxygen⁴, the grain size will primarily determine T_c . If $d \langle \langle g, as$ with ultra thin films deposited at pressures below 10^{-6} Torr⁵, the film thickness will determine T_c .

An expression for T_c has been derived by Abeles et al. for aluminum films where $g \ll d$. They assumed an ordered array of oxide bounded aluminum crystallites and developed a threedimensional generalization of de Gennes' expression⁶ for the

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enhancement of Tel The de Gennes derivation assumed a slab geometry of superconducting-normal-superconducting metals, whereas Abeles et al. were dealing with a three-dimensional superconductor-oxide-superconductor geometry. In the derivation, de Gennes was able to simplify a boundary condition by assuming the normal layer was not an insulating barrier. Abeles et al. were able to make the same simplification after comparing their films' normal resistances to those predicted by a model⁷ where each crystallite was an isolated superconductor. Since the experimental R_n was more than three orders of magnitude larger than those predicted, they assumed that each crystallite was strongly coupled to its neighbour, and that they too could simplify the boundary condition.

De Gennes also assumed that the coherence length, ξ , of his dirty superconductor model was larger than the width of the normal slab. Correspondingly, Abeles et al. found at least 100 grains contained within their calculated volume $\boldsymbol{\epsilon^3}$.

Both de Gennes and Abeles et al. assumed that hwand N of the sample were those of the bulk superconductor.

The resulting expression for T_c by Abeles et al. was:

$$T_c = 1.14 \ hw \exp(-1/p)$$
 (2)

where
$$p = p_0 + (p_B - p_0) \left[1 - (1 - 2d_g/g)^3\right]$$
 (3)

 $\hbar w = BCS$ cutoff frequency for bulk aluminum

 $p_0 = BCS$ coupling constant for bulk Al

 $p_s = BCS$ coupling constant within the surface region $d_8 =$ thickness of the surface region

g = average crystallite size.

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As can be seen from Eq. (3), p is actually the volume weighted addition of the bulk and surface ECS coupling constants. From the work of Pines⁸, they assigned values to $\hbar w$ and p_0 . The surface region thickness, d_g , was taken as 5 Å, the approximate thickness of an oxide monolayer, and the value of p_g was obtained from the best fit of Eq. (2) to their experimental data. With these values substituted for the above parameters, Eqs. (2) and (3) reduce to:

 $T_c = 216.6 \exp(-1/p)$ (4) where $p = 0.19 + 0.08 \left[1 - (1 - 10/g)^3\right]$, for g(<d and g has units of Ångströms.

For the case d $\langle\!\langle g, Strongin \ et \ al.^5$ have derived an expression for T_c. They assume a slab geometry of an aluminum film with a surface oxide layer. The Ginzberg surface layer, which enhances T_c, lies just below the oxide layer and is arbitrarily assumed to be the same thickness as the oxide layer, about 20 Å. Following the above theory of de Gennes⁶, the resulting expression for T_c is:

 $T_{c} = 1.14 \text{ hw} \exp(-1/p)$ where $p = (p_{0} d_{n} + p_{s} d_{s})/d$, for d((g. (5))

All the parameters have the same definition as in the theory by Abeles et al. except for d, which is the total film thickness. Both theories assigned the same values to the parameters fiw and p_0 . Strongin et al. assigned different values to d_8 and p_8 ($d_8 = 20$ Å and $p_8 = 0.35$) than did Abeles et al. The resulting expression for T_c by Strongin et al., is: $T_c = 216.6 \exp(-1/p)$ where $p = 0.19/d \left[(d-20) + 36.84 \right]$, for $d \ll g$ and d has units of Ångströms.

(6)

The two theoretical curves are shown in Fig. 3.

B. Thermal Time Constant Estimate

An estimate can be made of the film's frequency response to thermal excitation from the film's physical dimensions and steady state dc measurements. In the simplest model, one assumes that the time response of the detector to thermal excitation is amalogous to the response of a low-pass RC filter to electrical excitation. Neglecting the thermal capacitance of the substrate and thin film leads, the detector's capacitance is that of the superconducting film. The thermal conductance, G, from the film to the heat sink is identified with the reciprocal of R.

