High Current Pressure Contacts to Ag Pads on Thin Film Superconductors

L. F. Goodrich, A. N. Srivastava, T. C. Stauffer, A. Roshko, and L. R. Vale

Abstract—**High current, low resistance, nonmagnetic, and nondestructive pressure contacts to Ag pads on $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film superconductors were developed in this study. The contact resistance reported here includes the resistance of the current lead/Ag pad interface, the Ag pad/YBCO interface, and the bulk resistance of the contact material. This total contact resistance is the relevant parameter which determines power dissipation during critical-current measurements. It was found that regardless of the optimization of the Ag pad/YBCO interface through annealing, a pressure contact can yield a lower total resistance than a soldered contact. The lowest resistance obtained with pressure contacts was 3 $\mu\Omega$ (for a 2×4 mm^2 contact). These contacts may be useful for many different high temperature superconductor (HTS) studies where high-current contacts with low heating are needed.**

I. INTRODUCTION

THIS study of pressure contacts was undertaken to develop the capability to nondestructively measure the high critical current (I_c) of thin film samples at various stages during post-deposition processing. At liquid He temperatures, where the critical currents are the highest, and problems with film boiling occur easily, it is necessary to maintain low lead and contact resistances. The resistance of the pressure contacts was compared with that obtained with soldered contacts to determine the relative performance of the pressure contact design. Soldering is a common method for making high current contacts. However, soldering can degrade a specimen through chemical and/or mechanical alteration caused by the solder, the soldering temperature, or the soldering iron. The pressure contacts described here were developed to reduce the effect of sample preparation and mounting on the measured value of I_c.

A previous paper [1] on pressure contacts discussed their application to Bi-based oxide/Ag tape superconductors. The pressure contacts developed for tape conductors resulted in contact resistances in the range of 0.2 to 5 $\mu\Omega$. These low contact resistance (R_c) values indicate a low Ag/HTS interface resistance and allow high-current testing with a power dissipation of a few mW at 100 A. The force used in the tape pressure contacts was far too high for thin films due to the brittle nature of the substrates, so a more resilient design was needed.

In this paper we discuss pressure contacts for critical current density (J_c) measurements of patterned YBCO films. To ensure that our measurements were not limited by second phases and patterning defects, we needed to measure films 10 to 100 μm wide. Typically, YBCO thin films patterned to these widths carry currents on the order of 0.7 to 7 A at 4 K. For a contact resistance of 1 mΩ, these currents would lead to power dissipations between 0.5 and 50 mW. It is possible to try to limit the current by patterning the films into narrower strips. However, there is a trade-off in the patterned film width, since narrow strips have uncertainty due to inherent and/or patterning defects and wide strips have uncertainty due to sample heating.

These current contacts may be beneficial to other HTS applications which require high current contacts. Thick (1 to 5 μm) film superconductors may carry significantly more current than thin (0.1 to 0.2 μm) films [2]. Newer materials which are not nearly as defect-free as YBCO films may require wide lines to avoid statistical failures due to these defects. Also, some applications, such as microwave devices, which employ wide lines, may require high currents, and testing with dc current may be simpler than microwave testing. These pressure contacts could also be used on bulk HTS conductors.

Pressure contacts as low as 3 $\mu\Omega$ were obtained. These would allow testing to 50 A with 7.5 mW of dissipation. The R_c measurements use one voltage tap on the current lead and one on the YBCO film (V_2-V_3 on Fig. 1). Thus, the R_c values reported here include the resistance of the Ag/YBCO interface, the contact/Ag interface, and the bulk resistance of the contact material.

Wire bonding is a common method of lead attachment for low current applications. For the high current conditions discussed in this paper, they are inappropriate. For example, using typical parameters for Au wire bonded leads, a 1 cm length would have a resistance of approximately 60 mΩ at 4 K. At this resistance, the lead wire would enter into He film boiling at less than 0.4 A. At current levels of 5 A, an Au wire-bond wire would dissipate 1.5 W compared to 75 μW for our contacts and superconducting lead wire.