Pure superconductors exhibit a sharp rise in their specific heat ($\Delta C'$) in going from the normal state (C'_n) to the superconducting state (C'_s). The magnitude of the specific heat rise, for pure superconductors, is given by Rutgers' formula⁹. In the absence of a magnetic field, the specific heat rise in MKS units is:

 $\Delta C' = C'_{B} - C'_{n} = \frac{T_{C}}{e^{\mu_{o}}} \quad \left(\frac{dB_{C}}{dT}\right)_{T=T_{C}}$

where $\Delta C'$ has units of $J-Kg^{-1}-K^{-1}$

 ρ =film density (Kg/m³), assuming the density is that of bulk aluminum

 $B_c = \mu_e H_c$ in free space and assuming a demagnetizing factor of zero, with units of Teslas.

 $\left(\frac{dB_{C}}{dT}\right)_{T=T_{C}}$ = slope of the critical magnetic field T=T_c strength-temperature curve at T=T_c.

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The value of $(dB_c/dT)_{T=T_c}$ was taken as -183 G/K from Abeles et al.¹⁰ for a granular aluminum film whose T_c was near those of this work. One calculates that $\Delta C' = 0.19 \ J-Kg^{-1}-K^{-1}$. Now $C'_n = 0.11 \ J-Kg^{-1}-K^{-1}$ for bulk aluminum at T_c^{-11} . Assuming that Rutgers' formula correctly gives $\Delta C'$ for granular aluminum thin films, the upper limit of the film's specific heat is $C'_n + \Delta C' = 0.30 \ J-Kg^{-1}-K^{-1}$. With this upper limit on C', knowing the film's thickness, and the area of the film acting as the detector, one can estimate the upper limit of the film's thermal capacitance.

To determine the detector's thermal conductance, G, we followed the analysis of Martin and Bloor¹². The steady state heat flow equation for the film is:

$$G(T-T_8) = i^2 R$$
 (8)

where i^2R = electrical power dissipated in the film from the dc operating current

G=effective thermal conductance from the film to the heat sink (substrate and surrounding He bath

 $T-T_s = temperature difference between the film (T) and the heat sink <math>(T_s)$.

The resistance in Eq. (8) is a function of T. For low operating currents, joule heating raises the film's resistance by raising its temperature. However, with high enough currents, the film's resistance rise is due to a combination of the above joule heating temperature rise and a downward shift of T_c , caused by the magnetic field produced by the high current. Since, in writing Eq. (8)

one assumes that the film's temperature rise (and therefore resistance rise) is due only to joule heating, the equation is valid only for currents smaller than those causing a magnetic field shift in T_c .

Differentiating Eq. (8) with respect to T, with T_s held constant, we have:

$$G = \left(\frac{d(1^2 R)}{dT}\right)_{T_s = T_c}$$
(9)

The change in temperature of the film, ΔT , can be related to its change in resistance by using the transition slope $\frac{\partial R}{\partial T}$:

$$\Delta T = \frac{dT}{dR} \quad \Delta R \quad (10)$$

Substituting Eq. (10) into (9) results in:

$$\mathbf{F} = \left[\left(\frac{\mathrm{d}(\mathbf{1}^2 \mathbf{R})}{\mathrm{d}\mathbf{R}} \right)_{\mathbf{T}_{\mathbf{S}}} \quad \frac{\mathrm{d}\mathbf{R}}{\mathrm{d}\mathbf{T}} \right] \mathbf{T}_{\mathbf{S}} = \mathbf{T}_{\mathbf{c}}.$$

The slope of the transition curve is actually $\frac{dR}{dT_s}$, not $\frac{dR}{dT_r}$, since the temperatures measured are those of the He bath. However, if the temperature difference (ΔT_f) between the film and the He bath is constant over the transition region, then $\frac{dR}{dT_s} = \frac{dR}{dT}$. Now $\Delta T_f = T - T_s = i^2 R/G$. In constant current measurements of the transition curves, one would expect ΔT_f toodecrease as the film's resistance decreased, with this decrease in ΔT_f becoming larger for higher constant operating currents (See Fig. 5). This would result in a current dependent value of $\left(\frac{dR}{dT_s}\right)_i$. For the range of currents used in this investigation, $\left(\frac{dR}{dT_g}\right)_i$ was found to be independent of the operating current within experimental accuracy. We therefore conclude that ΔT_f was constant over the transition region and that $\frac{dR}{dT_g} = \frac{dR}{dT}$, for the range of currents used.

By measuring the film's resistance as a function of current, with the He bath temperature set on the linear portion of the $\frac{dR}{dT_s}$ slope, $\left(\frac{d(i^2R)}{dR}\right)_{T_s}$ can be found from the slope of the resulting power versus resistance curve. Again we must be careful to take the slope of this curve at current values below those which cause a magnetic field shift in T_c . If the film's temperature (resistance) rise is due only to joule heating, the slope of the power versus resistance curve will be of one value over most of the range of power values.

Since the physical dimensions of the film and the calculated specific heat places an upper limit on C, one can calculate the upper limit of the detector's thermal time constant T_{cc} . $T_{cc}=C/G$, where T_{cc} $w_c = 1$ and w_c is the RC corner frequency of the detector.

CHAPTER III

EXPERIMENTAL APPARATUS AND PROCEDURE

A. Film Preparation

Aluminum, 99.999% pure, was evaporated from an aluminum oxide crucible¹³, at pressures of $3-6 \times 10^{-6}$ Torr, onto polycrystalline quartz or microscope slide substrates. The substrates were degreased, ultrasonically cleaned in a detergent-distilled water solution, rinsed ultrasonically in distilled water, and dried just before evaporation in a stream of inert gas. The aluminum was degreased and etched in a KOH solution prior to evaporation. The aluminum vapour was masked to the shape of a bar-bell and deposited omto the ambient temperature substrate. The evaporator was then opened to air, to change sources, and approximately 2,000 Å of gold was evaporated on top of the aluminum to serve as electrical leads. Then # 40 AWG copper wires were indium soldered to the Al-Au-In overlap region (see Fig. 1). With the bar-bell shape, one can reasonably assume that the sensing area of the detector is the bar of the bar-bell. Since the smallest cross-sectional area of the Al film is in the bar, that region carries the highest and most uniform current density. Also the Al-Au-In alloyed regions are kept well away from the sensing area. The gold diffused through the aluminum oxide layer to provide electrical contact which withstood five thermal cycles from room temperature to 2 K.

A quartz crystal thickness monitor connected to a recorder was used to measure the film thickness, since the

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films were too thin to be directly measured by an interferometer. The monitor was calibrated with thicker films by plotting the frequency change of the quartz crystal against the interferometer measured film thickness. From this calibration and the frequency change measured by the recorder, the thickness of the 80-130 Å films were accurate to ± 10 Å.

B. Transition Curve Measurements

Steady state resistance-temperature measurements over the transition region were made for measuring currents ranging from 2-60 μ A. The temperature of the He bath was set by a pressure regulator¹⁴ which kept the bath temperature constant to 1 mK during the resistance measurements; for temperatures above the lambda point, a time lapse of 5 minutes was allowed for the system to come to thermal equilibrium before the resistance measurements were made. The He vapour pressure above the bath was measured by a butyl phthalate oil manometer and the corresponding bath temperatures were found from the "1958 He⁴ Scale of Temperatures"¹⁵. The resulting He bath temperature values were accurate to ± 3 mK.

The films' resistance was determined using a 4-point measurement technique. With a constant current flowing in one direction through the film, two voltage measurements were made: a positive voltage in the direction of the current and a negative voltage in the direction opposite to the current. The average of these voltages was then used to calculate the resistance. This procedure nullified the

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errors due to voltmeter drifts. The resulting error for all resistance measurements was at most ± 0.7 ohms.