II. DESIGN OF PRESSURE CONTACTS

The YBCO thin films on which the measurements were made were prepared by *in situ* pulsed laser ablation [3]. The 200 nm thick films were patterned using conventional microlithography with an acid etch. Ag pads with thick-

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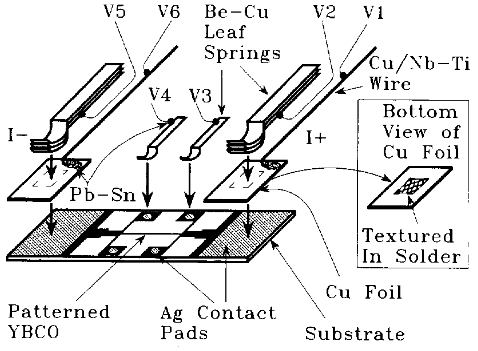

Fig. 1. Diagram of the pressure contact design using Be-Cu leaf springs and Cu/In current contacts to Ag pads on a YBCO thin film sample.

nesses from 0.25 to 3 μm were measured. The effect of spreading resistance could not be determined definitively for these thicknesses due to the high variability of the Ag pad/YBCO interface resistance. J_c of these conductors was on the order of 2.6×10^7 A/cm^2 at 0 T and 4 K. The current and voltage pads were prepared by e-beam evaporating 1 μm of silver onto the YBCO film through a shadow mask. The area of the Ag current pad was ~ 2 × 4 mm^2. On some of the films the contact resistance was measured before and after annealing the sample in oxygen.

Fig. 1 is a drawing of the pressure contact design. The current and voltage taps were made using Be-Cu leaf springs with a contact force of approximately 4.4 N (16 oz) and 0.5 N (2 oz), respectively. Be-Cu springs were chosen because they retain their elasticity at cryogenic temperatures and are nonmagnetic. For the current contacts, three stacked Be-Cu leaf springs pressed onto a Cu foil (0.2 × 2.5 × 7 mm) which had a textured In pad on its underside. The textured In pad was placed in direct contact with the Ag pad. Pure In was used since it is likely to cold-weld to the Ag surface of the YBCO specimen, thus reducing the contact resistance.

The textured In pad was made by soldering In onto the Cu foil current contact and removing residual flux with alcohol. It was then textured by rolling a knurled tool over it, thus creating a number of well-defined ridges. Since the local pressure on these ridges is high, cold welding is promoted. Texturing results in a relatively constant In thickness (0.24 mm), breaks up any surface oxide, and allows deformation to accommodate any slight misalignment of the pressure fixture. The textured In is kept in a localized area of the Cu foil so that the region of In is only positioned over the specimen and does not touch other parts of the apparatus. The area of the textured In is ~ 2 × 3 mm^2.

For the voltage contacts, narrow Be-Cu springs coated with a smooth layer of In 2% Ag solder were pressed onto the small Ag voltage pads. A low R_c is less important for the voltage contacts than it is for the current contacts. However, if the R_c of the voltage contact is larger than ~ 10 Ω, the voltage noise and uncertainty increase.

III. RESULTS

Contact resistances were measured both at liquid helium and liquid nitrogen temperatures. A valved warming chamber was used to reduce sample exposure to moisture during thermal cycling [1]. The measured contacts had linear voltage-current characteristics; R_c at 0.1 A was within 2% of R_c at 5 A. Typically, the V–I curves of the contacts were measured from 0 to either 0.2 or 1 A. Each sample was measured several times; the pressure contacts were removed and then remounted between each measurement. In some cases the sample was annealed between measurements. The results discussed below are typical of the data taken on many samples.

Fig. 2 shows the resistances of the current contacts from four successive measurements on a single sample at 4 and 76 K. The two data symbols for each measurement represent the contact resistances of the two current contacts. The R_c measurement for run A was performed with pressure contacts on as deposited Ag pads. The R_c measurement for run B was also made with pressure contacts, after the sample was annealed 1/2 hour at 200°C in flowing oxygen. The R_c measurement for run C was performed after removing the pressure contacts and then soldering leads to the Ag pads with In 2% Ag solder. The soldering iron temperature was 188°C (370°F) and the heating time was about 20 s. For run D, the R_c measurements were performed after re-soldering the contacts for a period of approximately 30 s at the same temperature.

The increase in the contact resistance between runs A and B is probably due to residual In from the pressure contacts contaminating the Ag/YBCO interfaces with In oxide during the annealing [4]. The same mechanism which increases R_c during the anneal is postulated to cause the R_c increase during soldering. The contact resistance at liquid helium temperatures was usually lower than that at liquid nitrogen temperatures. For runs C and D, however, the contact resistance was higher in liquid helium. This suggests that a semiconductor layer formed in the contact during soldering.

A similar study comparing the R_c of pressure and solder contacts was made on a YBCO film with Ag pads which had been annealed (400°C with flowing O_2 for 1/2 h). As expected this film had lower contact resistances than the unannealed film [4], and again the R_c of the pressure contacts was lower than the R_c of the soldered contacts.

Fig. 3 shows the high reproducibility of the contact resistance measurements; the maximum deviation was only 0.4 mΩ after 4 runs. The upper curve corresponds to side 1 of the conductor and the lower curve corresponds to side 2 of the conductor. The pressure contacts were removed and made again between each run. An effort was made to increase the force and change the configuration of the pressure mechanism between runs, in an attempt to lower R_c. Before run D, the sample was turned end-for-end. The contact resistance tracked with the conductor ends, not with the contact springs. The slight difference in R_c between runs C and D may be attributed to slight

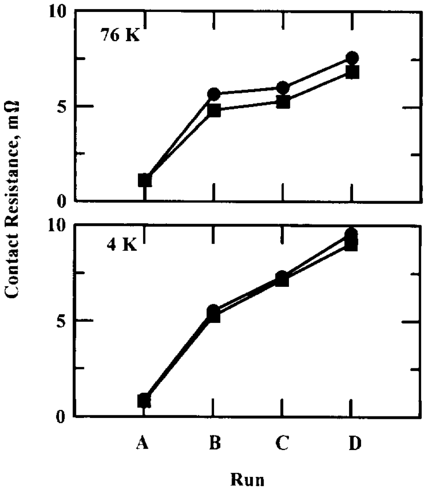

Fig. 2. Contact resistance of YBCO thin film versus run at 4 and 76 K. A) Cu/In pressure contact. B) Cu/In pressure contact after annealing film (200°C for 0.5 h in flowing oxygen). C) In-2% Ag solder contacts heated (188°C iron) for 20 s. D) Additional 30 s of heating to soldered contacts. •: side 1, ■: side 2 of the sample.

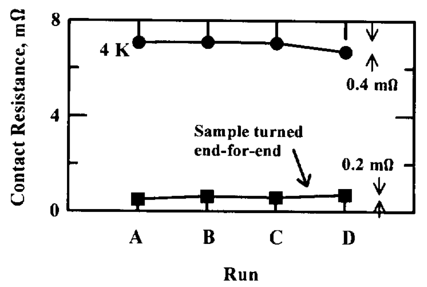

Fig. 3. Contact resistance of YBCO thin film versus run using pressure contacts at 4 K. The Ag pads on this film were not annealed after deposition. This figure demonstrates the high reproducibility of the pressure-contact resistance through repeated thermal cycles and removal and re-makes of the contacts between runs. The sample was turned end-for-end between runs C and D; R_c tracked the conductor ends. •: side 1, ■: side 2 of the sample.

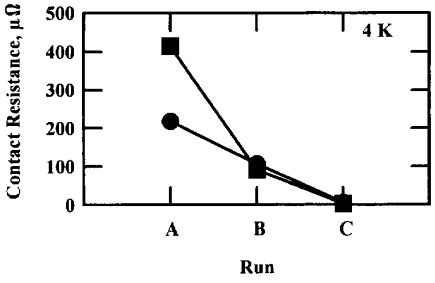

Fig. 4. Contact resistance of YBCO thin film versus run using pressure contacts at 4 K. The Ag pads on this film were not annealed after deposition before run A. A) Cu/Ag pressure contacts. B) Cu/Ag pressure contacts after the film had been annealed (400°C for 0.5 h in flowing oxygen). C) Cu/In pressure contacts •: side 1, ■ side 2 of the sample.

differences in the two spring mechanisms. The observed difference in R_c for the two ends of the film and the repeatability of the R_c measurement indicate that the Ag/YBCO interface is controlling the resulting R_c. Throughout the study, it was observed that the two ends of an unannealed film can have very different values of R_c. Changes in the force and design of the pressure contacts did not significantly change the resulting values of R_c.