C. Time Constant Measurement

The films were thermally excited by sweeping a laser beam across them. A 50 mW beam (4416 Å wavelength) from a helium-cadmium laser was reflected from a rotating mirror ll meters from the film. At the dewar, the 3 cm diameter beam swept across a variable iris and through a 10 cm focal length convergent lens onto the film. The resulting voltage pulse was transmitted out of the dewar through an ultraminiature coaxial cable¹⁶ and amplified by a wide band amplifier. The signal was displayed on an oscilloscope; the sweep being triggered by a light sensitive resistor placed in the beam's sweep path.

The method used to determine the film's time response to the light pulses was to measure the signal amplitude as the rise time of the beam intensity was varied. If the beam's intensity versus time profile could be equated to a sine wave of some "equivalent frequency", then a plot of the signal amplitude as a function of the "equivalent frequency" would give the RC corner frequency of the detector, and therefore its time constant. A typical signal is shown in Fig.2. In this figure, the camera shutter was open for about 100 oscilloscope sweeps, so the resulting photograph shows the signal superimposed on the wide band of amplifier noise. The signal to noise ratio observed, during the amplitude

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FIGURE 2. Typical Detector Signal Vertical Axis - 5 mv per division Horizontal Axis - 100 ns. per division. measurements, varied from about 5:1 to becoming lost in the amplifier noise. The signal appeared to remain approximately symmetric during the measurements.

The following procedure was used to determine the beam's intensity-time profile. With a light sensitive resistor placed in the film's position, an oscilloscope trace of its voltage was photographed as the beam swept by: the beam repetion rate was also measured by the oscilloscope. Since the minimum rise time of the light sensitive resistor was approximately 5 m sec, the beam's repetition rate was adjusted so that the resistor would accurately follow the intensity rise. An intensity-voltage calibration was then used to transform the voltage-time profile to an intensitytime profile. Since the laser beam was linearly polarized, its intensity could be quantitatively varied relative to its minimum by rotating a polarizer. The resulting intensityvoltage curve was normalized to the highest intensity transmitted by the polarizer. Renormalized intensity-voltage curves were drawn for each photograph of the resistor's voltage-time profile, with the renormalized intensity corresponding to the minimum voltage across the resistor during a sweep (the voltage decreased as the intensity increased). From the voltage-time profile of the photograph and the intensity calibration, an intensity-time profile was plotted for the corresponding repetition rate. To obtain the intensity-time profile for a faster repetition rate, one merely reduced the time scale of the profile by a factor

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equal to the ratio of the two repetition rates.

To determine the effect of the amplifier and coaxial cable on the detector signal amplitude, the frequency response of the two components was measured for direct electrical excitation; the results are shown in Fig. 6.

CHAPTER IV

RESULTS AND ANALYSIS

A. Transition Temperature Behaviour

As previously defined, Tc is the temperature of the He bath at which the film resistance is one-half of its normal state resistance. From the fit of the experimental transition temperatures to the theoretical curve of Eq. (6), which assumes that the film thickness determines Tc, one notices a lack of T_c dependence on film thickness (see Fig. 3). This lack of thickness dependence indicates that the parameter enhancing T, is probably the grain size, not the thickness, and that all the films have approximately the same grain This explanation of Fig. 3 is supported by work done size. by Cohen and Abeles¹⁷. They produced granular aluminum films $(g(\langle d))$ with an alumina crucible source, where the pressure before evaporation was 10⁻⁵ Torr, increasing to $3 \times 10^{-5} - 10^{-4}$ Torr during evaporation. Normally aluminum films evaporated at these pressures are not granular since the partial pressure of oxygen is too low. Cohen and Abeles assumed that the crucible outgassed enough oxygen when heated to produce a film composed of pure aluminum crystallites. each surrounded by an oxide layer. From Eqs. (2) and (3), we can conclude that the 80-130 Å filmsprepared in this investigation all have an average grain size of 83-88 Å.

If one wishes to increase the transition temperature closer to the lambda point, it could be done by two methods.