Fig. 4 shows the contact resistances of pressure contacts from three successive runs on another sample at 4 K. For measurements A and B in this sequence, the Cu foil and textured In contact, shown on Fig. 1, were replaced with a Cu foil that had an Ag film deposited on one side (no In solder present). The Ag film was deposited on the Cu foil by first backsputtering the Cu, sputtering 0.5 μm of Ag, and then thermally evaporating Ag for a total thickness of about 5 μm. For run A, R_c measurements were made on the as-deposited Ag pads with these Ag-coated Cu foil contacts. Run B was made with the same contacts after the sample had been annealed at 400°C for 0.5 h in flowing oxygen. R_c dropped as expected. Finally, run C was made with the Cu foil and textured In pressure contacts. The contact resistances for run C were 3.1 and 5.6 μΩ. These results demonstrate that fairly low R_c can be obtained without using In. When no In is present, annealing lowers the contact resistance as opposed to the data of Fig. 2 where In was present. However, with an In pressure contact, R_c is ~ 100 μΩ lower than that with the Ag coated Cu foil contact.

IV. DISCUSSION

There are trade-offs between the Cu foil with a textured In surface and the Cu foil coated with Ag. The In has to be retextured before each run, and trace amounts of In can increase R_c if the sample is annealed. A thicker Ag pad on the YBCO may decrease this effect and the effect of a soldered contact, but this has not been studied on YBCO thin films. Soldered contacts to Bi-based oxide/Ag tapes where the Ag was about 25 μm thick [1] yielded lower R_c than pressure contacts. The textured In pad also tends to cold-weld to the Ag pad, thus increasing the likelihood of damaging the Ag pad when the contact is removed. The Ag-coated Cu foil yields a higher R_c but avoids the possible problems of In contamination. Au-coated Cu foil and Au pads on the film are other options which may result in lower and more repeatable values of R_c than the Ag films since Au surfaces oxidize less.

Typical Cu foil with textured In pressure current contacts had values of R_c between 0.2 and 10 mΩ for unannealed Ag pads and between 3 and 100 μΩ for annealed (400°C for 0.5 h in flowing oxygen) Ag pads. The effective resistance-area ($R \cdot A$) product of the total contact resistance can be estimated using the 2×4 mm^2 area of the Ag pads. The highest resistance, 10 mΩ, gives an $R \cdot A$ product of 8×10^{-4} $\Omega \cdot \mathrm{cm}^2$, and the lowest resistance, 3 μΩ, gives an R · A product of 2.4×10^{-7} $\Omega \cdot \mathrm{cm}^2$. These R · A products include two interfaces and some bulk resistance. Given this difference and the fact that the annealing was not optimized here, these $R \cdot A$ products are comparable to the range of numbers reported elsewhere [4] and are sufficiently low for most J_c measurements.

Placement of the voltage taps for contact resistance measurements is very important. The assumption that the voltage between V_2 and V_3 (or V_4 and V_5; see Fig. 1) gives the total contact resistance between the Cu foil and the YBCO film was tested by comparing the voltage V_1–V_6 to (V_2–V_3) + (V_4–V_5). This was done at 4 K where the Cu/Nb-Ti current leads are superconducting and the resistance of the Cu foil is low. In general, these voltages agreed to within 1%, except when the contact resistance was low. For the lowest R_c case, the two contact resistances were 3.1 and 5.6 $\mu\Omega$ and the R_c of the overall voltage taps was 10.9 $\mu\Omega$: a difference of 2.2 $\mu\Omega$. This difference is probably due to the Cu foil, the In layer, and the additional solder joints. These measurements verify the assumption that the voltage tap placement used to measure each contact (for example V_2–V_3 in Fig. 1) determines essentially all of the contact resistance. We estimate the uncertainty in our contact resistance measurements to be $\pm(2\% + 2\ \mu\Omega)$.

V. SUMMARY

Pressure contacts yield lower contact resistance than soldered contacts on thin film superconductors and are less destructive. Other HTS applications could use these high current contacts for currents as high as 50 A with dissipations on the order of 10 mW. Cu/In pressure contacts to Ag pads on bulk HTS will probably yield lower resistances than soldered contacts unless the Ag pads are very thick or the soldered contact is located away from the superconductor.

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