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The first way would be to increase the oxygen partial pressure during evaporation, as was done by Abeles et al⁴. This has been done by the author by bleeding oxygen into the evaporator at a rate about equal to the pump speed. With a low flow rate valve, the pressure can be stabilized to tlo⁻⁷ Torr. The pressure would then be the reproduceable parameter predominantly determining T_c . The other method of achieving a higher T_c would be to evaporate thinner films using the procedure of this work. With thinner films (≤ 60 Å), one should be able to enter the region where d $\langle \zeta$ g and the thickness would determine T_c . The limitation to this method, however, is that the lower limit to electrically continuous aluminum films is about 30 Å¹⁸.

Six films were thermally cycled five times from room temperature to 2 K, with no special precautions taken to avoid thermal shock. The first reason for thermally cycling the films was to determine whether they were securely adhered to the substrate and to ensure that they would remain electrically continuous upon cycling. One film, out of the six thermally cycled, became electrically discontinuous on the fourth cycle. Since the other five, films remained electrically continuous, one concludes that they mechanically withstood the thermal shock of the five thermal cyclës.

The effect of thermal cycling on R_n , $\frac{dR}{dT}$, and T_c was determined for three films. The normal resistance, R_n (resistance at temperatures just above the transition), was typically 180 ohms for the first thermal cycle. Upon thermal

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cycling, R_n rose monotonically for all films; by the fifth thermal cycle, R_n was as much as 80% larger than R_n for the first cycle (see Fig. 4). The slope of the transition curve, $\frac{dR}{dT}$, was typically 2,000 ohm/K for the first thermal cycle. For the films of thickness less than 100 Å, thermal cycling increased $\frac{dR}{dT}$ by at most 30%.

This increase in $\frac{dR}{dT}$ and the decrease in T_c upon thermal cycling (to be discussed) may have been caused by the reannealing of the films as they were cycled. Since the cycled values of these two quantities are closer to the expected values of a bulk aluminum superconductor, the trends indicate an increase of the films' average crystallite size upon thermal cycling.

Within experimental accuracy, there was little, if any, effect of the measuring current on $\frac{dR}{dR}$ for the range 2-60 μ A.

Another reason for thermally cycling the films was to determine the stability of T_c and to check if the "fine tuning" of T_c by varying the bias current could compensate for the thermal cycling instability of T_c . Typical results of the effect of thermal cycling on T_c are shown in Fig. 4. For the tree films tested, T_c varied over a range of 0.05 K during the five thermal cycles. The variation of T_c with I_{dc} , for currents of the range 6-60 μ A, was at most 0.025 K, and only in the direction of lower temperatures (see Fig. 5).

Since the slope of the power versus resistance curve of eleven films was constant over most of the bias current range (see discussion of Chapter II, p. 8), we assume that the dependence of T_c on I_{dc} is due only to joule heating.

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360 X 320 280 240 R (ohms) 200 160 Symbol Thermal Cycle Δ 120 12345 0 . X D 80 40 Tλ Å 0 1.95 2.00 2.05 2.10 2.15 2.20 T_{bath} (K) .

FIGURE 4. Typical Effect of Thermal Cycling on T_c and R_n

 $I_{dc} = 10 \mu A$.

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For, as I_{dc} is increased, $\Delta T_f = T - T_s = i^2 R/G$ (the difference between the film temperature and the sink temperature) increases. So even though the film's transition to the superconducting state occurs at the same temperature T, the transition temperature T_c , as defined by the He bath temperature, decreases with increasing current.

The limit to the "fine tuning" range in these films was the maximum current at which the films could be operated without destroying their electrical continuity. One 130 Å film became electrically discontinuous with an operating current of 80 μ A. A larger "fine tuning" range can be realized in very narrow films, if the width is less than a critical width (about one micron) and if the thickness is less than the penetration depth. T.K. Hunt¹⁹ has reported current induced shifts of T_c of 2.6 K in 500 Å tin films of width 1.9 microns.

B. Thermal Time Constant

Following the analysis of Chapter II, the intensitytime profile of the laser beam was found to be approximately Gaussian in shape. It is assumed that the detector's response to this Gaussian shaped excitation is equivalent to its response to a sinusoidal excitation of some "equivalent frequency". The "equivalent frequency" is defined as that in frequency of a sine wave whose rise time (the time between 10% and 90% of maximum amplitude) is the same as the rise time of the Gaussian shaped pulse - with its "tail" replaced by the extention of its steepest slope. Since the "equivalent frequency" of the faster light pulses were past the corner frequency of the amplifier, the corresponding detector signal amplitudes were compensated for the lower amplification.

The bottom curve of Fig. 6 shows the frequency response of the coaxial cable and amplifier, normalized to low frequency signals. The top curve shows the compensated frequency response of the detector alone. From the graph, one can safely assume that the detector's RC corner frequency, f_c , is greater than 3.5 MHz, which means that the film's RC time constant, T_{Rc} , is less than 45.5 n sec.

One can check the validity of the above measurement, and the underlying assumptions, by calculating T_{cc} , for the film of Fig. 6, as discussed in Chapter II. Recalling that $T_{cc} = C/G$, one needs only to calculate C and G. From the film's power versus resistance curve, we find $\frac{dP}{dR} |_{T_S=T_C} \geq$ 2.25 x 10⁻⁸ W/ohm, and from the transition curve of this film,

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 $\frac{dR}{dT}$ = 3,040 ohm/K. So that: $\frac{dR}{dT}T_s = T_c$

 $G = \left[\frac{dP}{dR} \frac{dR}{dT} \right]_{T_s = T_c} \ge 6.85 \times 10^{-5} \frac{W}{K} .$

From direct measurements of boundary thermal resistivities by Holt²⁰, one calculates that, within an order of magnitude, Holt's value of G for this film should be $G = 5 \times 10^{-2}$ W/K, with 10% of the total heat flow passing across the film-He bath boundary. The reason for the large discrepancy between the above values of G is probably a result of the different film structures. The aluminum films used by Holt were at least 2,000 Å thick and were evaporeted at a pressure of 10^{-6} Torr. Therefore, Holt's films probably contained a lower concentration of lattice defects than the granular films used in this investigation. Since the mechanism of thermal conduction is mainly phonon transmission across interface boundaries, the higher concentration of lattice defects in the granular films would increase the scattering of longitudinal phonons within the film and at the boundary and interfere with the coupling of the transverse phonons across the boundary. The value of G used in calculating *L*, will therefore be the experimentally determined value for the film of Fig. 6, $G = 6.85 \times 10^{-5}$ W/K.

To calculate C, we use the equation C=C'eLWd, where: $C'=0.30 \text{ J-Kg}^{-1}-\text{K}^{-1}$, as determined in Chapter II $e^{2.7 \text{ gm/cm}^3}$, assuming the film's density is that of bulk aluminum $d = 80 \pm 10 \text{ Å}$, the film thickness $W \leq 1.5 \text{ mm}$, the area of the film covered by the $L \leq 5 \text{ mm}$, laser pulse (from visual inspection).

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From these values, one finds that $C \leq 5.4 \times 10^{-11} \text{ J/K}$. Since we have now found the upper limit of C and the lower limit of G, the resulting T_{c6} shall be an outside upper limit. For the film of Fig. 6, we find $T_{c6} \leq 800$ n sec, which is in agreement with the experimental time constant, $T_{Rc} \leq 45.5$ n sec.

CHAPTER V

CONCLUSIONS

Some of the properties of superconducting thin aluminum films, with T_c near the lambda point of He, have been tested. The films are useful as sensitive thermometers over the temperature range of their superconducting transition, $\Delta T_c = 0.06K$. An indication of the thermometer's sensitivity is given by the slope of the transition curve, typically $\frac{dR}{dT} = 2-3 \times 10^3 \frac{ohm}{K}$.

Because of the high adhesion of aluminum to polycrystalline quartz substrates and the technique used to attach the leads, these films mechanically and electrically withstood the thermal shock of five thermal cycles from room temperature to 2 K. The instability of T_c during the thermal cycling was at most 0.05 K. By increasing the bias current, T_c could be decreased by at most 0.025 K. Therefore, the thermal cycling instability of T_c could not beewholely compensated by the bias current "fine tuning" of T_c . However, with films of a smaller cross-sectional area, with a corresponding higher degree of current "tuning", the thermal cycling instability may be compensatable.

The normal resistance, R_n , rose monotonically for all the films tested upon thermal cycling. By the fifth thermal cycle, R_n was as much as 80% larger than R_n for the first thermal cycle.

The transition slope increased by at most 30% upon thermal cycling, but was not effected by bias current variation, for the range 2-60 μ A. This increase in the transition slope by thermal cycling would not subtract from these films' usefulness as a second sound <u>detector</u>. If, however, the films were to be used to measure the absolute amplitude of second sound, the transition slope would have to be determined each time the film's temperature was lowered from room temperature to T_c .

From measurements of one film's time response to thermal excitation, the RC time constant was found to be less than 45.5 n sec, which means that the film is capable of fully responding to second sound frequencies of at least 3.5 MHz.

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REFERENCES AND FOOTNOTES

1.	D.L. Johnson and M.J. Crooks, Phys. Rev. <u>185</u> , 253 (1969).
2.	K.L. Chopra, <u>Thin Film Phenomena</u> (McGraw-Hill, New York, 1969), p. 544.
3.	V.L. Ginzberg, Phys. Letters 13, 101 (1964).
4.	See, for example, B. Abeles, Roger W. Cohen, and G.W. Cullen, Phys. Rev. Letters <u>17</u> , 632 (1966).
5.	See, for example, Myron Strongin, O.F. Kammerer, and Arthur Paskin, <u>Proceedings of the International Symposium</u> , <u>Basis Problems in Thin Film Physics</u> (Vandenhoeck and Ruprecht, Göttingen, West Germany, 1966), p. 505.
6.	P.G. de Gennes, Rev. Mod. Phys. <u>36</u> , 225 (1964).
7.	C.J. Thomson and J.M. Blatt, Phys. Letters 5, 6 (1963).
8.	D. Pines, Phys. Rev. <u>109</u> , 280 (1958).
9.	A.C. Rose-Innes and E.H. Rhoderick, <u>Introduction to</u> <u>Superconductivity</u> (Pergamon Press, London, 1969), p. 60.
100.	B. Abeles, Roger Cohen, and W.R. Stowell, Phys. Rev. Letters <u>18</u> , 902 (1967).
11.	V.J. Johnson, ed., <u>A Compendium of the Properties of</u> <u>Materials at Low Temperature, Phase I</u> , WADD Technical Report 60-56, Part II (Wright-Patterson Air Force Base, Ohio, U.S.A., 1960), p. 4.132.
12.	D.H. Martin and D. Bloor, Cryogenics 1, 159 (1961).
13.	Integral Tungsten Ceramic Crucible (AlO), Sylvania Type CS-1002-A, Sylvania Emissive Products, Exeter, New Hampshire, U.S.A.
14.	Edward J. Walker, Rev. Sci. Instr. <u>30</u> , 834 (1959).
15.	The "1958 He ⁴ Scale of Temperatures", U.S. Department of Commerce, National Bureau of Standards, NBS Monograph 10 (U.S. Government Printing Office, Washington, D.C., U.S.A., 1960).
16.	Ultraminiature Cable, BTX-42-1950, Berk-Tek Inc., Reading, Pa., U.S.A.
17.	Roger Cohen and B. Abeles, Phys. Rev. 168, 444 (1968).

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R. Meservey and P.M. Tedrow, J. Appl. Phys. <u>42</u>, 51 (1971).
T.K. Hunt, Phys. Rev. <u>151</u>, 325 (1966).

20. V. E. Holt, J. Appl. Phys. <u>37</u>, 798 (1966).